

The Spatial and Temporal Difference between Economic-Environment-Renewable Energy Coupling Coordination under the “Dual Carbon” Target: Evidence from China

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Abstract. Under the background of China’s “Dual Carbon” Target (carbon peaking and carbon neutrality goals), this article in order to explore the development of economic, environmental and renewable energy (REE) coupling coordination and spatial differences in 30 provinces and cities in China from 2013 to 2021, study and analyze the relevant factors affecting the coupling coordination of the REE systems, and predict the future coupling of China's four regions, coordinate the development situation, expand the research perspective of renewable energy, and put forward countermeasures and suggestions based on the research content. Research methods: coupling coordination model, geographical detector, GM (1.1) gray prediction model. The study results reveals that the coupling coordination of REE in 30 provinces and cities across the country shows a steady upward development trend from 2013 to 2021, but the number of provinces in the category of coordinated development is small, and most of them are concentrated in the eastern and coastal provinces, and the coupling and coordination between the western and northeastern provinces is not for optimism. Economic and environmental factors have a significant impact on the coupling and coordinated development of the REE systems, among which the economic impact plays a leading role. The eastern and central provinces will take the lead in reaching a strong coupling state in the future, followed by the western and the northeast provinces.

Keywords: Coupling coordination; renewable energy; gray prediction.

1. Introduction

In order to accelerate the green transformation of the economy and society, improve the quality of the ecological environment and promote global sustainable development, general secretary Xi Jinping, solemnly put forward the “dual carbon” target at the 75th session of the General Assembly in 2020. As an important foundation for the development of human society, national economic growth and modern civilization, traditional fossil energy still plays an irreplaceable and fundamental role at this stage. China's current energy structure also presents obvious high-carbon characteristics, and the way to realize the “dual carbon” target is to adjust the energy structure and promote the development of the clean energy industry. As an important influencing factor in the process of energy acquisition and utilization, the environment will not only be affected by the many negative impacts brought about by the exploitation and use of fossil energy but will also determine to a large extent whether the socio-economic development can be healthy and sustainable. For a long time, the rapid development of industrialization and urbanization has brought much attention to the environmental problems, and in achieving China's economic leaping development is also accompanied by serious resource consumption and environmental pressure. However, China has laid a solid technological and industrial foundation in areas related to low-carbon transformation and development, and most of the renewable energy reserves have good potential for development. Therefore, how to promote the coordinated coupling of renewable energy, environment and economy will be a must for the implementation of China's sustainable development strategy. This paper takes the "energy-economy-environment" system (hereinafter referred to as the 3E system) as the basic theoretical framework, chooses renewable energy as the main research object, focuses on 30 provinces and cities in China to conduct research, analyses and explores China's high-quality green development mode and road in the target period with the regional perspective.

2. Literature Review

Along with the end of the second oil crisis and the increase of energy demand, energy issues have become a key area of concern for scholars at domestic and abroad. In terms of model construction, most of the scholars' researches have obvious progressiveness, from the initial econometric general equilibrium model gradually to the comprehensive integrated model; with the rise of 3E system research, scholars realize that the energy, economic and environmental systems show the characteristics of geographic as well as coupled and coordinated analysis of the basic research methodology of the academic results have increased rapidly [1-3]. However, most of these studies have a high degree of similarity in paradigm, and the interaction between the three has been fully confirmed. From the point of view of energy types, compared with traditional energy sources, China's renewable energy research is relatively insufficient, while foreign scholars as early as in the last century have paid attention to its economy and its role in environmental protection [4]. With the landing of the "dual carbon" target, China's renewable energy has ushered in a critical period of opportunity, and scholars have contracted the relevant foreign research, focusing on the domestic market, forming three major research areas of technology, industrial development, and specific applications [5-7]. In addition, in terms of research content, some scholars refer to the "energy-economy", "environment-economy" and other research structure to new energy as the main body of the construction of the "renewable energy-economy", "renewable energy-environment" binary system [8].

