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Original Research

Environment and Energy: Research on the Impact of Collaborative Governance of Pollution Reduction and Carbon Reduction on High-quality Development of Energy

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Abstract

This paper aims to empirically assess the effect of collaborative governance of pollution reduction and carbon reduction on high-quality development of energy across China's provinces. Against the backdrop of "peak carbon dioxide emissions and carbon neutrality", high-quality development of energy is an important part of achieving high-quality development. As China's ecological civilization construction enters a new stage, whether the collaborative governance of pollution reduction and carbon reduction can effectively guide and empower the high-quality development of energy requires both theoretical explanation and empirical testing. To solve this problem, this paper employs China's provincial panel data from 2013 to 2022. The projection pursuit method and the coupling coordination model are used to measure the core variables. On this basis, its direct effects, heterogeneity effects, and nonlinear effects are discussed by using a variety of models. The results show that: firstly, the collaborative governance of pollution reduction and carbon reduction has a direct role in promoting the high-quality development of energy, the influence coefficient is 0.065; secondly, the promotion effect has a heterogeneous effect, showing the gradient decline feature of "eastern > central > western" and "non-energy-rich areas > energy-rich areas"; finally, its influence has a threshold effect, when the advancement of industrial structure is higher than the threshold value of 2.474, the level of urbanization is between 0.734 and 0.748 threshold values and environmental regulation is higher than the threshold value of 2.793, the impact is more positive. This paper not only provides a scientific basis and theoretical reference for helping China to achieve the high-quality development of energy, but also further looks forward to the potential policy actions in the future. These actions include driving technological innovation, optimizing policies and regulations, deepening

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international cooperation, and raising public awareness of environmental protection. The paper aims to contribute to China's energy transition and sustainable development within a broader global context.

Keywords: collaborative governance of pollution reduction and carbon reduction, high-quality development of energy, projection pursuit, coupling coordination model, multiple threshold effects

Introduction

In recent years, fossil energy has persistently maintained its dominance on a global scale, notwithstanding the substantial growth in installed renewable energy capacity. The most recent Statistical Review of World Energy, published by the Energy Institute, indicates that 81% of the world's energy came from fossil fuels in 2023. This long-term consumption pattern of dependence on fossil fuels has resulted in unprecedented levels of global primary energy consumption and carbon emissions. This situation exacerbates the climate change crisis and poses significant challenges to energy transition issues, including international energy security and scarcity. China, as the leading energy consumer and the top carbon emitter globally [1, 2], has drawn significant international attention due to its adjustments in energy structure and the swift growth of renewable energy, thereby demonstrating strong potential for future development. World Energy Outlook 2023, published by the IEA, highlights that "China's average investment in clean energy technologies is well over USD 650 billion per year, and by 2050, it will account for half of global solar PV capacity". This suggests that the global energy transition will be greatly impacted by China's changes to its energy strategy. In this context, the Chinese government is dedicated to promoting the high-quality development of energy (*HQDE*). At the policy level, it requires that *HQDE* make significant strides and construct a contemporary energy system by 2035, and further enhance the proportion of non-fossil energy consumption, building upon the objective of achieving 25% by 2030. This magnificent blueprint not only embodies the proactive role of the Chinese government in contributing to global climate governance but also demonstrates its firm stance on the deep adjustment of the domestic energy structure. However, connecting the evolution of energy policies and legal documents of various countries, as shown in Fig. 1, although the Chinese government has recently promulgated a series of clean energy action plans and strategies, how to effectively raise the share of renewable energy shortly and accelerate the smooth transition and replacement process of fossil energy still faces obstacles, and there is still a considerable gap from the set goals. Therefore, it is imperative to promote China's *HQDE*.

On March 19, 2025, a World Meteorological Organization report indicated that in 2024, the indication of climate change caused by humans is evident and has intensified. Since satellite observations started, the rate of sea level rise has doubled, and the last ten years have all been the warmest on record. This dire situation underscores the pressing need to enhance international climate action and improve environmental governance. To facilitate a more intuitive understanding of China's

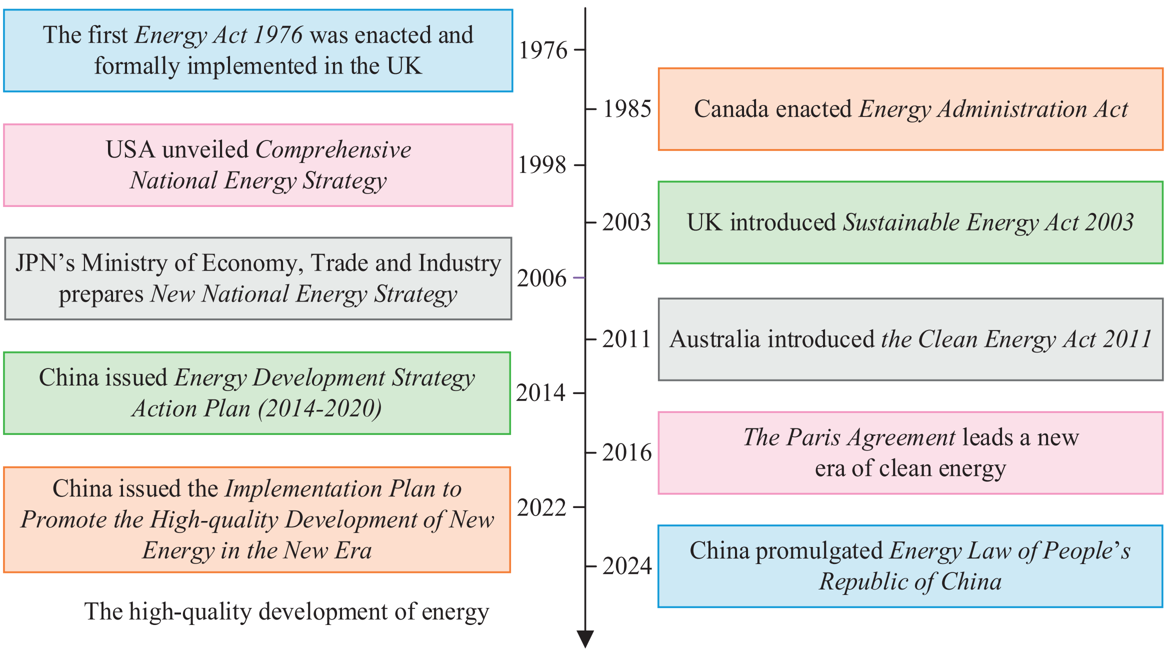

Fig. 1. International energy development process.

situation within the global carbon emission pattern, this paper selects representative countries from five continents and compares their per capita CO_2 emissions, as illustrated in Fig. 2. Even though every country across the globe strives to foster energy conservation and reduce emissions, per capita CO_2 emissions still show great differences and fluctuations. Standing as the largest developing nation on a global scale, China occupies a distinctive and significant position in global environmental governance. Compared to RUS, USA, ZAF, and AUS, China's per capita CO_2 emissions are relatively low. This can be attributed primarily to two factors: First, the "dilution effect" resulting from China's large population; Second, China's proactive engagement in fulfilling its climate commitments and participating in global climate governance cooperation, thereby demonstrating its responsibility as a major nation. Concurrently, this phenomenon underscores the necessity and strategic value of advancing environmental governance within China. China's economy and society have entered a significant stage of development, which also represents a crucial opportunity for promoting energy transformation and environmental protection. During this period, China faces the dual tasks of environmental governance. Greenhouse gas emissions and other environmental pollutants have strong emission homology and the same effect as control measures. Pollution reduction and carbon reduction gave birth to a transition in correlation from weak to strong [3]. In this context, China's energy and environmental policies have undergone a series of major adjustments and innovations, aimed at intensifying carbon emission reduction efforts and strengthening environmental pollution control. Promoting the collaborative governance of pollution reduction and carbon reduction (*CGPRCR*) has emerged as a pivotal environmental regulatory instrument in China for the foreseeable future. The innovative implementation of this governance model is instigating significant transformations within the energy system and creating unparalleled opportunities for *HQDE*.

Therefore, a realistic question worth pondering is: Can *CGPRCR* become an engine for *HQDE*? If the answer is yes, what is the influence mechanism between the two? Simultaneously, does the influence present distinct laws and characteristics, given the heterogeneity of China's different regions? This study aims to answer the previously mentioned queries and provide a feasibility study and proposals for promoting *HQDE* through *CGPRCR*. It will also have an impact on global environmental governance and sustainable development: On the one hand, *CGPRCR* is a novel strategy put forth in response to the pressing demands of environmental preservation and global climate change. The simultaneous control of pollution reduction and carbon reduction can effectively promote global environmental governance and serve the green earth project. Additionally, it serves as an effective reference for the achievement of the Paris Agreement and peak carbon dioxide emissions and carbon neutrality, and it adds to Chinese wisdom and Chinese solutions for global environmental governance. On the other hand, other developing countries, such as India and other countries with similar development conditions to China, also face multiple challenges of environmental pollution control and energy structure adjustment. For these countries, this research can provide a theoretical foundation as well as a reference, facilitating their further integration into the global "environment-energy" composite governance system.

