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Research on the coupling model of low-carbon energy restructuring and regional economic growth based on stochastic optimization algorithm

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Abstract This paper proposes a coupled coordination model of low-carbon energy restructuring and regional economic growth based on stochastic optimization algorithm, revealing the dynamic association between the two. Based on the spatial autoregressive model, the influencing factors of regional economic growth are explored. The dynamic spatial panel data model integrating FMOLS and panel LM test is used to verify the reasonableness of the selection of indicators for the low carbon energy structure adjustment subsystem. Combined with the entropy method of weighting, the level of synergistic development is quantified relying on a coupled coordination analysis index system containing 6 energy indicators and 8 economic indicators. Based on the panel data of 15 provinces in China from 2020 to 2024, it is empirically found that the coupling degree of China's low-carbon energy structural adjustment and regional economic growth is maintained at a high level of 0.89-0.99, while the degree of coordination is developed from near-dislocation recession zigzagging to intermediate coupling coordination, and the degree of the two coupling coordination is increased from 0.46 (near-dislocation) in 2020 to 0.79 (intermediate coordination). The study provides theoretical support for the formulation of regional differentiated energy policies and the realization of synergistic optimization of economic-energy-environmental systems.

Index Terms low carbon energy structure, regional economy, coupled coordination model, spatial autoregressive model, spatial panel data model

I. Introduction

Due to resource depletion and environmental pollution so that countries around the world began to pay attention to the development of low-carbon economy, low-carbon economy is increasingly becoming the trend of future social development [1]. Industrial civilization has brought a series of resource and environmental problems to mankind along with high economic growth. Traditional fossil energy sources are facing depletion, climate change is abnormal, air pollution, and the frequency of haze weather is increasing [2], [3]. To solve these problems, the only choice is to take the path of sustainable development, i.e., the path of low-carbon economy [4]. The proposal of low carbon economy is suitable for the long-term advocated sustainable development is consistent, can be seen as a sustainable development to deepen, and has the reality of the operability of the pathway.

Energy structure is the basis of economic development, energy structure problems will inevitably lead to a series of other problems, now the problems in the energy structure is not the development of individual energy industries, but the imbalance between supply and demand and the uneven distribution of energy types and other problems [5], [6]. In terms of energy consumption structure, Wei, C et al [7] a research study shows that: China's CO2 emissions increased from 3385 tons in 2000 to 107.88 million tons in 2020, an increase of nearly three times. Among them, the emission surface of energy activities accounts for more than 90% of the total emissions, which shows that energy activities are the most important source of CO2 emissions. For this reason, Dong, K. Y et al [8] in their study pointed out that under the strongest policy influence, it is expected that low carbon energy sources such as natural gas, nuclear energy and renewable biofuels will account for nearly 60% of total energy consumption in China by 2040.

For the research on the impact of energy structure on regional economy, Guan, H et al [9] examined the impact of China's energy structure adjustment on regional productivity and found that technological progress is the main driver of productivity growth, while the energy structure and scale effect have a slight negative impact on productivity growth.Zhang, S et al [10] found that the optimization and adjustment of energy consumption structure has has significant promotion and spatial spillover effects, in which industrial structure upgrading has a certain mediating role, while technological innovation and public concern have a certain moderating role. Wang, S [11] found that there is a significant interaction between energy consumption and regional economic growth, but the relationship varies among regions, with the correlation coefficient between economic growth and energy consumption below 0.2 in economically developed regions, while it reaches 0.8 in rapidly developing regions. Sun, X and Onuh, W. O [12], through the system dynamics model established that simulates the impact of low-carbon economic policy variables on the energy consumption structure, under the optimal policy combination, the consumption share of coal energy in Shaanxi Province will decrease to 57.8% by 2030, and the share of non-fossil energy and natural gas will increase, promoting the development of low-carbon economy.