In terms of research scale, the current scholars mainly to a single province or resource-based city group as the object, at the national level for the 3E system and even renewable energy ternary synergistic research content is less or even still in the blank stage. As one of the countries with the world's fastest development of renewable energy and the largest development potential, China has no experience or case to learn from other countries in the exploration of REE, which also provides a huge development space for the research of this paper. Combining the data related to renewable energy, economy and environment in 30 provinces and cities in China during 2013-2021, this paper adopts the entropy value method to determine the weights, uses the coupling coordination degree model to analyze the spatial and temporal characteristics of the interaction among the three, combines the geographic detector to explore the key driving factors affecting the degree of coordination of the coupling and introduces the gray prediction model to estimate the future regional trends, and overall the study will analyze the comprehensive development the whole country's level of REE, and further explore the effective path to realize high-quality sustainable development in China under the background of "dual carbon".

3. Methodology

3.1. Data Source

This paper is based on the statistical data provided by China Electricity Statistical Yearbook, China Urban Statistical Yearbook, EPS database and China National Bureau of Statistics during the period of 2013-2021, and takes 30 provinces, municipalities and autonomous regions in China as the research object for data construction. In the previous study, due to multiple factors such as geography and environment, the development trend of the renewable energy sector in Shanghai was proved to be not significant. In order to ensure the scientific validity and rationality, the study decides not to include Shanghai in this study.

3.2. Entropy Method

Since different indicators have positive and negative impacts on renewable energy, the environment and the economy, they need to be standardized separately by scaling all the indicator data to an interval of 0 to 1 to establish comparable linkages between the indicators for different factors. The calculation formula is as follows:

$$y_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}} \tag{1}$$

$$y_{ij} = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}} \tag{2}$$

In order to avoid that some of the indicators are 0 values that cannot take logarithm, the indicators are shifted by 0.001. Then by using the product of the percentage of the score of each influencing factor under each indicator and the weight of the indicator to indicate the score of the factor in the whole decision-making process, according to the entropy value method, the entropy of the j indicator of each system is calculated as:

$$e_j = -k \sum_{i=1}^m p_{ij} \ln p_{ij} \quad k > 0, 0 \leq e_{ij} \leq 1 \tag{3}$$

The entropy method weights are calculated as:

$$w_j = \frac{g_j}{\sum_{j=1}^n g_j} \tag{4}$$

As shown in Table 1, this study obtains 16 tertiary indicators, including total indicators, efficiency indicators and environmental pollution indicators [9].

Table 1. Coupled REE development harmonization indicator system

First index	Second index	Third index	Weight	Indicator effect	
x(Renewable Energy Subsystem)	x ₁ (Total amount index)	x ₁₁ (Hydropower generation)	0.4 274	+	
		x ₁₂ (Wind power generation)	0.2 612	+	
		x ₁₃ (Solar power generation)	0.3 114	+	
y(Environment subsystem)	y ₁ (Environmental pollution index)	y ₁₁ (Total per capita emissions of sulfur dioxide)	0.0 279	-	
		y ₁₂ (Total per capita ammonia nitrogen emissions)	0.8 066	-	
		y ₁₃ (Urban wastewater discharge)	0.0 156	+	
	y ₂ (Environmental governance indicators)	y ₂₁ (Volume of wastewater recycling)	0.0 556	+	
		y ₃ (Environmental Optimization Indicators)	y ₃₁ (Green coverage rate of built district)	0.0 711	+
			y ₃₂ (Per capita public green space area)	0.0 233	+
z(Economy subsystem)	z ₁ (Total amount index)	z ₁₁ (Gross domestic product per capita)	0.1 248	+	
		z ₁₂ (Value added of the primary industry)	0.1 420	+	
		z ₁₃ (Value added)	0.1 988	+	
	z ₂ (Performance indicator)	z ₁₄ (Total retail sales of consumer goods)	0.1 873	+	
		z ₁₅ (General budget revenue)	0.1 722	+	
		z ₂₁ (Per capita disposable income)	0.1 004	+	

z_{22} (Per capita consumption expenditure of residents)	0.0 745	+
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3.3. Coupling Coordination Model