In contrast to other research, this paper is dedicated to delving into the multifaceted effects of *CGPRCR* on *HQDE*, and there may be three marginal contributions: First, with respect to research theme, this paper focuses on the core theme of the relationship between the two, which is different from previous studies from a single angle or local scope. By comprehensively and systematically discussing the complex influences between the two, this paper provides theoretical support for them. Second, in terms of variable measurement, this paper constructs an evaluation index of *HQDE* according

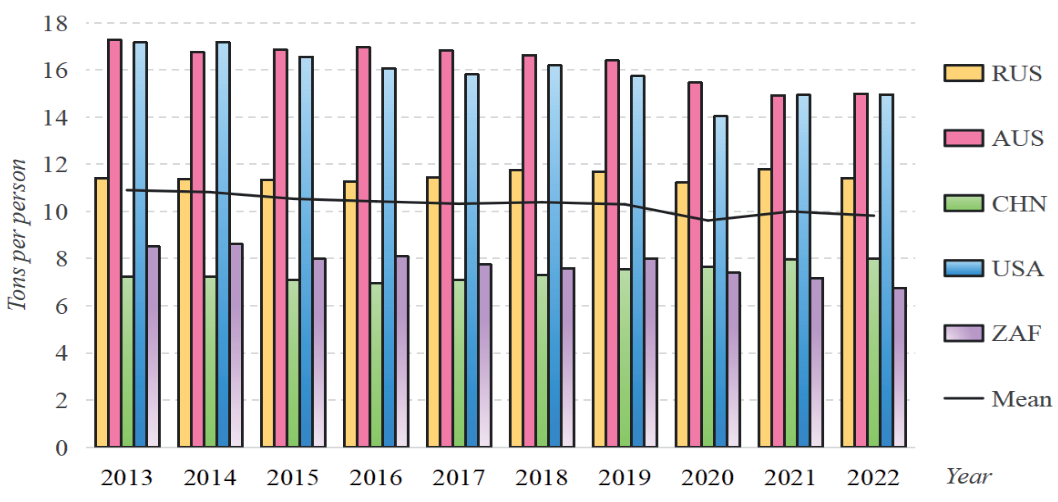

Fig. 2. Comparison of international per capita CO_2 emissions.

to the Energy Production and Consumption Transition Strategy (2016-2030), which can scientifically measure the degree of it. Third, in terms of research methods, this paper applies an empirical research approach that examines the intricate relationship between the two and identifies notable geographical variations in this effect. Meanwhile, this paper also uses threshold regression analysis and other methods to undertake a penetrative analysis of the nonlinear effects between the two. Three threshold variables are added to explore its complex mechanism. It can effectively identify the critical point of the enabling effect and the change law of the marginal effect, help the government to formulate more accurate and effective policy measures, provide theoretical support for *CGPRCR* to promote *HQDE*, and contribute theoretical basis and reference for China's construction of energy power.

The second section comprises a literature review, sorting out the relevant research on *CGPRCR*, the relevant research on environmental governance and energy development, and the relevant research on *HQDE*. The paper's hypotheses are expounded upon in the third section. The fourth section introduces the model's creation, the measurement of linked variables, and each of the data sources. The analysis of the empirical data and a series of thorough robustness tests are performed in the fifth section to reaffirm the study hypothesis's validity. The sixth part draws the main conclusions and research enlightenment of this paper.

Literature Review

Relevant Research on CGPRCR

Three aspects can be used to categorize the research of *CGPRCR*: concept traceability, antecedents, and after-effects. Concerning the concept of traceability, the concept of synergy was first put forth by Haken [4], which was mainly applied to the field of natural science. In 1991, Weidlich introduced the function of synergy into the domain of social science research and established a comprehensive framework for quantitative analysis in social sciences [5]. The study of *CGPRCR* emerges from the convergence of synergy effects and public environmental governance [6]. Based on the theory of collaborative governance, highlights moving from a disorderly to an orderly collaborative emission reduction in the subsystem for reducing greenhouse gas emissions and pollutants [7]. Concerning antecedent studies, current research has validated the positive impacts of advancements in energy-saving technology progress, financial inclusion, and upgrading of industrial structure on pollution reduction or carbon reduction governance [3, 8, 9]. Concerning after-effect studies, coordination of efforts to lower carbon emissions and pollution benefits inhabitants' health [10], decreasing the entire society's cost of emission reduction [11], and giving impetus to the green transformation of industry [12].

Relevant Research on Environmental Governance and Energy Development

The research on environmental governance and energy development is placed on two distinct levels: macro and micro.

At the macro level, governments worldwide are promoting the harmonious coexistence of energy and environment through various policy tools. The EU's European Green Deal is a major highlight at the international level, aiming to reduce emissions, improve efficiency, and promote renewable energy among member states, to build a modern economic system that is resource-efficient and environmentally friendly. The Chinese government is leading the optimization of the energy structure and environmental improvement through laws and regulations, strategic planning, and financial subsidies, such as carbon trading policies and green financial tools [13]. The negative externalities of environmental issues, as well as the scarcity of energy, have underscored the limitations of market mechanisms. Therefore, environmental regulations have become a common choice for governments worldwide to address market failures and encourage enterprises to diminish their dependence on fossil fuels while simultaneously enlarging investments in renewable energy [14, 15]. Against this backdrop, local governments also respond actively, strictly focusing on the construction of ecological civilization, pushing forward the transformation of industrial structure [16], and accelerating the development of clean energy by reducing fossil energy consumption and applying negative carbon technology [17]. Meanwhile, international cooperation projects, such as the photovoltaic power station jointly built by China and the Central African Republic and the Xaysomboun Low-Carbon Demonstration Zone in Laos, demonstrate the significant role of cross-border cooperation in addressing climate change and fostering the combined advancement of energy and environment.

At the micro level, global enterprises are actively exploring technological innovation, combining clean production with comprehensive waste utilization, and realizing a circular economy model, which not only reduces environmental governance costs but also improves environmental benefits [18]. Industrial enterprises, as the main source of air pollution emissions and the key force in control, have installed advanced treatment equipment, strengthened environmental management, and promoted clean energy transformation through production process innovation [19, 20]. In addition, with the awakening of global environmental awareness, individual actors have become a force to be reckoned with. They contribute to global environmental governance and sustainable energy development by reducing energy consumption, choosing environmentally friendly products, and participating in corporate behavior supervision.

Relevant Research on HQDE

Scholars have carried out extensive research on *HQDE*, mainly involving three aspects: energy consumption transformation, energy structure adjustment, and energy technology innovation. Firstly, with the limited traditional energy resources and the escalating environmental issues, the development of environmentally friendly and renewable new energy has become a momentous component of sustainable development [21]. Promoting the transformation of energy consumption and the direction of low-carbon development of new energy, and establishing a self-sufficient, regulated, secure, and dependable energy security framework can advance *HQDE* [22]. Secondly, scholars analyzed China's energy demand and the challenges and opportunities it faces. Relatively little amounts of renewable energy are propelling economic progress [23], and the unbalanced energy development remains a persistent challenge. The key point of attaining high-quality economic development in China resides in the capacity to effectively modify the energy structure [24]. Thirdly, new energy technologies are the pillar of the high-tech industry, opening up a new era of energy and gradually improving the grid-related performance of new energy power generation [25]. Renewable energy technologies are expected to progressively contribute to industry growth. These technologies generate learning effects and foster the development of persistent innovation [26].

Based on the aforementioned studies, there exists potential for enhancement in the current research: Firstly, there is no unified standard for the measurement of the synergy degree of pollutants and CO_2 emissions and *HQDE* in the current research, and there exists a certain scope for exploration. Secondly, existing studies mostly focus on promoting *CGPRCR*, however, the guiding role of *CGPRCR* proposed in the Implementation Plan for Collaborative Governance of Pollution Reduction and Carbon Reduction has not garnered adequate attention. Moreover, no literature has paid attention to the impact of *CGPRCR* on *HQDE*. Thirdly, studies on energy transition have not fully taken into account significant regional heterogeneity, especially differences in energy endowment enrichment.

Mechanism Analysis and Research Hypothesis

Direct Conduction Mechanism and Research Hypothesis

Based on the theory of energy economics, firstly, *CGPRCR* can improve energy utilization efficiency, and accomplish green, efficient, safe, and low-carbon energy development by lowering energy consumption and pollutant emissions. Secondly, *CGPRCR* can promote energy technology innovation and progress, encourage the energy industry's technological transformation and advancement, boost market and industry competitiveness, and ultimately encourage the energy sector's healthy growth [27]. Thirdly, *CGPRCR* not only encourages a positive cycle of environmental preservation and economic growth but also advances the integrated development of energy and environment, contributing to the sustainable growth of society as a whole and *HQDE*.

H1: *CGPRCR* can directly promote *HQDE*.

Heterogeneity Effects and Research Hypothesis

The eastern region is more economically developed and endowed with higher technical endowments, and possesses more sophisticated technologies for energy exploitation and utilization, along with the backing of associated industrial chains. Additionally, it has more extensive environmental protection laws and regulations, which can produce more significant effects for *CGPRCR* on *HQDE*. However, due to the relatively limited market demand in the central region and the comparatively underdeveloped economic conditions in the western region, the environmental governance system remains inadequately established. This situation hinders industrial clustering and prevents the realization of "scale effects". Consequently, it poses challenges for *CGPRCR* to achieve *HQDE*. Therefore, different economic development levels, policies, and governance systems in different regions may lead to unbalanced investment in *CGPRCR*, which will affect the process of *HQDE*.

Some scholars have shown that in China, the distribution of energy resources and loads is inverse, with wind and solar energy concentrated in the western region and loads concentrated in the eastern and central regions [28]. Energy-rich areas contain rich resources such as light energy and wind energy, but the key lies in facing a series of problems such as insufficient capital and technology development capacity. Factors such as resources and technology will have a limited space for *CGPRCR* to affect the dividends of *HQDE*. Although non-energy-rich areas lack rich natural resources, they are mostly developed areas, which can make the best use of high-tech equipment, reduce raw material consumption and maximize energy utilization efficiency. *CGPRCR* can fully utilize the advantages of *HQDE*. Thus, the disparity in the way energy resources are distributed and the degree of growth and usage in various areas could result in variations in the way *CGPRCR* promotes *HQDE*.

H2: Promoting *HQDE* through *CGPRCR* will be heterogeneous due to China's actual background of uneven regional economic development and disparities in energy endowments.

Nonlinear Conduction Mechanism and Research Hypothesis

Considering the externality of environmental governance and the notable geographical diversity of

China's different regions, *CGPRCR* is expected to exert a nonlinear impact on *HQDE*.