The above is a detailed analysis and discussion of China's energy structure and regional economy, and a preliminary study based on the connotation and essence of low-carbon economy. It is not difficult to see from the current state of research that there is a certain correlation between economic growth and energy consumption [13]. Therefore, the adjustment of energy structure and the development of low-carbon energy industrial structure is both an environmental issue and an economic and social issue. As an environmental issue, low-carbon energy restructuring is an important way to mitigate the global public problem of environmental degradation [14]. As an economic issue, from the macro-strategy energy restructuring is an inevitable choice for China's economic structure, promoting industrial structure transformation and upgrading, occupying the high ground of the development of the new economy and guaranteeing energy security [15]. And from the micro level, it is a favorable opportunity to improve the competitiveness of enterprises, stimulate the innovation ability of enterprises, and move steadily to the international market [16]. As a social issue, energy restructuring will change people's consumption mode, living habits and value orientation, leading mankind from industrial civilization to ecological civilization [17].

The essence of energy restructuring is to balance the relationship between economic growth and environmental protection, which requires the government to formulate relevant policies to guide and couple the coordinated development [18]. The means of government policy regulation should be flexible, spontaneous and reliable, however, at present, China's energy structure adjustment is usually planned and adjusted in a static way, which is far from being able to adapt to today's economic development situation [19]. To change the imbalance of energy structure adjustment, it is necessary to realize the change from “static adjustment” to “dynamic adjustment”, and dynamically adjust the energy structure according to the current situation of regional development and long-term demand, so as to make it match with the needs of regional economic development [20]. Recently, some emerging stochastic optimization algorithms have shown the advantages of fast search capability and strong optimization ability in dealing with dynamic planning problems [21]. This provides a powerful tool for us to study the dynamic adjustment of low-carbon energy structure.

In this paper, we first analyze the influence path of industrial structural adjustment on the shape of low-carbon energy structure from the dual perspectives of structural effect and technological effect, and use the LM panel test method based on FMOLS to construct the low-carbon energy structure influence model. The coupling coordination analysis index system is designed, and the comprehensive evaluation index is measured by linear weighting method. Utilize the uniform distribution function method to set the system coupling degree and coupling coordination degree, and build the coupling model of low-carbon energy structure adjustment and regional economic growth. Utilizing the spatial autoregressive model to explore the mechanism of low-carbon energy structure upgrading on regional economic growth. Analyze the influencing factors of low-carbon energy structure adjustment from the perspective of double change law in space and time. Based on the entropy method to determine the weights of indicators, analyze the coupling and coordination between low-carbon energy structure adjustment and regional economic growth in China.

II. Construction of a coupled coordination model of low-carbon energy structure and regional economic growth

The global consensus on combating climate change and realizing sustainable development has been reached, and China's proposed “dual-carbon” goal has put forward urgent requirements for energy system transformation. As a typical technology-intensive and resource-dependent process, energy restructuring is not only related to the effectiveness of emission reduction, but also deeply coupled with the regional economic growth path. Existing research focuses on single-dimensional analysis, and the two-way dynamic mechanism between the two is still insufficient. This paper breaks through the traditional static analysis framework and introduces a stochastic optimization algorithm to construct a coupling model, aiming to accurately identify the long-term equilibrium relationship between low-carbon energy and economic growth.

II. A.Mechanisms of industrial restructuring on the low-carbon energy mix

(1) Structural effect

An important connotation of industrial structure upgrading is the optimization of the proportion structure of each industry, and the change of the proportion of each industry will affect the overall energy consumption structure of the industry. Research shows that the structure of the three industries and the energy consumption structure are interrelated and have mutual influence, especially the proportion of the secondary industry is closely related to the energy consumption structure, and the development of industrial industry has obvious influence on the energy consumption structure.