Coupling refers to the mechanism in which two or more systems interact and influence each other. The coupling coordination degree model mainly evaluates the degree of interaction and coordinated development between systems by calculating the coupling degree C value, the coordination index T value and the coupling coordination degree D value. The specific formulas for constructing the coupling coordination degree model of REE are as follows:

$$C_j = \sqrt[3]{\frac{Y_{1j}+Y_{2j}+Y_{3j}}{\frac{Y_{1j}+Y_{2j}+Y_{3j}}{3}}} \tag{5}$$

$$T_j = \alpha Y_{1j} + \beta Y_{2j} + \gamma Y_{3j} \tag{6}$$

$$D_j = \sqrt{C_j * T_j} \tag{7}$$

Where D_j is closer to 1, which represents the more the three systems tend to be ordered and coordinated, this study refers to the study of Lu and Guo’s study and the classification of coupling coordination degree hierarchy for the classification is shown in Table 2 [10].

Table 2. Criteria and classification type for coupling coordination model

Disorder decline class		Coordinated development class	
Coordination degree	Type	Coordination degree	Type
0~0.09	Extreme disorder recession class (EDRC)	0.50~0.59	Reluctantly coordinated development category(RCDC)
0.10~0.19	Severe dysfunctional recession(SDRC)	0.60~0.69	Primary coordinated development category(PCDC)
0.20~0.29	Moderate disorder recession class(MDRC)	0.70~0.79	Intermediate coordinated development category(ICDC)
0.30~0.39	Light disorder recession class(LDRC)	0.80~0.89	Good coordinated development category(GCDC)
0.40~0.49	Near disorder recession class(NDRC)	0.90~1.00	Quality coordinated development class(QCDC)

3.4. Geographical Detector

Geographical detector can detect the spatial heterogeneity of the dependent variable under different stratification of the independent variable and can explain the driving force [11]. The equation is:

$$q = 1 - \sum_{h=1}^L N_h Q_h^2 \tag{8}$$

3.5. Gray Prediction

Gray prediction model is a method of predicting gray systems by constructing mathematical models using a small and incomplete amount of information. Its core lies in exploring the future development trend and condition of things by establishing gray GM (1.1) differential equations.

At the same time, in order to facilitate the research, this paper decomposes the 30 provinces and cities in the country under study into 9 provinces and cities in the east; 3 provinces in the northeast; 6 provinces in the center and 12 provinces in the west, taking into account the division of the region by the scholars of Xu J and Xie HQ and the relevant standards of the National Bureau of Statistics [12, 13].

4. Result and Analysis

4.1. Spatial and Temporal Distribution of the REE

As shown in Figure 1, the overall trend of the coupled coordination degree of the three systems in the nine provinces in the region is heading towards a good direction, showing an upward trend, without a significant decline. In 2017, the coupled coordination degree of the three systems in Guangdong, Jiangsu and Shandong exceeded 0.5 and entered the degree of coordinated development, and Hebei and Zhejiang have also realized the economic-environmental-renewable energy barely coordinated development in 2018 and 2019 successively. With a coupling degree of coordination of 0.3 as the boundary, the initial value of the coupling degrees of Beijing, Tianjin and Hainan were low and slow growth rate, 2021 were still in the category of intermediate and mildly dysfunctional decline, compared with other provinces and municipalities with a large gap; the northeastern provinces, REE coupling and coordinated development of the situation of steady upward to 2015 as a turning point, 2013-2015 showed a steady upward trend. The northeastern provinces' REE coupling and coordination development were stable and upward, with 2015 as the turning point, a stable trend from 2013 to 2015, and a significant increase in the degree of coupling coordination from 2016 to 2021.