(1) Analysis of the threshold effect of *AIS*

In light of the theory of industrial structure optimization, the pivotal driver of sustainable economic growth is the evolution of industrial structure. In areas characterized by a low level of the advancement of industrial structure (*AIS*), the economic benefits and energy utilization efficiency of the production process are relatively low [29]. This results in significant resource wastage and limits the ability to fully leverage the guiding role of *CGPRCR*, thereby making its contribution to *HQDE* unclear. In areas characterized by a higher degree of *AIS*, the transformation of the industrial structure into one that is knowledge and technology-intensive aids in factor allocation optimization and can lower energy usage, reduce pollutant emissions, and fully demonstrate the synergy of *CGPRCR*. According to the Petty-Clark theorem and the Kuznets law, the upgrading of this industrial structure contributes to advancing the economy towards a higher quality of development, thus fostering *HQDE*.

(2) Analysis of the threshold effect of *LU*

According to urban evolution theory, the level of urbanization (*LU*) reflects the stages and characteristics of regional economic and social development. Industrial development primarily concentrates on heavy industries and high energy consumption industries when *LU* is low. This results in a substantial rise in energy consumption and carbon emissions, as well as low efficiency of *CGPRCR*, which significantly impedes *HQDE* [7]. When *LU* is high, based on the sustainable development goals, all regions strengthen environmental regulations to meet the public's urgent demand for green consumption behavior and low-carbon life, improve energy utilization efficiency by strengthening technological research and development input and innovation output, and promote *HQDE*. This is in line with the trend in urban evolution theory that cities pay attention to ecological environmental protection and sustainable development when they evolve to higher levels.

(3) Analysis of threshold effect of *ER*

According to the incomplete market theory, the market cannot fully reflect the scarcity and environmental cost of resources in some cases, resulting in the distortion of resource allocation. In the early stages of environmental regulation (*ER*), companies may have to incur additional costs to comply with new environmental standards, such as purchasing pollution control equipment, improving production processes, or paying higher charges for pollutant discharge. These costs may crowd out enterprises' investment in energy technology innovation or production efficiency improvement, thereby exerting a short-term inhibitory effect on *HQDE* [30]. Based on Porter's hypothesis, when *ER* is strict, enterprises can be forced to innovate, offset the compliance cost caused by pollution control, and form an "innovation compensation effect" [31]. This effect is conducive to optimizing resource allocation, improving enterprise production efficiency, and enhancing the effect of *CGPRCR* on *HQDE*.

H3: The impact of *CGPRCR* on *HQDE* is nonlinear, and this positive impact is more significant when *AIS* is more advanced, *LU* is appropriate, and *ER* is stricter.

Fig. 3. shows the theoretical framework of this paper.

Materials and Methods

Model Construction and Variable Description

Model Construction

To evaluate the three research hypotheses put forward in this paper, a variety of statistical models, including the fixed effect model and the threshold regression

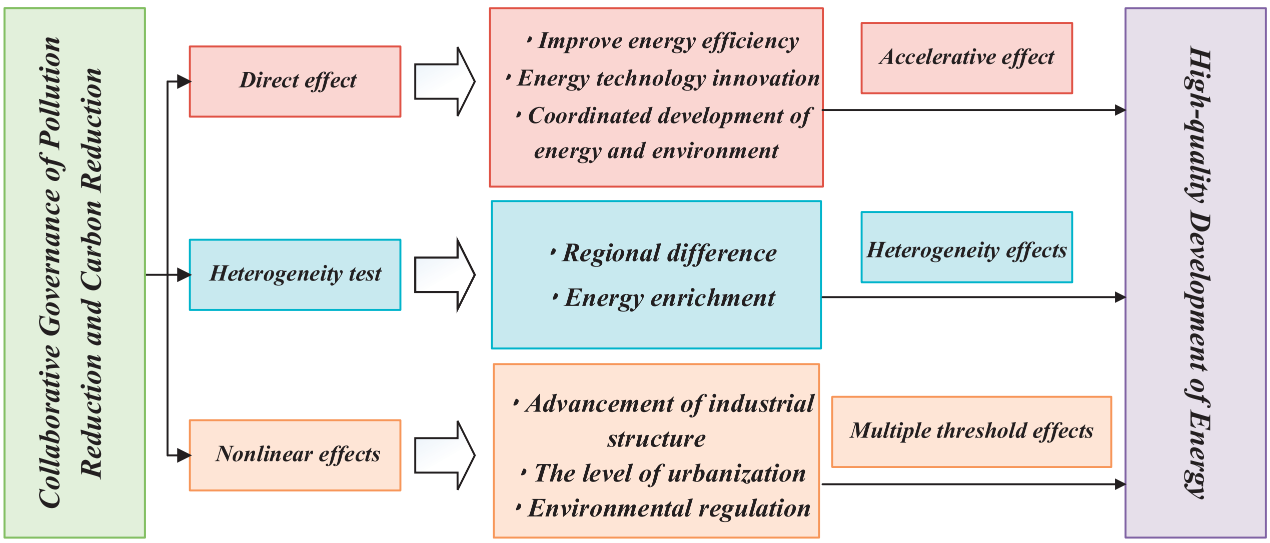

Fig. 3. Theoretical framework figure.

model are employed to thoroughly investigate both the direct and nonlinear effects of *CGPRCR* on *HQDE*. The fixed effect model is a statistical methodology that deals with the specificity of individuals that does not change over time. It assumes that the individual cross-section data have particular impacts, which could be processing effects or unique individual features between various individuals (observation units). Randomization trials cannot confirm these particular effects. In fixed effect models, the relationships between individual characteristics or treatment variables and explanatory variables are estimated separately in the model to control for these idiosyncrasies. This approach can effectively mitigate the influence of individual fixed characteristics, thereby enhancing both the accuracy and consistency of estimation.

$$HQDE_{it} = \alpha_0 + \alpha_1 CGPRCR_{it} + \alpha_n X_{it} + \lambda_i + \varepsilon_{it} \quad (1)$$

where, X_{it} denotes the control variables utilized in the model, including water pollution control (*WPC*), financial development (*FD*), opening to the outside world (*OOW*), market size (*MS*) and education level (*EL*). In addition, α_0 in Equation (1) denotes the intercept term, α_1 and α_n are the corresponding coefficients, λ_i denotes the individual fixed effect that remains unobserved, and ε_{it} refers to the stochastic disturbance term.

Furthermore, this paper employs Hansen's panel threshold regression model to examine the threshold impact of *CGPRCR*. This model not only helps determine the direction and magnitude of several parameters influencing the effect of *CGPRCR* on *HQDE* but also significantly enhances our understanding of their complex relationship. Its advantages are mainly reflected in two aspects: Firstly, the model can automatically determine the threshold value based on the data characteristics, avoiding the subjectivity of artificial division of the interval, thus ensuring the objectivity and accuracy of the research results. Secondly, through rigorous statistical tests, the likelihood ratio test can be employed to determine the existence and significance of the threshold, thereby enhancing the credibility of the conclusions drawn. Concurrently, this method allows for precise estimation of the threshold value, which offers compelling evidence in favor of the comprehension of the nonlinear link between the two. The single threshold regression model developed in this research can be described as follows, using *AIS*, *ER*, and *LU* as threshold variables:

$$\begin{aligned} HQDE_{it} = {} & \beta_0 + \mu_i + \beta_n X_{it} + \beta_1 CGPRCR_{it} \cdot I(Threshold_{it} \le \gamma) \\ & + \beta_2 CGPRCR_{it} \cdot I(Threshold_{it} > \gamma) + \varepsilon_{it} \end{aligned} \quad (2)$$

where, $Threshold_{it}$ is the threshold variable of this paper, namely *AIS*, *ER*, and *LU*. γ is the threshold value, μ_i reflects the unobserved individual effect of the province, β_n, β_1, and β_2 are the corresponding coefficient, $I(\cdot)$ is defined as the indicator function, which takes a value of 1 when the corresponding conditions are satisfied, otherwise, it takes a value of 0. The remaining variables remain consistent with those presented in Equation (1).

The model methods and steps adopted in this study are shown in Fig. 4. Make use of graphics for a more intuitive presentation.

Measurement and Description of Variables

Explained Variable

HQDE. According to the 14th Five-Year period to promote the energy revolution, to build a safe, secure, clean, and efficient energy system, the Energy Bureau and the National Development and Reform Commission jointly released the Energy Production and Consumption Transition Strategy (2016-2030), for the comprehensive construction of modern society, China's energy transformation should take security as the starting point, conservation as the priority policy, green and low-carbon as the direction, and active innovation as the driving force. Therefore, this paper evaluates

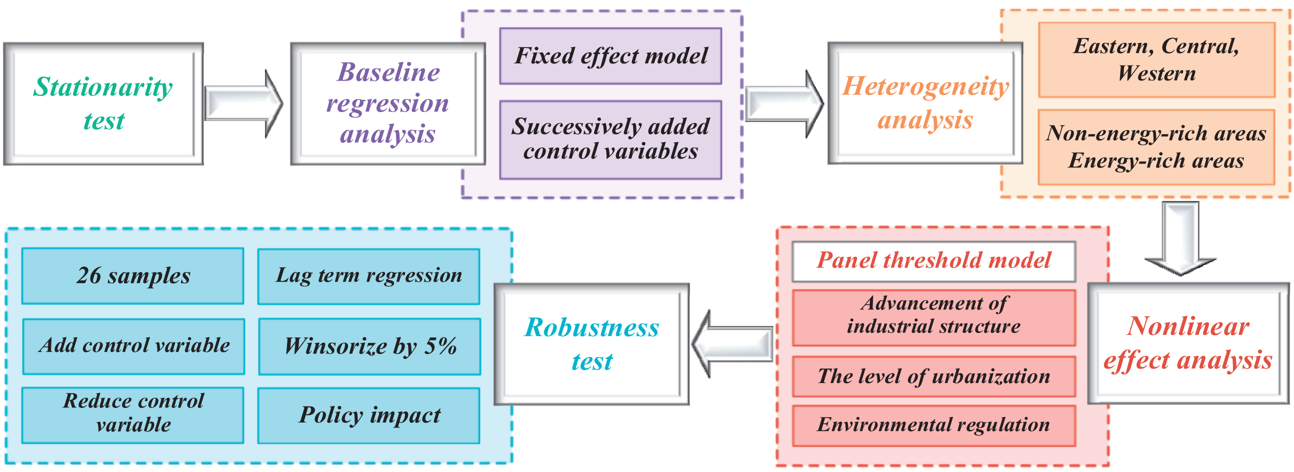

Fig. 4. Model method summary.