The structural effect of industrial structural adjustment refers to the adjustment of the ratio between industries and the change of the internal structure of industries, which will lead to the corresponding change of the energy consumption structure. On the one hand, the production and development of each industry cannot be separated from energy consumption, but the main types of energy consumption and energy intensity of different types of industries will differ. In terms of the consumption of different types of energy, the consumption of fossil energy, such as coal and oil, is mainly concentrated in coal and oil mining, petrochemical processing, power supply and other industries. The energy intensity of different industries is also different, such as technology-intensive industries will have a higher energy use efficiency than resource-intensive, and the energy intensity of the service industry is significantly lower than that of the heavy chemical industry. Therefore, the adjustment of the proportion of industries in the economy will bring about a promotional effect on the improvement of the energy structure, such as reducing the economy's dependence on heavy chemical industries is conducive to reducing energy demand, the development of high-tech emerging industries, new energy industries, etc. will be conducive to reducing the consumption of fossil energy and increasing the use of new energy. When the proportion of industries with clean and efficient energy consumption increases, the overall energy consumption structure of the economy will be optimized. On the other hand, from the perspective of the evolution of industrial structure, the upgrading of the industrial chain within each industry, the upgrading of the production level, the increase in value-added products, the upgrading of the production structure and production links within the industry, the production of energy consumption will be greatly reduced, and the energy inputs in the production of energy categories are also cleaner and more efficient, and the energy consumption structure of the industry will also be improved.

(2) Technology effect

Technological innovation is the fundamental driving force of social development, and has a profound impact on the extraction and utilization of energy. Some studies believe that technological progress can improve the efficiency of energy utilization and reduce energy consumption; others believe that the improvement of technological level will ultimately lead to an increase in energy consumption; in addition, there are significant regional differences in the impact of technological progress on energy demand. The upgrading of industrial structure is often accompanied by the improvement of industrial production efficiency and technological level, which will also affect energy consumption.

The technical effect of industrial structure adjustment mainly refers to the fact that the progress of production technology and the improvement of production methods in the process of industrial structure upgrading can promote the optimization of energy consumption structure. From the perspective of technological innovation, the process of industrial structure optimization and upgrading is accompanied by a large number of technological innovations, and the enhancement of the innovation capacity of enterprises will stimulate the development of new energy, energy optimization and allocation, energy conservation and other technological advances, and the use of new technologies will save a large amount of energy, which is also conducive to the realization of new energy sources for the substitution of traditional fossil energy sources. From the point of view of the enhancement of the production process of each industry, the introduction of new industrial production methods or the improvement of product technology content will bring about the enhancement of production efficiency, which is conducive to reducing the input of raw materials and energy consumption per unit of output; at the same time, in the process of industrial enhancement of the enterprise technology investment accounted for an increase in the proportion of the production equipment upgraded and modernization of the production process, the production process is more energy-saving and environmentally friendly, and the structure of energy consumption in the industry will be cleaner.

II. B.Modeling the impact of low-carbon energy structure

Based on the null hypothesis of cointegration, this paper adopts the LM panel test based on FMOLS for the different cross-sections i under study, assuming that q_{it} is equal to $(gdp_{it}, pop_{it}, str_{it})$ and β_i is equal to $(\beta_{1i}, \beta_{2i}, \beta_{3i})$, and the model can be collapsed as:

$$\begin{cases} eff_{ij} = \alpha_i + q_{ij}\beta_i + v_{ij} \\ q_{ij} = q_{ij-1} + \varepsilon_{ij} \\ v_{ij} = \gamma_{ij} + u_{ij} \\ \gamma_{ij} = \gamma_{ij-1} + \theta_{uij} \end{cases} \tag{1}$$

Iterate over v_{ij}, there:

$$eff_{ij} = \alpha_i + q_{ij}\beta_i + \theta\sum_{t=1}^{j} u_{it} + u_{ij} = \alpha_i + q_{ij}\beta_i + e_{ij} \tag{2}$$

Assuming that θ is equal to 0, it indicates that the accumulation does not exhibit a stochastic trend in the perturbations and that there is a significant cointegration between $e_{ij} \sim I(0)$ and $\left(eff_{ij}, gdp_{ij}, pop_{ij}, str_{ij}\right)$ role, otherwise $e_{ij} \sim I(1)$ indicates that panel cointegration does not exist. In order to better apply FMOLS to estimate regional economic growth and low-carbon energy structure, suppose $w_{ij} = \left(u_{ij}, varepsilon_{ij}\right)$, then for w_{ij}, $\Omega = \lim \frac{1}{T} E\left(\sum_{j=1}^{T}\omega_{ij}\right)\left(\sum_{j=1}^{T}\omega_{ij}\right)' = \Sigma + \Gamma + \Gamma' = \begin{bmatrix} \tilde{\omega}_1^2 & \omega_{12} \\ \tilde{\omega}_{21} & \omega_{22} \end{bmatrix}$ denotes its long-term covariance matrix, and the self-covariance matrix can be further expressed as $\Gamma = \lim \frac{1}{T}\sum_{k=1}^{T-1}\sum_{j=k+1}^{T} E = \begin{bmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{bmatrix}$, then the FMOLS estimate is:

$$\beta_{i,FM} = \left[\hat{\alpha}_i \ \hat{\beta}_i\right] = \left(X_i'X_i\right)^{-1}\left(X_i'eff_i^* - \pi T\delta^*\right) \tag{3}$$

where $X_i = (I_T, q_i)$, is a vector with all elements 1; $\pi = (0,1,1)'$, and $\delta^* = \Pi_{21} - \Pi_{22}\Omega_{22}^{-1}\tilde{\omega}_{21}$ provides a correction for self-correlation. Let $S_{it}^{*2} = \sum_{t=1}^{j} e_{ij}^*$, $e_{ij}^* = eff_{ij}^* - X'\beta_{iFM}$ and the FMOLS-based test statistic be:

$$LM^* = \frac{\left(NT^2\sum_{i=1}^{N}\sum_{j=1}^{T} S_{it}^{*2}\right)}{\tilde{\omega}_{1,2}^2} \tag{4}$$

That is, $LM = \sqrt{N}\left(LM^* - \mu_v\right) \Rightarrow N\left(0, \sigma_v^2\right)$, and $\mu_v = E\left(\int_0^1 omega(r)^2 dr\right)$, and $\sigma_v^2 = Var\left(\int_0^1 \omega(r)^2 dr\right)$. Further analyzing and calculating the statistics of LM and its corresponding p-value based on the normal distribution, assuming that the original hypothesis is valid, the panel cointegration vector based on FMOLS can be further expressed as $(1, \beta_i)' = \left(1, \hat{\alpha}_i \ \hat{\beta}_{1i} \ \hat{\beta}_{2i} \ \hat{\beta}_{3i}\right)$, and this equation is the coefficients of improvement of the different factors for the low-carbon energy structure.

II. C. Stochastic algorithm-based coupling model construction of low-carbon energy restructuring and regional economic growth

II. C. 1) Construction of Coupling Coordination Analysis Indicator System

In constructing the indicator system of low-carbon energy structure adjustment and regional economic growth, the low-carbon energy structure adjustment subsystem of this paper selects six indicators: the proportion of non-fossil energy consumption, energy consumption per unit of GDP, per capita energy consumption, energy processing and conversion efficiency, per capita CO2 emissions, and the proportion of renewable energy power generation. The regional economic growth subsystem selects the proportion of green GDP to reflect the upgrading of low-carbon energy structure, the proportion of output value of the third industry, the proportion of output value of the second industry, the proportion of investment in fixed assets to reflect the adjustment of industrial structure, the proportion of the elderly population, the proportion of the labor force to reflect the age structure, and then selects the density of the population, the intensity of energy consumption, and then a total of eight indicators to reflect the level of growth of the regional economy, the coupled and coordinated analysis indicator system constructed. The constructed coupled coordination analysis index system is shown in Table 1.

Table 1: Index system of coupling coordination analysis

Primary index	Secondary index	Three-level index	Unit and index positive and negative
Low-carbon energy structure and regional economic system	Low-carbon energy structure	Share of non-fossil energy consumption (X1)	% (Positive)
		Energy consumption per unit of GDP (X2)	t standard coal/ten thousand yuan (Negative)
		Per capita energy consumption (X3)	t standard coal/person (Negative)
		Energy processing and conversion efficiency (X4)	% (Positive)
		Per capita CO_2 emissions (X5)	t/person (Negative)
		The proportion of renewable energy generation (X6)	% (Positive)
	Regional economic system	Proportion of green GDP (Y1)	% (Positive)
		The proportion of the output value of the three industries (Y2)	% (Positive)
		The proportion of the output value of secondary production (Y3)	% (Positive)
		The proportion of fixed asset investment (Y4)	% (Positive)
		Proportion of elderly population (Y5)	% (Negative)
		Working-population ratio (Y6)	% (Positive)
		Population density (Y7)	Person/km^2(Positive)
		Energy consumption intensity (Y8)	t standard coal/ten thousand yuan GDP (Negative)