However, the coupling coordination degree of the REE systems in the northeastern region was in the category of dysfunctional decline, with the maximum value of 0.4633 in Liaoning province in 2021, which has not yet exceeded the threshold value of 0.5; in addition to the relatively large decline in Henan province in 2013-2014, the coupling coordination degree of the six central provinces has also shown a general increase in the situation. , Anhui, Shanxi and Jiangxi are basically converging until 2018. Hubei had the highest initial coupling coordination value of 0.3947, while Henan maintained a high rate of growth in four years after some decline, and finally reached a three-system coupling coordination degree of 0.5871 in 2021, ranking first in the central region. Half of the six provinces are in the category of barely coordinated development in 2021, including Anhui, Henan, and Hubei, while the other half were in the category of on the verge of dysfunction and decline, including Hunan, Jiangxi, and Shanxi; and there was a relatively large gap in the coordinated development of the three-systems coupling among the 12 western provinces, with only the Neimenggu, Sichuan, and Yunnan in the category of barely coordinated development in 2021. Among them, Guangxi, Guizhou, Gansu, Chongqing, and Ningxia had a relatively homogeneous degree of three-system coupling development, with a mean value in the 0.31-0.37 range. Comparatively speaking, the degree of REE coupling coordination in Sichuan was relatively good, reaching 0.6154 in 2021, which was a state of primary coordinated development. On the other hand, Xinjiang and Xizang showed the development trend of "rise-fall-rise", and there was a certain gap between the coupling and coordination of the three systems and that of other regions in the west.