Table 1. Evaluation system of *HQDE*.

Primary index	Secondary index	Unit
Energy security	Energy industry investment	100 million yuan
Energy conservation	Energy consumption per unit of *GDP*	100 million yuan / 10,000 tons
Energy low-carbon	Per capita energy carbon emissions	10,000 tons / person
	Environmental protection investment intensity	100 million yuan / 100 million yuan
Energy innovation	Green patent grants	Number / year
	Internal *R&D* expenditure	Ten thousand yuan

HQDE from four aspects: energy security, energy conservation, energy low-carbon, and energy innovation. Among them, energy security is measured by investment in the energy industry; energy usage per *GDP* unit serves as a proxy for energy conservation; energy low-carbon is measured by per capita energy carbon emissions and environmental protection investment intensity; and energy innovation is measured using the number of green patent grants and internal *R&D* expenditure.

The specific measuring indicators for *HQDE* are presented in Table 1. The projection pursuit method is a nonlinear dimensionality reduction technique that originates in the field of statistics. Its basic idea is to reveal complex structures and patterns in high-dimensional data sets through a series of linear or nonlinear projections. This method is especially suitable for visualizing high-dimensional data and is widely used in many fields such as data mining, pattern recognition, bioinformatics, and financial data analysis. Compared with other methods, the projection tracking method shows higher flexibility and effectiveness in processing high-dimensional and nonlinear data. Since the indicators of *HQDE* are multidimensional, this paper employs the projection pursuit method, grounded in an accelerated genetic algorithm, to assess *HQDE* from four distinct dimensions: energy security, energy conservation, energy low-carbon, and energy innovation.

Core Explanatory Variable

CGPRCR. Considering that the root, origin, and process of air pollutant emissions and CO_2 emissions are the same. Regarding pollution reduction, SO_2, soot, and NO_x emissions are selected for measurement. Regarding carbon reduction, CO_2 emissions are chosen for measurement. The coupling coordination model is employed to investigate the interactions and coordinated development among multiple systems (or subsystems) and is used to analyze the level of coordinated development. The interaction and reciprocal influences between two systems can be quantified through the degree of coupling, which effectively reflects the cooperative development trends among two subsystems as well as the overall effects across systems. The coupling coordination model, which enables the discussion of discrepancies in the degree of coordination between the control of air pollutant emissions and the reduction of CO_2 emissions in various regions, is therefore used to evaluate *CGPRCR*. Based on the research methods of existing scholars, this paper divides the coupling degree and coupling coordination degree levels and revises the model. The initial step is to refer to the research of Wang et al. [32] and calculate twice the square root of the product of U_1 and U_2, and then divide it by the sum of U_1 and U_2 to obtain the value of *C*, that is the coupling degree. In the second step, referring to the research of Nie and Lee [33], U_1 and U_2 can be multiplied by their respective weights, and then summed accordingly to obtain the value of *T*, that is, the coupling coordination index of the two. The third step is to refer to the study of Zhang et al. [34], take the square of the product of *C* and *T*, and calculate the geometric mean of *C* and *T*, which is the index of *CGPRCR*.

$$C = \frac{2\sqrt{U_1 U_2}}{U_1 + U_2} \tag{3}$$

$$T = aU_1 + bU_2 \tag{4}$$

$$CGPRCR = \sqrt{C \times T} \tag{5}$$

where, U_1 is the pollutant emission, and U_2 is the carbon emission, the range standardization approach in this paper is used to carry out dimensionless treatment of indicators; *D* is the coupling coordination degree, and the value is [0, 1]. The greater the value of *D*, the better the coordination; The smaller the value of *D*, the worse the coordination. *C* denotes the coupling degree between the two systems, the greater the value of *C*, the smaller the degree of dispersion difference among subsystems, and consequently, the higher the degree of coupling. Conversely, a lower value of *C* corresponds to a reduced degree of coupling. *T* represents the integrated coordination index; *a* and *b* are the respective weights assigned to each system. Following Wang et al. [35] and Zhu et al. [36], this paper sets $a = b = 0.5$, indicating that air pollutant emission and carbon emission reduction are considered equally important. If a particular weight is excessively high (for instance, $a>b$ or $b>a$), the model may exhibit bias towards the separate performance of "pollution reduction" or "carbon reduction", thereby straying from the core objective of "coordination". The equal weighting approach aligns more closely with the definition of coupling coordination degree and is more consistent with policy orientation, which represents a rational selection for achieving the balance between the dual objectives of pollution reduction and carbon mitigation.

Threshold Variables

According to the above discussion, this paper selects *AIS*, *ER*, and *LU* as the threshold variables in the empirical study. (1) *AIS*. Regarding Li's study [37], to determine the level of industrial structure upgrading, this paper calculates the ratio of added values between the secondary and tertiary sectors. The degree of modernization of the industrial structure increases with increasing value. (2) *LU*. Concerning the study of Di et al. [7], this paper selects the internationally accepted urbanization rate indicator, that is, the percentage of permanent urban residents among the region's overall population, which indicates the degree of urbanization development. The greater the value, the more urbanization there is. (3) *ER*. This paper draws on the practice of He and Luo [38] to measure *ER* by industrial pollution control investment per thousand yuan of industrial added value. The more pollutant discharge fees, the more stringent *ER*.

Control Variables

HQDE is not only affected by *CGPRCR* but also affected by many internal and external factors. This paper builds upon existing studies and identifies the following five variables as control variables. (1) *WPC*, this paper uses the wastewater discharge of each region to characterize. (2) *FD*, based on the study of Jiang et al. [11], is shown as the *GDP* divided by the total of deposits and loans. (3) *OOW*, represented by the volume of imports and exports by each region. (4) *MS* is represented by population density according to the research of Chen and Liang [39]. (5) *EL*, referring to the research of scholars such as Zhan and Liu [40], this metric is stated by the number of college and university students in school per 100,000 persons.

To clarify the correspondence between the variables and their abbreviations utilized in this paper, we have created a variable abbreviation table, as presented in Table 2. Simultaneously, when a variable name first appears in this paper, show the corresponding abbreviation by following its full name with "()".

Data Source and Descriptive Analysis

This paper uses panel data samples that include pertinent data from 30 Chinese provinces, cities, and autonomous regions between 2013 and 2022. Data from Tibet, Taiwan, Hong Kong, and Macao were excluded due to significant gaps in energy statistics. The study period 2013-2022 was chosen for the following reasons: Firstly, the white paper China's Energy Policy (2012) issued in 2012 comprehensively expounds on the current situation, policies, and goals of China's energy development. It explicitly calls for promoting the clean development of fossil energy, vigorously developing new and renewable energy, strengthening the progress of energy science and technology, and deepening the reform of the energy system. These measures aim to improve energy utilization efficiency and universal service levels and to strengthen international cooperation to jointly safeguard global energy security. This policy has had an important impact on *HQDE* of China. To avoid obvious impact effects, the sample base period is set as 2013. Secondly, the current data is updated until 2022. On the issue of partial incomplete data in 2023,

Table 2. Variable abbreviation table.

Category	Variable	Abbreviation
Explained variable	High-quality development of energy	*HQDE*
Core explanatory variable	Collaborative governance of pollution reduction and carbon reduction	*CGPRCR*
Threshold variables	The advancement of industrial structure	*AIS*
	The level of urbanization	*LU*
	Environmental regulation	*ER*
Control variables	Water pollution control	*WPC*
	Financial development	*FD*
	Opening to the outside world	*OOW*
	Market size	*MS*
	Education level	*EL*
Added control variable	Technology maturity	*TM*

Table 3. Results of descriptive statistics.

	HQDE	*CGPRCR*	*WPC*	*FD*	*OOW*	*MS*	*EL*
N	300	300	300	300	300	300	300
Mean	0.288	0.584	2.111	3.695	15.503	7.919	7.917
SD	0.244	0.312	1.336	2.376	1.593	0.388	0.279
Min	0.048	0.001	0.126	0.221	10.404	6.965	7.058
Max	1.487	0.999	6.194	14.356	18.667	8.620	8.599

this is mainly due to the timeliness of data collection and collation. There is often a lag in the release and update of some key data. To guarantee the precision and dependability of the research, we chose the period from 2013 to 2022, which offers more complete and consistent data availability. The data primarily originates from the China Statistical Yearbook, China Energy Statistical Yearbook, and China Environmental Statistical Yearbook. To reduce the possible heteroscedasticity in the data, perform logarithmic processing on relevant variables. For the missing data in certain years across certain regions, the method of linear interpolation is employed to address and fill these gaps.

To thoroughly understand the fundamental characteristics of the data, this study begins with a systematic descriptive statistical analysis of the relevant variables. This analysis encompasses sample size, mean, standard deviation, minimum value, and maximum value. Among these, the mean serves to represent the central tendency of the data, while the standard deviation quantifies the degree of dispersion within the data. Additionally, the minimum and maximum values are instrumental in identifying potential outliers. Table 3 presents a detailed overview of the descriptive statistical results for each variable. The means of the variables are distributed within the range of 0.288 to 15.503. The standard deviation of *HQDE* is 0.244, indicating relatively stable distribution characteristics. In contrast, the standard deviation of *FD* is 2.376, which reflects significant volatility. In addition, the value interval of each variable exhibits significant diversity, with the observed values for *MS* falling between 6.965 and 8.620. Overall, this analysis establishes a solid data foundation for subsequent in-depth inquiry.

Results and Discussion

Stationarity Test

In this paper, the ADF test is used to conduct unit root tests on all variables in the model to ensure that all variables can pass the stationarity test and avoid spurious regression. The ADF test results are shown in Table 4, and all variables' test statistics are significantly below the critical value of 5% (-2.878); that is, the stationarity test has been passed. Therefore, it can be concluded that all the variables utilized in this paper are stationary sequences, which may warrant further empirical investigation.