II. C. 2) Coupled Coordination Modeling

(1) Integrated evaluation model of subsystems

Low-carbon energy subsystems, regional economic systems, the interaction between the two systems, the subsystems within the order of the degree of order of the “degree of contribution” can be realized by using the integration method, for the system contains fewer indicators, the general use of single-indicator analysis, if the indicators are more, it is necessary to use the integrated score calculation method, through the corresponding calculation to analyze the value of the indicator in different periods, and comparative analysis, multiplication synthesis method and linear weighting method are commonly used in the calculation method. Calculation to analyze the value of the indicator in different periods, and comparative analysis, multiplication synthesis method and linear weighting method is a commonly used calculation method in the integrated score calculation method, and due to the linear weighting method is not high on the requirements of the index data, so the integrated evaluation index of each sub-system in this paper is measured by the linear weighting method, and the formulas are as follows, respectively:

Comprehensive evaluation index of low carbon energy subsystem:

$$U_x = \sum_{i=1}^{m} e_i x_i \tag{5}$$

Comprehensive evaluation index for regional economic subsystems:

$$U_y = \sum_{j=1}^{n} v_j y_j \tag{6}$$

In Eqs. (5) and (6), e_i denotes the weights of i indicators in the low-carbon energy subsystem, and v_j denotes the weights of j indicators in the regional economic subsystem; x_i and y_j denote the standardized values of indicators in the two subsystems, respectively.

(2) Coupling and coordination model between two systems

Coupling can be described as a phenomenon in which two and more systems or forms of motion influence each other through various interactions, and the degree of coupling describes the degree of interaction and mutual influence between the systems or between elements within the systems. From the point of view of synergism, the key of the system from disorder to order lies in the synergistic effect between the sequential parameters within the system, which controls the characteristics and laws of the system, and the measure reflecting this synergistic effect is the degree of coupling. The role and degree of coupling determines what kind of order and structure the system goes to when it reaches the critical region, or it determines the trend of the system from disorder to order, if the subsystems have a high degree of coupling, the subsystems cooperate with each other and push each other forward; if the subsystems are not coordinated and cooperated with each other, they produce a constraining effect on each other. Energy consumption subsystems, low carbon economic subsystems interact with each other and influence each other, and the coupling and coordination model formula between low carbon energy subsystems and regional economic subsystems is:

Low-carbon energy structure-regional economic system coupling coordination model:

$$C_{xy} = \left\{ U_x * U_y \Big/ \left[(U_x + U_y)/2 \right]^2 \right\}^2 \tag{7}$$

$$T_{xy} = \alpha U_x + \beta U_y \tag{8}$$

$$D_{xy} = \sqrt{C_{xy} * T_{xy}} \tag{9}$$

In the above equation: U_x, U_y denote the comprehensive evaluation index of low-carbon energy subsystem and regional economic subsystem respectively, T_{xy} denotes the comprehensive coordination index between low-carbon energy subsystem and regional economic subsystem, C_{xy} denotes the degree of coupling between low-carbon energy subsystem and regional economic subsystem, and the process of increasing the value of C_{xy} from 0 to 1 indicates that the system is the process of disordered structure to orderly structure, D_{xy} indicates the coupling coordination degree between low carbon energy subsystem and regional economic subsystem, α, β are the parameters to be determined, set the sum of the two of α, β is 1, and because the low carbon energy subsystem, regional economic subsystem has the same important position in the system, so take $\alpha = \beta = 0.5$.

(3) Coupling degree and coupling coordination degree level division criteria

The size of the coupling degree (C) value, coupling coordination degree (D) value reflects the degree of coupling coordination between the systems, in order to better reflect the coupling and coordination between the low carbon energy subsystem and the regional economic subsystems, based on the results of the analysis of this paper's data, through the use of the uniform distribution function method to set the degree of system coupling and the type of coupling coordination, the classification criteria. Coupling coordination degree type, the division standard is shown in Table 2 and Table 3.