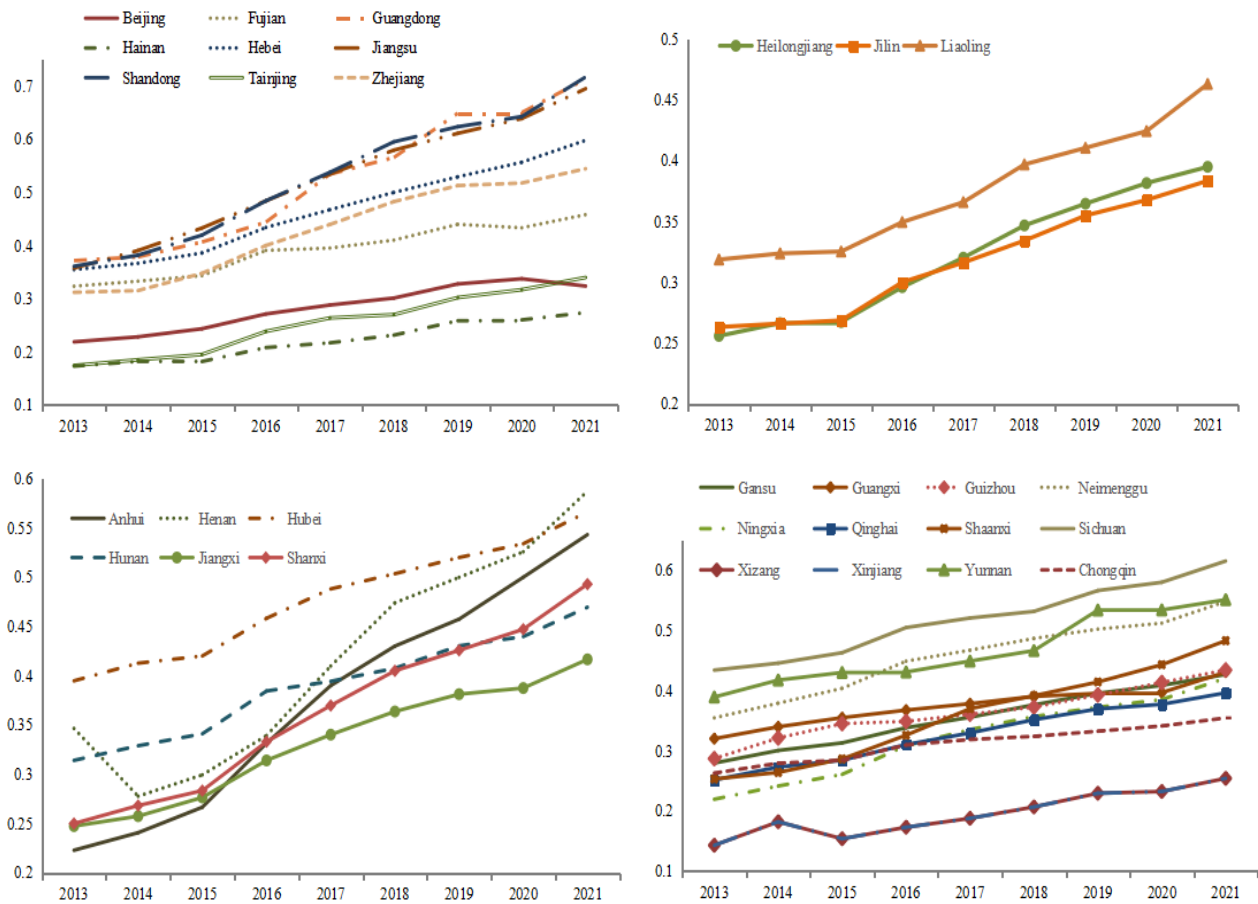


Fig 1. Evolution of the coupling coordination degree of the four regions (Picture credit: Original)

Overall, the development of REE coupling coordination degree of the 30 provinces and cities in the country have shown an upward trend, with the eastern part and the central part of the country showing a more significant situation, and at the same time, the phenomenon of development imbalance is more serious, combined with Figure 2, exhibiting that the degrees of coordination of the coupling of the coastal areas are higher, while the western part and some inland areas are poorer.

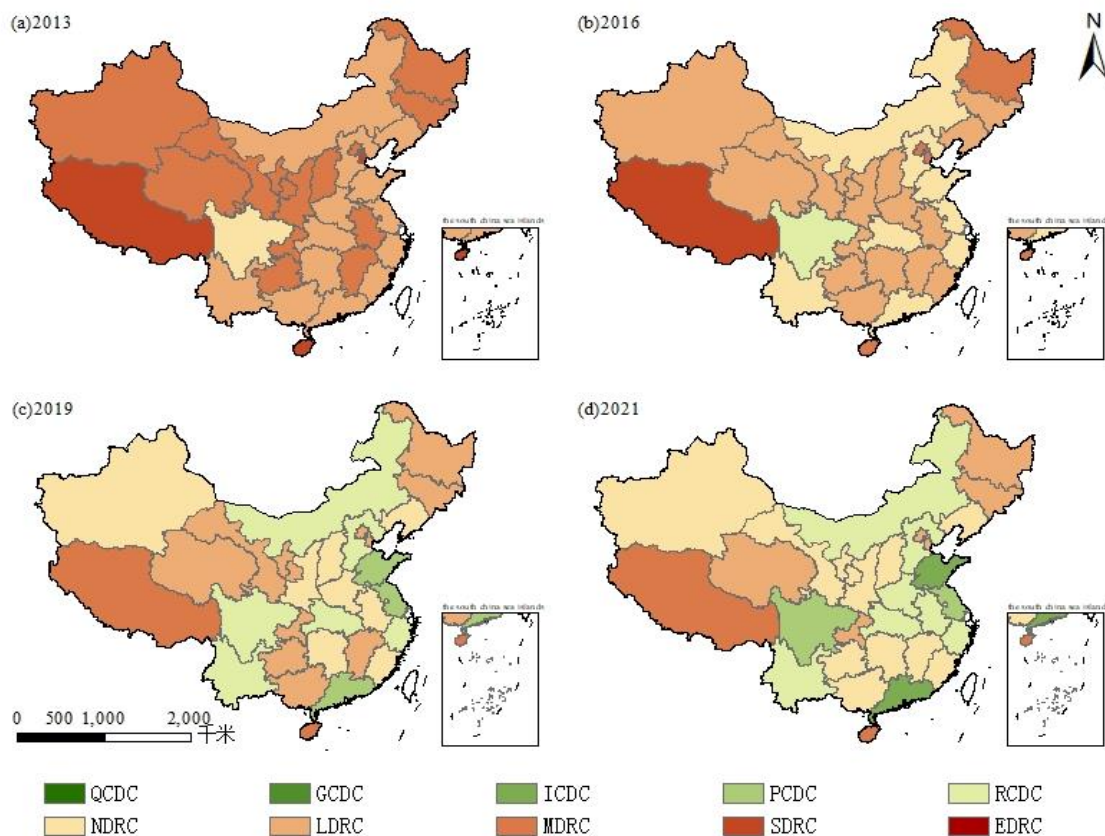


Fig 2. The evolution diagram of coupling coordination degree in the study area (Picture credit: Original)