Baseline Regression Analysis

Before conducting the benchmark regression analysis, this paper first performs the Hausman test to ascertain whether the fixed effect model or the random effect model is more appropriate for selection. The rigorous test results indicate that the P value is 0.019, which leads to the rejection of the null hypothesis, suggesting that the fixed effect model is more appropriate. Consequently, this study employs the fixed effect model.

Table 5 reports the results of *CGPRCR* that directly affects *HQDE*. Under the test of the fixed effect model with successively added control variables, the promoting effects are all significant, which confirms research Hypothesis 1 of this paper. This finding offers strong evidence for policymakers, evidencing that implementing the strategy of *CGPRCR* is effective and should be included in the core of energy policy. Model (6) shows that the coefficient of *CGPRCR* on *HQDE* is 0.065 and relatively significant, which implies that every one-unit increase in *CGPRCR* improves *HQDE* by 6.5%, controlling for other factors. *CGPRCR* has the potential to enhance energy use efficiency and foster innovation

Table 4. ADF test results.

Variable	Test statistic	P-value	Stationarity test
HQDE	-5.181	0.000^{***}	Yes
CGPRCR	-12.051	0.000^{***}	Yes
AIS	-6.454	0.000^{***}	Yes
LU	-4.554	0.000^{***}	Yes
ER	-7.665	0.000^{***}	Yes
WPC	-8.881	0.000^{***}	Yes
FD	-3.641	0.005^{***}	Yes
OOW	-3.268	0.016^{***}	Yes
MS	-4.861	0.000^{***}	Yes
EL	-6.452	0.000^{***}	Yes

Table 5. Baseline regression results.

	(1)	(2)	(3)	(4)	(5)	(6)
CGPRCR	0.075***	0.048**	0.043**	0.063***	0.064***	0.065***
	(0.023)	(0.020)	(0.021)	(0.020)	(0.020)	(0.020)
WPC		-0.054***	-0.052***	-0.032***	-0.030***	-0.023***
		(0.006)	(0.006)	(0.007)	(0.007)	(0.008)
FD			0.010	0.024*	0.025*	0.015
			(0.014)	(0.013)	(0.013)	(0.014)
OOW				0.150***	0.149***	0.134***
				(0.023)	(0.023)	(0.024)
MS					0.052	0.050
					(0.044)	(0.044)
EL						0.108**
						(0.054)
_cons	0.244***	0.373***	0.336***	-2.093***	-2.493***	-3.090***
	(0.015)	(0.019)	(0.056)	(0.384)	(0.512)	(0.589)
N	300	300	300	300	300	300
R^2	0.038	0.280	0.282	0.377	0.380	0.390

Note: *** indicates a significance level of 0.01; ** indicates a significance level of 0.05; * Indicates significance at the level of 0.1. Standard errors are in parentheses. (The following tables are the same)

and advancement in energy technology, achieve green, efficient, safe, and low-carbon development of energy, and then promote *HQDE*.

In reality, against the backdrop of global warming, 148 countries and 655 cities or regions have put forward carbon neutrality commitments. This figure not only reflects the importance the international community attaches to the climate issue but also underscores the common determination of all countries in pollutant control and carbon emission reduction. More significantly, 120 countries have incorporated carbon neutrality targets into laws or policy documents, demonstrating their willingness and action to actively participate in global climate governance. Setting a global carbon neutrality target has become an irreversible trend, not only reflected in policy commitments but also in the actual energy structure transformation. The global installed capacity of renewable energy has reached 3,870 GW, making renewable energy a crucial driver of the energy transition. The number of countries setting 100% renewable power generation targets increased from 30 in 2022 to 37 in 2024. This increasingly prominent trend further underscores the growing global emphasis on renewable energy. *CGPRCR* has emerged as a global strategic initiative, which is not only significant in improving the quality of the ecological environment but also in providing solid support for the development of energy by promoting the optimization of energy structure, promoting energy technology innovation, and improving energy utilization efficiency. In addition, environmental governance has also given rise to new energy forms and business models, bringing new development opportunities for the energy industry. Therefore, we firmly believe that *CGPRCR* will inevitably effectively drive *HQDE* and lead the global energy system into a new era of cleaner, low-carbon, and efficient energy.

Heterogeneity Analysis

Table 6 shows the heterogeneity test results of this paper. According to model (7) - model (9), it can be concluded that the impact of *CGPRCR* on *HQDE* presents a characteristic of "eastern > central > western". The reasons may lie in: On the one hand, the eastern coastal areas possess a distinct advantage in terms of capital and high-quality labor input, attributable to their status as policy forerunners. This enables a more rational allocation of resources, energy, capital, and human capital. Consequently, these economic advantages can be effectively transformed into benefits related to energy structure and ecological and environmental protection [41]. Its advantageous geographical position, both at sea and on land, facilitates the development of an export-oriented economy, with *GDP* contributing to 50% of the national total. Leveraging advanced technology and equipment, this region has achieved significant results in pollutant treatment and carbon emission reduction.

Table 6. Results of the regional heterogeneity test.

	(7)	(8)	(9)	(10)	(11)
	Eastern	Central	Western	Non-energy-rich areas	Energy-rich areas
CGPRCR	0.120***	0.071***	0.041***	0.079***	0.043**
	(0.044)	(0.018)	(0.010)	(0.028)	(0.018)
Control variables	Yes	Yes	Yes	Yes	Yes
_cons	-6.939***	-4.247***	-1.284***	-3.543***	-2.154***
	(2.000)	(0.555)	(0.248)	(0.911)	(0.476)
N	110	80	110	210	90
R^2	0.558	0.797	0.597	0.384	0.607

In addition, the energy consumption structure has been transformed towards clean and low-carbon alternatives, resulting in high energy utilization efficiency, and *CGPRCR* can play a crucial role in *HQDE*. On the other hand, as a national demonstration area for ecological civilization construction and an industrial transfer undertaking zone, the central region has proactively adjusted its industrial structure. This includes eliminating numerous enterprises characterized by high pollution and high energy consumption. Furthermore, there has been a transformation towards “green” in industry and technology research and development [42]. However, the overall investment in technology and equipment remains behind that of the eastern region, and the demand for energy in the central region market is relatively limited. Although the western region has strong energy endowments such as solar energy and wind energy, due to the relatively remote geographical environment, the market potential has not been fully developed, and it mostly depends on the mining and processing of energy resources. Moreover, the cost of energy development is high, infrastructure construction lags, and the promotion and application of advanced technologies are insufficient, resulting in insufficient investment and capacity in pollution control and carbon emission control. *CGPRCR* is relatively backward, which further affects the improvement of energy utilization efficiency and environmental quality, hinders the optimization of energy structure and industrial upgrading, and it is difficult to promote *HQDE* [43].

Models (10) and (11) show that *CGPRCR* to promote *HQDE* presents a characteristic of “non-energy-rich areas > energy-rich areas”. This paper posits that the primary causes are as follows: Although the resource endowment of energy-rich areas is strong, it relies too much on the development of some specific resources, while inhibiting the growth of other high-value-added industries and resulting in a singular industrial structure. Excessive development of the resource-driven economic model produces a “lock-in effect”, which restricts the development of other local industries and has strong path dependence on the traditional energy industry [44]. *CGPRCR* faces multiple challenges, such as difficult technological transformation, insufficient capital investment, and complex interest coordination, and its ability cannot support the role in *HQDE*. In contrast, non-energy-rich areas are mostly developed areas with relatively diversified economic structures. In the face of the pressure of pollution reduction, carbon reduction, and energy transformation, it can respond faster to changes in the external environment, adjust the industrial structure more easily, reduce the dependence on traditional energy, and thus promote *HQDE*. Meanwhile, under the infiltration of capital, technology, and policies, a green and sustainable development model has been formed, which gives a stronger foundation to *CGPRCR*. By boosting the growth of renewable industries, optimizing the energy structure, and improving energy efficiency, thus playing a more obvious positive role in *HQDE*.

In conclusion, there is variation in how *CGPRCR* promotes *HQDE* in various geographical areas, and shows a gradient decreasing trend of “eastern > central > western” and “non-energy-rich areas > energy-rich areas”. This conclusion harmoniously aligns with the findings of Lu et al. [45]. In the book of Auty [46], the “resource curse” is formally defined as: abundant natural resources are not sufficient favorable conditions for the economic growth of some countries or regions, but a limitation. At present, the phenomenon of “abundant energy, lagging development” in the western region and energy-rich areas is consistent with Auty’s definition of “resource curse”. It is evident that the energy endowment and development in the western region and the energy-rich region have produced a “resource curse” effect on the impact of *CGPRCR* on *HQDE*. Policy design needs to fully consider the actual situation and demand of the eastern, central, and western regions, as well as non-energy-rich areas and energy-rich areas, especially the backward regions, which are faced with multiple bottlenecks such as lagging infrastructure construction. In addition, facing the reality that energy utilization causes great pressure on the ecological environment, so precise differentiation strategies

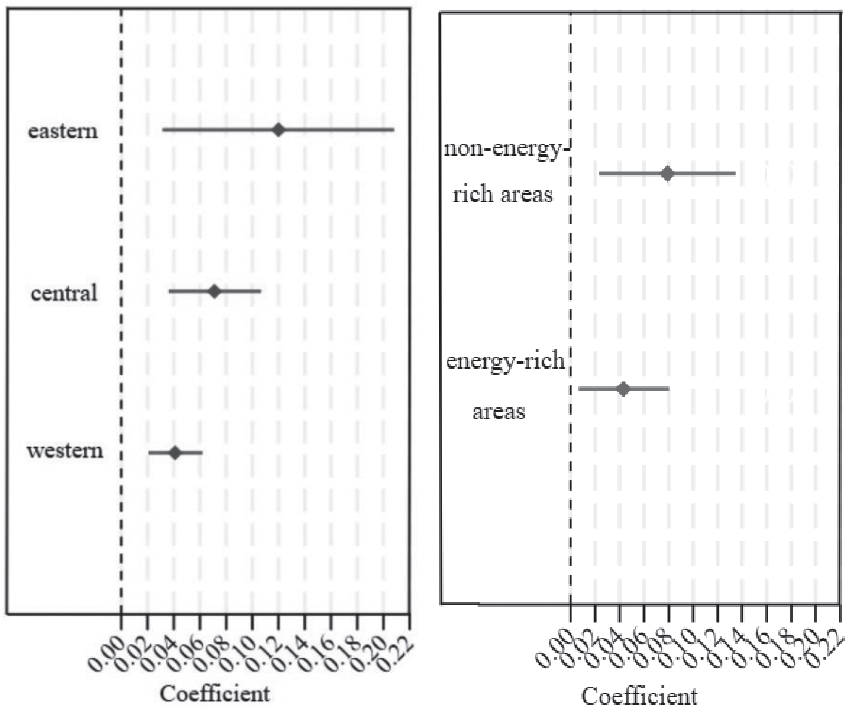

Fig. 5. Visual comparison of heterogeneity test.

should be formulated. Meanwhile, strengthening cross-regional collaboration and policy coordination is also an indispensable and important aspect. Attention should also be paid to balancing the interests of non-energy-rich areas and energy-rich areas, ensuring the rational distribution and effective utilization of energy resources, and preventing further aggravation of the "Matthew effect" of unbalanced regional development caused by differences in resource endowments.

To show the heterogeneity test results more clearly and intuitively, a visual graph is drawn, as shown in Fig. 5.

Nonlinear Effects Analysis

In this section, the threshold effect's existence is tested using the panel threshold model estimate approach, determining the specific threshold value, and estimating the parameter values under different threshold intervals. After 1,000 repeated samples, the specific F-value and P-value are obtained. The results indicate that *AIS* exhibits a single threshold, which is significant at the 10% level, but does not pass the double threshold test. *LU* passed the double threshold and was significant at the 10% level, but does not pass the triple threshold test. *ER* passed the single threshold and was significant at the 10% level, but did not pass the double threshold. The results verify that under the constraints of the three threshold variables of *AIS*, *LU*, and *ER*, *CGPRCR* has a nonlinear impact on *HQDE*. The specific results are shown in Table 7.

Secondly, the likelihood ratio function graph displays the threshold variable estimates along with

Table 7. Test results of threshold effect significance.

Threshold variable	Threshold effect	F-value	P-value	BS number	The critical value		
					1%	5%	10%
AIS	Single threshold	26.770	0.094	1000	24.739	41.139	88.612
	Double threshold	6.990	0.415	1000	19.608	35.633	66.355
LU	Single threshold	67.720	0.023	1000	28.628	47.049	105.690
	Double threshold	37.430	0.053	1000	26.307	38.772	78.036
	Triple threshold	52.140	0.252	1000	97.883	125.677	179.232
ER	Single threshold	16.840	0.070	1000	15.182	18.500	28.437
	Double threshold	-10.510	1.000	1000	17.595	23.007	34.739

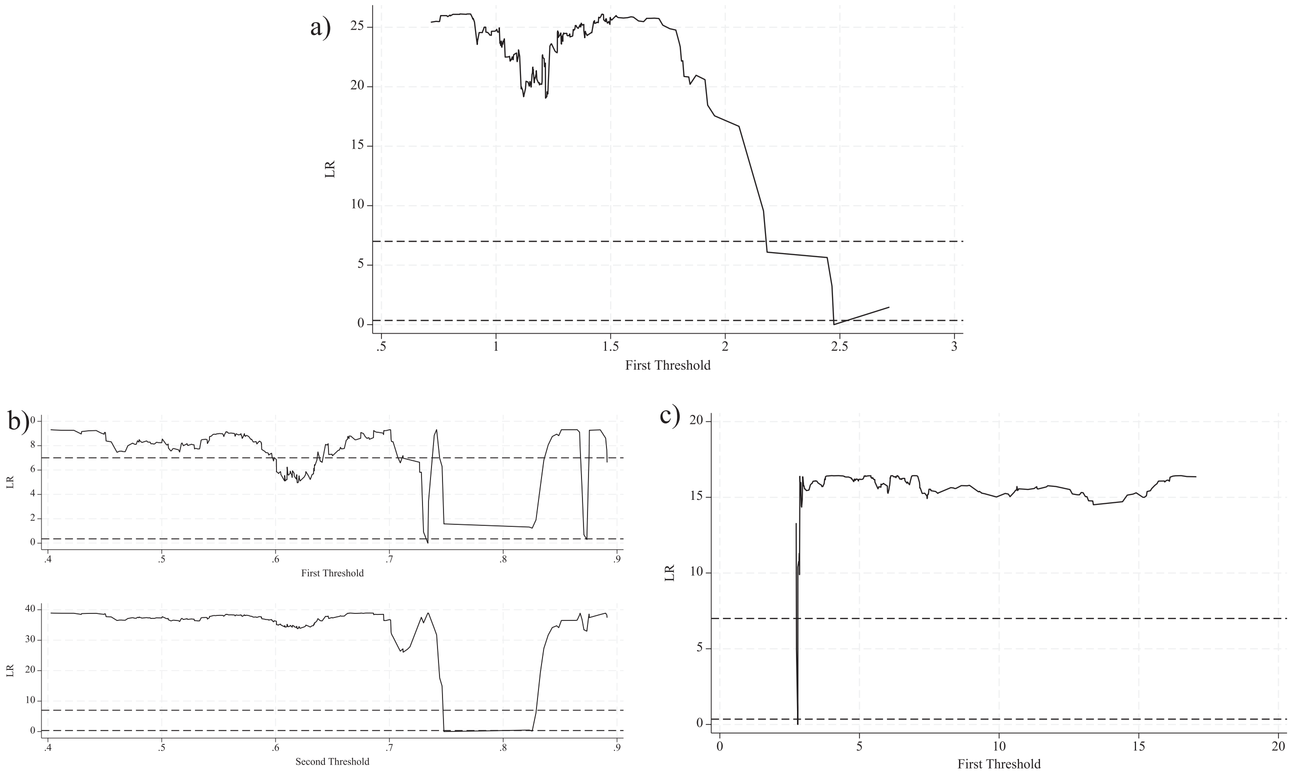

Fig. 6. Likelihood ratio function diagram of each threshold variable: a) *AIS*, b) *LU*, c) *ER*.

the appropriate 95% confidence interval. Fig. 6 illustrates that when the threshold value of *AIS* is 2.474, the threshold value of *LU* is 0.734 and 0.748, and the threshold value of *ER* is 2.793; the LR value of the likelihood ratio statistical test is zero.

Table 8 presents the results of the nonlinear test in detail. When *AIS* is the threshold variable, the model estimation results are shown in model (12). With *AIS* crossing the threshold value of 2.474, *CGPRCR* has improved the promotion effect of *HQDE*. When *AIS* is lower than the threshold value, the actual level of *HQDE* changes by 0.051 for every 1 unit change in *CGPRCR*; When *AIS* is higher than the threshold value, the actual level of *HQDE* changes by 0.281 for every 1 unit change in the degree of *CGPRCR*. *AIS* facilitates the enhancement of resource allocation efficiency, and the

Table 8. Results of threshold regression.

Threshold variable	(12)	(13)	(14)
	AIS	*LU*	*ER*
CGPRCR	0.051^{***} (threshold ≤ 2.474) (0.020)	0.036^{**} (threshold ≤ 0.734) (0.018)	-0.194^{***} (threshold ≤ 2.793) (0.069)
	0.281^{***} (threshold > 2.474) (0.051)	0.698^{***} (0.734 < threshold ≤ 0.748) (0.069)	0.078^{***} (threshold > 2.793) (0.020)
		0.197^{***} (threshold > 0.748) (0.047)	
Control variables	Yes	Yes	Yes
_cons	-3.016^{***} (0.568)	-2.833^{***} (0.502)	-2.964^{***} (0.575)
F	28.900	41.970	27.550
N	300	300	300
R^2	0.435	0.562	0.423

degree of "green" is high. In such areas, *CGPRCR* can be fully demonstrated, thus boosting *HQDE*.

When *LU* serve as the threshold variable, model (13) shows the model estimate results. When *LU* is in the second threshold range (i.e., 0.734 < threshold ≤ 0.748), the influence coefficient is largest, which is 0.698. The coefficient of 0.698 indicates that every one-unit increase in *LU* will raise the impact of *CGPRCR* on *HQDE* by 69.8%, assuming other variables are controlled. Because of the increased energy use efficiency brought about by high *LU*, the effect of *CGPRCR* has become increasingly enhanced, and its positive impact on *HQDE* has also increased. As soon as *LU* exceeds the second threshold amount, the impact coefficient of *CGPRCR* on decreases from 0.698 to 0.197, 0.197 indicates that every one-unit increase in *LU* will result in a 19.7% amplification of the effect of *CGPRCR* on *HQDE*, assuming all other factors are held constant, indicating that with the acceleration of *LU*, the promotion effect shows a trend of "marginal decline". The reason may be that the phenomenon of "development cost" is greater than "development compensation" in some regions, thus slowing down the overall process. This finding indicates that only when *LU* is appropriately optimized can the positive effect be significantly enhanced. Conversely, rapid *LU* may undermine this positive effect.

The results of the model estimation when *ER* is utilized as the threshold variable are presented in the model (14). When *ER* is less than 2.793, *CGPRCR* exerts an inhibitory effect on *HQDE*. In contrast, when *ER* is greater than 2.793, the influence of *CGPRCR* on changes from inhibition to promotion. The coefficient of the promotion effect is 0.078, which means that when other variables remain unchanged, every one-unit increase in *ER* will increase the influence coefficient between the two by 7.8%. This nonlinear effect of "first inhibition and then promotion" is called a form of "Environmental Kuznets Curve", that is, the influence of *ER* presents a "U-shaped" relationship, which is essentially a process of "creative destruction" triggered by *ER*. With the continuous improvement of *ER*, various regions have extensively carried out *CGPRCR*, used cutting-edge technologies to successfully lower energy expenses, improve energy utilization efficiency, and promote *HQDE*.