Sichuan shifted from the category of on the verge of dysfunctional recession to the category of barely coordinated development during 2013–2016, while central and coastal provinces gradually shifted from the category of moderate or mild dysfunctional recession to the category of on the verge of dysfunctional recession. During this period, the National Energy Board in 2013 issued opinions on promoting the development of the wind power industry, the following year China issued opinions on comprehensively deepening the revolution in energy production and consumption to promote the clean and low-carbon development of energy, which put forward the overall requirements of the energy revolution and the main tasks. In 2015 Renewable Energy Development The release of the "13th Five-Year Plan" clarified the overall goal as well as the overall path of renewable energy development, promoting the green transformation and upgrading of energy, and further promoting the restoration and improvement of the environment. Between 2019–2021, Shandong and Guangdong have achieved intermediate coordinated development, with the National Development and Reform Commission, the Energy Bureau of wind power, solar photovoltaic power and other favorable policies continued to be introduced, only the Xizang among the 30 provinces and cities in the country was still in a state of moderate dislocation and decline, the differences between the regions were shrinking, and the efficiency of the utilization of renewable energy was also improving.

4.2. Factors Influencing the Spatial and Temporal Variability of Coupled REE

4.2.1. Selection of influencing factor

By drawing on the results of previous researchers and combining the actual situation of this study, this paper retains the three major fields covering REE while introducing the field of science and technology [14]. 12 influencing factors were finally selected in Table 3.

Table 3. Related influencing factors

Influencing factor	Impact factors	Code
economy	The added value of the primary industry (billion yuan)	X1
	Total retail sales of social consumer goods (billion yuan)	X2
	General budget expenditure of local finance (billion yuan)	X3
	Local fiscal expenditure on environmental protection (billion yuan)	X4
environment	Total sulfur dioxide emissions per capita (tons / ten thousand people)	X5
	Sewage recycling (ten thousand tons)	X6
	Green coverage rate of built-up area (%)	X7
renewable energy source	Power generation (hydropower) (billions of kilowatt hours)	X8
	Power generation (wind power) (billions of kilowatt hours)	X9
	Power generation (solar power) (billions of kilowatt hours)	X10
science and technology	Number of patent applications (number)	X11
	R & D expenditure (ten thousand yuan)	X12

4.2.2. Detection result

In this study, the q-value and P-value of each influencing factor affecting the level of coupled and coordinated development of 30 provinces and cities across the country are derived with the help of factor detector analysis. The factor detectors are utilized to detect the level of influence of 12 influencing factors on the spatial and temporal divergence of the coupled economic-environmental-renewable energy system as in Table 4.

Table 4. Results of exploring impact factors (time period)

		2013		2021	
factor	q statistics	p value	factor	q statistics	p value
X1	0.5675	0.0000	X1	0.7124	0.0000
X3	0.4739	0.0297	X3	0.6951	0.0327
X7	0.3618	0.0984	X7	0.5980	0.0000

The analysis results showed that among the 12 influencing factors, the economic factor value added of the primary industry, the general budget expenditure of local finance, and the environmental factor greening coverage rate of built-up areas had a significant influence on the spatio-temporal divergence of the coupled system, with the strongest explanatory power in the economic domain. In Table 4, compared and measured the influence of the three factors separately, the paper illustrated the influence of all three increases gradually over time. As an important indicator of agricultural production, the added value of primary industry not only reflected the level and efficiency of agricultural production, but also directly related to the sustainable use and protection of the environment; the size and structure of the general budget expenditure of the local finance directly affected the coverage and quality of local public services, and had an important supporting role for the sustainable development of the economy and society; and the greening coverage rate of built-up areas, as one of the important indicators of environmental quality, at the same time, had an important supporting role. The greening coverage rate of built-up areas, as one of the important indicators of environmental quality, can also reflected the investment of local governments in environmental protection and other fields.