In general, under the constraints of *AIS*, *LU*, and *ER* as threshold variables, *CGPRCR* has a significant nonlinear promoting effect on *HQDE*, which reinforces the research findings of this paper even more and aligns with the findings of other scholars. Hypothesis 2 is confirmed. Meanwhile, to further analyze the potential nonlinearity, this paper further analyzes the correlation of threshold variables *AIS*, *LU*, and *ER* among partitions with *HQDE* respectively, and finds that: all three have different nonlinear effects on *HQDE*, especially when *AIS* is higher than 2.474, *LU* is in the range of 0.734 and 0.748, and *ER* is higher than 2.793. The promoting effect on *HQDE* shows an obvious growth trend. The above conclusions provide an important reference for policy design. Policymakers should take *AIS*, *LU*, and *ER* as the starting points to plan and flexibly adjust policy strategies and objectives scientifically and reasonably. Backward regions are especially faced with multiple challenges, such as unreasonable industrial structure, great pressure on resources and the environment in the process of urbanization, and weak environmental governance capacity. It is necessary to fully consider the particularity and complexity of backward areas and vigorously help them.

Robustness Test

To assess the robustness of the findings, this paper performs a robustness test on the effect of *CGPRCR* on *HQDE*. The outcomes of the estimation are meticulously presented in Table 9. Firstly, the robustness test method proposed by Qi and Li [47] was used to adjust the research samples, extreme values can exacerbate the variance of residual differences, resulting in inaccurate estimations of standard errors and influencing the test outliers on the results. The largest and smallest sample areas of core explanatory variables, specifically those at approximately 1%, 5%, and 10%, are sequentially removed. Subsequently, baseline regression was conducted on 28 regions, followed by 26 regions and then 24 regions in China. This approach is employed to enhance the credibility of the conclusions drawn from the study. There are no noticeable differences between the coefficients and significance levels of the results and those obtained from the previously mentioned test. (Only 26 regions' empirical results are presented in this report due to space constraints). Secondly, by incorporating potentially omitted control variables, we can assess whether the influence coefficients between the core variables are biased due to the absence of important confounding factors. Therefore, this study tests by increasing the control variable of technology maturity (*TM*), and the model coefficient agrees with the findings of this study, which verifies the robustness of the model results. Thirdly, reducing the selection of insignificant control variables facilitates the examination of whether core variables are obscured or distorted by the inclusion of redundant variables. This paper draws upon the robust testing methodology put forth by Sun and Deng [29], which entails reducing control variables, and conducting regression analysis after excluding the variable of *MS*. According to the investigation, a significant positive relationship persists between the two variables, which aligns with the fundamental regression findings. This consistency further substantiates the robustness of the empirical results presented in this paper. Fourthly, to further alleviate the endogeneity problem and ensure the robustness and reliability of the conclusion, this paper refers to the research of Lyu and Zhang [48], winsorizes the explained variable by 5% to mitigate the effect of outliers, and uses the lagged term regression to solve the bidirectional causality problem to verify the robustness of the conclusion. It can be found that

Table 9. Robustness test.

	(15)	(16)	(17)	(18)	(19)	(20)
	26 samples	Add control	Reduce control	*L. Energy*	5% Winsor	Policy impact
CGPRCR	0.055**	0.041**	0.063***	0.052***	0.071***	0.055***
	(0.023)	(0.020)	(0.020)	(0.020)	(0.012)	(0.021)
WPC	-0.022***	-0.014*	-0.025***	-0.019**	-0.015***	-0.022***
	(0.008)	(0.008)	(0.007)	(0.007)	(0.004)	(0.008)
FD	0.017	0.001	0.014	0.021	0.013	0.015
	(0.015)	(0.014)	(0.014)	(0.015)	(0.008)	(0.014)
OOW	0.131***	0.085***	0.136***	0.131***	0.131***	0.124***
	(0.027)	(0.026)	(0.024)	(0.024)	(0.014)	(0.025)
MS	0.056	0.033		0.051	0.033	0.042
	(0.047)	(0.043)		(0.046)	(0.025)	(0.044)
EL	0.110*	0.079	0.109**	0.064	0.080**	0.110**
	(0.058)	(0.052)	(0.054)	(0.053)	(0.031)	(0.053)
TM		0.043***				
		(0.010)				
Policy						0.067*
						(0.034)
_cons	-3.096***	-2.533***	-2.713***	-2.748***	-2.711***	-2.873***
	(0.651)	(0.584)	(0.488)	(0.573)	(0.342)	(0.596)
N	260	300	300	270	300	300
R^2	0.352	0.431	0.387	0.343	0.576	0.398

the regression coefficients of the influence of *CGPRCR* on are significantly positive, which substantiates the research Hypothesis 1 of this paper furthermore. Fifthly, the promotion effect of *CGPRCR* on *HQDE* may include the influence of other contemporaneous policies, and ignoring such contemporaneous policies may lead to bias in the research conclusions. Therefore, this paper collects data on the implementation of Energy-consuming Right Trading System in provinces (implemented in 2017) and quantifies them as policy variables to be included in the empirical model, to exclude their impact. The robustness of the conclusions in this work is confirmed by the results of model (20), which demonstrate that the results are consistent with the previous results after taking into account the influence of policies throughout the same period.

To more clearly show the results above, we adopt a more intuitive visual method for comparison, which is shown in Fig. 7.

Further Discussion

In light of the empirical findings presented above, the relevant research conclusions and action mechanisms are not only robust within the Chinese context but also possess broad applicability on a global scale. Subsequent research can further investigate the practical pathways and successful experiences of different countries and regions, thereby providing additional insights for

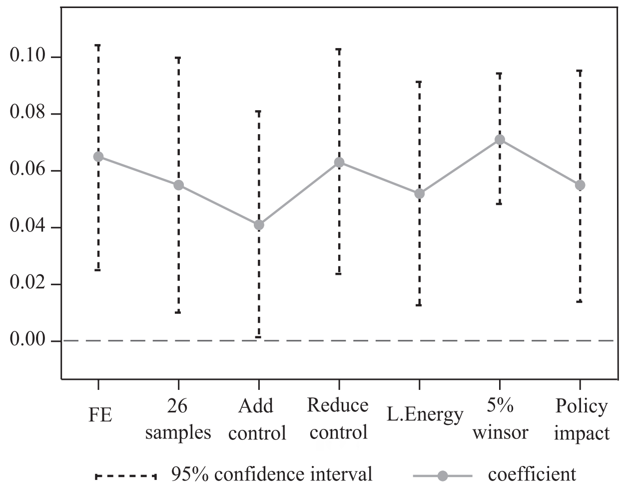

Fig. 7. Visual comparison of the robustness test.

global climate governance. Through empirical analysis, this study has elucidated the influencing mechanisms between the two and has arrived at the following conclusions:

(1) Universality effect

This study demonstrates that *CGPRCR* promotes *HQDE*, exhibiting robustness not only in China but also suggesting that the underlying growth logic and mechanisms may apply to other regions. *CGPRCR* continues to offer momentous support for *HQDE* through breakthroughs in technological research and development, upgrades in industrial models, and environmental sustainability. This mechanism adheres to an inherent law that possesses universal applicability on a global scale. For instance, in India, the government implements institutional measures to guide consumption. These include levying taxes on luxury goods and vehicles with high emissions, developing energy-efficient home appliances and clean emission technologies, establishing a green technology system for energy research and development, and advancing the modernization of consumption and efficient use of resources. These methodologies align with the underlying logic of the present study. In Southeast Asia, countries such as Singapore, Malaysia, and Indonesia are planning to sequentially implement carbon taxes. They are actively promoting the transition from coal to clean energy and encouraging the application of *CGPRCR* in *HQDE*. Consequently, the promotion effect should be expected in other regions as well.

(2) Heterogeneity effects

This study reveals that, within the context of China, the effects of *CGPRCR* on *HQDE* are heterogeneous, which arises from unbalanced economic development and variations in energy endowments across different regions. This empirical finding is not only validated within the Chinese context, but it also possesses significant applicability and enlightening implications from a global perspective. On a global scale, countries and regions exhibit varying levels of economic development, accompanied by significant disparities in the distribution and structure of energy resources. This divergence leads to notable differences in the mechanisms and effects that link the two. Developed countries typically possess a robust economic foundation and allocate substantial resources to scientific and technological research and development as well as innovation. This strategic investment enables them to achieve energy transition and high-quality development more efficiently through advanced technological means. For instance, Germany is at the forefront of the development and application of renewable energy technologies. By promoting solar energy, wind energy, and other forms of clean energy on a large scale, the country not only effectively reduces carbon emissions but also facilitates the upgrading of its energy industry. This approach enhances both the stability and sustainability of the energy supply. Many developing countries are currently experiencing rapid industrialization and urbanization, leading to an increasing demand for energy. However, due to their relatively low levels of economic development, as well as limited technical capacity and financial resources, these nations encounter significant challenges in advancing *CGPRCR*. For instance, India, as a burgeoning nation with a developing population, exhibits an immense appetite for energy. However, coal continues to play a preeminent role in its energy structure. Similarly, the energy composition of Southeast Asian nations remains heavily reliant on conventional fossil fuels, leading to grave challenges related to environmental degradation and carbon emissions. In pursuing this objective, these countries must strike a balance between economic development and energy supply. This is essential not only to meet the increasing energy demand but also to gradually reduce carbon emissions. Consequently, the interplay between the two is relatively complex, necessitating a more flexible and progressive strategy.

(3) Threshold effects

This study reveals that the driving effects of *CGPRCR* on *HQDE* exhibit significant threshold characteristics, and its nonlinear mechanism of action is influenced by three key factors. The driving effects are more significant when *AIS* is more advanced, *LU* is appropriate, and *ER* is more stringent. This empirical finding is not only validated within the Chinese context, but it also offers valuable insights into the governance and development of similar countries. The case in point is that, in India, traditional agriculture and heavy industry constitute a relatively significant portion of the economy, distinguished by high energy consumption and heavy environmental pollution. The urbanization process is rapid yet uneven, leading to numerous environmental challenges faced by big cities. By accelerating the transformation of *AIS*, increasing the share of emerging industries, strategically planning urban development, and enhancing *ER* and law enforcement, enterprises can be incentivized to conserve energy and reduce emissions. In Southeast Asia, the industrial structure primarily consists of agriculture, manufacturing, and tourism. The manufacturing sector is characterized by its labor-intensive nature and high energy consumption, which contributes to significant environmental pollution. While the urbanization process is accelerating, it encounters challenges such as inadequate planning and underdeveloped infrastructure. Furthermore, there are considerable disparities in environmental regulatory policies across countries, coupled with limited regulatory capacities.

This empirical result has not only been validated in the Chinese context, but also from a global perspective, *CGPRCR* has also become a trend. The effectiveness of promoting *HQDE* is not only of considerable significance to China, but it also serves as an important reference for global environmental governance and sustainable development. Especially at the strategic intersection of global climate change and energy security, China's exploration and practices in coordinated pollution reduction and carbon governance may offer valuable insights and inspiration for other developing countries that share similarities with China regarding economic development levels, energy consumption structures, and environmental governance needs. These nations are all confronted with multiple challenges related to environmental pollution control and adjustments in their energy structures.

Conclusions

Research Summary

Based on the perspective of promoting *HQDE* through *CGPRCR*, this paper examines the impact of *CGPRCR* on *HQDE* by analyzing direct effects, heterogeneity effects, and nonlinear effects, utilizing provincial panel data from China spanning the years 2013 to 2022. After measuring the indicators of *HQDE* from four aspects: energy security, energy conservation, energy low-carbon, and energy innovation, the fixed effect model and a threshold regression model are used. The direct effects, heterogeneity effects, and nonlinear effects between the two are explored from the national level, the three major regions, and the rich and non-rich areas of energy endowments. The main conclusions are as follows:

(1) Based on the conditions of energy endowment, economic development, and environmental protection in China, *CGPRCR* can significantly enhance *HQDE* and is conducive to the realization of Chinese-style green modernization. This conclusion lays a foundation for future research on the benign interaction between *CGPRCR* and *HQDE* and the exploration of other governance models. Moreover, China's governance experience will provide a valuable case for international comparative research, helping to identify international commonalities and differences, further reveal the best practices of global "environment and energy" composite governance, and deal with potential challenges.

(2) The present state of uneven regional economic development and disparities in energy endowments across China makes *CGPRCR* promote *HQDE* heterogeneous in different regions, and the effect shows characteristics of "eastern > central > western" and "non-energy-rich areas > energy-rich areas". Given the heterogeneity of different regions, this paper provides a decision-making basis for further exploring the key influencing factors and action mechanisms in the influencing process of *CGPRCR* on *HQDE* in different regions in the future. Sequentially, formulate more accurate, effective, and characteristic regional renewable energy innovation policies and establish a cooperation mode of "surplus and shortage mutual help" between regions of renewable energy, to promote balanced development across the country.

(3) At the national level, when *AIS*, *LU*, and *ER* are threshold variables, *CGPRCR* has significant multiple threshold effects on *HQDE*. When *AIS* is higher than the threshold value, *LU* is between the two threshold values, *ER* is higher than the threshold value, the positive effect of *CGPRCR* on *HQDE* is stronger. This result provides key ideas and implementation guidelines for future renewable energy policy innovation, which should focus on guiding the energy supply structure to match with *AIS*, take into account the balance between the process of *LU*, energy demand, and environmental protection, and cooperate with stricter *ER* to build an "ideal kingdom" with effective environmental governance and efficient energy development.

Policy Implications

Although this study primarily focuses on China, the impact mechanism of *CGPRCR* on *HQDE* is broadly applicable. In light of the increasingly pressing global challenges related to climate change and sustainable development, nations are actively seeking pathways for *HQDE*. As one of the largest developing countries worldwide, China undoubtedly serves as a valuable reference point for other countries regarding practical approaches and experiential insights. In light of the study's findings, several suggestions are put forth:

(1) This paper shows that comprehensively advancing *CGPRCR* can promote *HQDE*, and shows regional heterogeneity characteristics of "eastern> central> western" and "non-energy-rich areas > energy-rich areas". 1) National authorities should develop a unified policy framework and establish standards for pollution reduction and carbon mitigation. Additionally, they should provide macro-level guidance and policy support, which may include financial subsidies and tax incentives, to facilitate joint prevention and control across the nation in addressing both pollution reduction and carbon mitigation. 2) Regional authorities must adopt a localized approach. For instance, regions such as Guangdong and Jiangsu, along with other eastern regions that are non-energy-rich areas, should fully utilize the significant effect between the two to develop the plan of "deep emission reduction of key industries + vigorous cultivation of emerging industries". For sectors marked by elevated carbon emissions and considerable pollution, such as the steel and chemical sectors, establish mandatory emission reduction targets. Additionally, promote Carbon Capture, Utilization, and Storage technology and integrate it into the framework of carbon market regulation. Meanwhile, it is essential to prioritize new energy vehicles, hydrogen energy, energy storage, and other related industries. Implementing some policies like combination punches, such as "carbon market expansion + energy use right trading", can encourage enterprises to pursue low-carbon transformation. This approach aims to further enhance the cleanliness of energy sources and thus promote energy transition. 3) The mere intervention of *CGPRCR* on *HQDE* can not yield a significant promotional effect. More critically, it is essential for the central and western regions, as well as energy-rich areas such as Gansu

and Ningxia, to optimize their business environments. They should actively engage in industrial transfers from the eastern region and implement supportive measures such as special subsidies and talent recruitment policies. In addition, the abundant local resources, including coal, wind energy, and solar energy, are utilized to build integrated landscape storage projects. These initiatives will support high-end manufacturing sectors such as photovoltaic module production and battery manufacturing, thereby establishing a regional low-carbon industrial chain. Countries should also enhance collaboration and share experiences to collectively address climate change and environmental pollution.

(2) This paper also finds that when *AIS* and *ER* exceed a certain threshold value, and *LU* falls within a range by the double threshold values, the promotion effect between the two is stronger. Therefore, we should expedite the process of *AIS*, appropriately improve *LU*, rigorously enforce *ER*, and fully leverage the leading role of *CGPRCR*. 1) It is necessary to establish a more advanced and reasonable industrial structure and promote emission reduction at the source. Accelerate the phasing out of obsolete production capacity, establish a negative list for industries, delineate the exit timeline for high energy-consuming and high-polluting sectors, and implement policies such as employee retraining programs and subsidies for equipment renewal. Targeted support for high-value-added industries, with a particular emphasis on low-carbon sectors such as artificial intelligence and biomedicine. This involves the establishment of specialized development funds, the provision of tax exemptions, research and development subsidies, and enhanced market access facilitation. 2) The pace of urbanization should be appropriately controlled to alleviate the ecological pressures resulting from the rapid process of urban development. Establish red lines for development intensity and permanently protect boundaries for basic farmland in ecologically sensitive regions and cities that face resource overload, such as Shanxi Province. Furthermore, implement stringent controls on the scale of construction land. Implement a mechanism for a “flexible planning period” in high-potential urban agglomerations, such as the Yangtze River Delta. This should include dynamic evaluation and adjustment every three years to ensure that growth aligns with infrastructure and environmental capacity. Such measures aim to mitigate energy inefficiency and reduce carbon emissions resulting from unreasonable spatial layouts. 3) Effectively utilize the instrument of *ER* and implement regulations in a phased manner. In the initial phase, priority should be given to incentives, including flexible policies such as the reduction and exemption of environmental protection taxes for enterprises that meet emission reduction standards, which aims to encourage businesses to proactively engage in pollution and carbon reduction efforts. In the later phase, progressively enhance regulatory constraints, implement mandatory carbon quotas, increase pollutant discharge charging standards, and support the establishment of a carbon emission trading market. By implementing environmental and economic policies, including pollution discharge fees, carbon emissions trading, and green credit systems, alongside the application of real-time monitoring technologies such as satellite remote sensing, a blacklist of environmental violations will be established. Production or financing restrictions should be enforced under legal regulations for entities engaged in illegal or irregular emissions.

It is important to recognize that, owing to the economic, social, and cultural disparities across various countries and regions, each nation should implement suitable adjustments and optimize relevant policies according to its specific circumstances. For instance, considering the unique characteristics of its energy structure, India can draw lessons from China in green credit initiatives and other policy incentives that promote renewable energy development. By implementing these policies, India can lower the initial investment costs associated with renewable energy projects, enhance their economic viability, attract increased social capital investment, and expedite the transition pace of its energy structure from coal to renewable sources. Southeast Asian nations can draw valuable insights from China’s successful experiences in regional energy cooperation. By doing so, they can enhance collaboration in the construction of energy infrastructure and the research and development of technology within the region. Through this approach, countries can achieve resource sharing and leverage complementary advantages, which will jointly enhance the stability and sustainability of energy supply, enabling a more effective response to environmental and energy challenges and facilitating integration into the global “environment-energy” composite governance system.

Future Outlook

Despite this paper meticulously quantifying and examining the intricate mechanisms through which *CGPRCR* influences *HQDE*, and making recommendations in light of the current circumstances, there remain certain limitations: (1) Connecting research objects, this paper focuses on 30 provinces in China as the objects of research. In the future, it can attempt to lower the research level, use city microscopic data to conduct focused research and propose more precise guidelines tailored to the specific characteristics of various industries; (2) Connecting research design, other threshold variables such as resource mismatch can be included in subsequent studies to more comprehensively reveal the mechanism “black box” of *CGPRCR* on *HQDE*; (3) With regard to research data, this paper conducts analysis based on China’s historical data, which may be lagged to a certain extent. Future research can combine global real-time data and future development trends, use text mining methods to obtain more scientific and comprehensive data, more comprehensively predict and evaluate the promotion effects between the two, and carry out cross-border and cross-cultural comparative research, to more comprehensively reveal the realization path of *HQDE*.

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Conflict of Interest

The authors declare no conflict of interest.

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