4.3. Future Evolution of the Coupled REE

Combined with the division criteria in the previous section, the coupling coordination degree of each region is aggregated and calculated based on the gray GM (1.1) prediction model, and the length of the prediction stops when the coupling coordination degree reaches 1.

As shown in Table 5, the development trend of the coupled REE coordination degree in the four major regions will roughly continue the change characteristics from 2013-2021. Among them, the eastern provinces have the best development, and will reach high-quality coordinated development after 2022; the northeastern provinces have a relatively slow degree of coordinated development, and are expected to change from the dysfunctional decline category to the coordinated development category in 2029, and enter into the high-quality coordinated development type after 2037; compared with the northeastern provinces, the central and western provinces have higher initial values, and reach the strong coupling in 2027 and 2032, respectively. However, due to the limitation of data acquisition, the constructed regional coupled coordinated development system of the three systems does not completely and fully reflect the development of the economy, environment and renewable energy in each province, which will also have a certain impact on the prediction results.

Table 5. Projected development of coupled REE harmonization in four regions

Forecast year	East provinces	Northeast provinces	Provinces in central part	Estern provinces
2022	0.9174	0.3317	0.6821	0.5786
2023	0.9824	0.3548	0.7275	0.6200
2024	0.0000	0.3795	0.7760	0.6484
2025	0.0000	0.4059	0.8276	0.6781
2026	0.0000	0.4342	0.8827	0.7091
2027	0.0000	0.4644	0.9414	0.7415
2028	0.0000	0.4967	0.0000	.7754
2029	0.0000	0.5312	0.0000	0.8109
2030	0.0000	0.5682	0.0000	0.8480
2031	0.0000	0.6077	0.0000	0.8868
2032	0.0000	.6500	0.0000	0.9274
2033	0.0000	0.6953	0.0000	0.9698
2034	0.0000	0.7436	0.0000	0.0000
2035	0.0000	0.7954	0.0000	0.0000
2036	0.0000	0.8507	0.0000	0.0000
2037	0.0000	0.9099	0.0000	0.0000
2038	0.0000	0.9732	0.0000	0.0000

5. Conclusion

This paper mainly draws the following conclusions. First, the development of the coupled coordination degree of the three subsystems in 30 provinces and cities across the country from 2013 to 2021 generally shows an upward trend, with different increases in each province and large differences in starting values. From a regional perspective, the degree of REE coupling coordination is significantly higher in the eastern and central regions than in the northeastern and western regions. However, in general, there are fewer provinces with high coupling, and most of them are still in the range of extreme dislocation to near-dislocation recession, which is urgently needed for realizing green sustainable development; Secondly, the factors affecting the level of coordination of the REE system coupling in 30 provinces and cities across the country are composed of multi-party factors, which cover the two major categories of the economy and the environment; Thirdly, dynamic simulation predictions show that the coordination of the REE system coupling in the 30 provinces and cities of China will improve significantly, but the starting value is quite different in the future.

Based on the above findings, the following recommendations are proposed. First, enhance inter-regional cooperation and policy coordination: In view of the current situation and characteristics of REE development in different regions, it is recommended to strengthen inter-regional cooperation and exchanges, and formulate policies and measures in line with the actual situation of the localities, so as to promote synergistic development of the economic, environmental and energy fields and to realize the goal of sustainable development. Second, strengthening environmental protection awareness and technological innovation: It is recommended to reasonably increase local financial expenditures on environmental protection projects, continue to strengthen public awareness and education on environmental protection in all sectors of society, and raise public awareness of and attention to environmental issues. At the same time, enterprises should be encouraged to increase their investment in environmental protection and promote the development of green technology and environmental protection industries, so as to realize a virtuous cycle of economic growth and environmental protection. Third, continue to improve the energy structure and security of supply: it is recommended to increase investment in and support for renewable energy, and promote the innovation and application of renewable energy technology. At the same time, the government should strengthen the regulation and standardization of the energy market, establish a sound energy security system, ensure the safety and reliability of energy supply, gradually reduce the dependence on traditional fossil energy sources, alleviate the pressure on the environment, and realize the sustainable development of the economy, environment and energy.

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