Table 2: Standards for classification of coupling degree between systems

Coupling degree (C) value	0.0~0.4	0.4~0.6	0.6~0.8	0.8~1.0
Coupling degree level	Low horizontal coupling	Primary horizontal coupling	Moderate horizontal coupling	Good horizontal coupling

Table 3: Standards for classification of coupling coordination degree between systems

	Degree of coordination	Coupling coordination degree (D) value	Coupling coordination type
Coordinate	Highly coupling coordination	0.9~1.0	High-quality coupling and coordinated development type
		0.8~0.9	Good coupling and coordinated development type
		0.7~0.8	Intermediate coupling coordinated development type
	Basic coupling coordination	0.6~0.7	Primary coupling coordinated development type
		0.5~0.6	Barely coupled coordinated development type
Dysfunctional	Near-coupling coordination	0.4~0.5	Borderline dysfunctional recession type
		0.3~0.4	Mild dysregulated recession type
	Dysfunctional recession	0.2~0.3	Moderate-dysfunction recession type
		0.1~0.2	Severely dysfunctional recession type
		0.0~0.1	Extremely dysfunctional recession type

III. Example analysis of synergies between low-carbon energy restructuring and regional economic growth

The empirical data in this paper are mainly from the National Bureau of Statistics and local statistical yearbooks, and the PM2.5 data are from the Atospheric Composition Analysis Group. Excluding regions with a large number of missing data, panel data for 15 provinces in China for the period of 2020-2024 are finally obtained.

III. A. Regional economic growth impact analysis

III. A. 1) Descriptive statistics

The descriptive statistics of each variable are shown in Table 4. The maximum value of regional economic growth (Hged) is 0.663, the minimum value is 0.195, and the average value is 0.368, indicating that there are large regional differences in China's economic growth level. The average value of Low-carbon Energy Structure Upgrade (Upgrade) is 1.485, the minimum value is 1.204, and the maximum value is 2.147. Only a few regions have a much higher proportion of relative clean energy consumption than the average, suggesting that there are little regional differences in China's low-carbon energy structure. The mean value of Industrial Structure Adjustment (Is) is 1.197, and the extreme deviation is 3.071, indicating that China has entered the post-industrial era as a whole, but there are large regional differences in industrial structure. The average value of Age is 0.648, and the extreme deviation is 0.179, indicating that China has gradually entered an aging society, but the regional differences in age structure are not large. The average value of Density is 0.486, with an extreme difference of 3.906, indicating that China's population distribution is extremely uneven. The average value of Energy is 1.048, with an extreme difference of 3.393, indicating that China is still in the late stage of the rough economic growth mode, with large regional differences in energy consumption per unit of GDP.

Table 4: Descriptive statistics of variables

Variable	Mean value	Standard deviation	Minimum value	Maximum value
Hged	0.368	0.083	0.195	0.663
Upgrade	1.485	0.142	1.204	2.147
Is	1.197	0.539	1.084	4.155
Age	0.648	0.045	0.537	0.716
Density	0.486	0.563	0.011	3.917
Energy	1.048	0.604	0.312	3.705

III. A. 2) Analysis of regional economic growth assessment

The 15 provinces are numbered as A1~A15, and the evaluation value of regional economic growth of each province is calculated, and the results are shown in Table 5. As shown in Table 5, in 2024, X3, X7, X8, X9 and X2 ranked in the top five in terms of the level of high-quality development of the economy, and the overall level of high-quality development of the economy shows a rising trend year by year. China's economic high-quality development level still exists in a spatial distribution imbalance situation, which is manifested in regional imbalance and regional high-value aggregation.

Table 5: Evaluation of high-quality regional economic development

Region	2020	2021	2022	2023	2024
X3	0.408	0.447	0.563	0.607	0.628
X7	0.365	0.377	0.462	0.553	0.592
X8	0.343	0.362	0.411	0.454	0.552
X9	0.328	0.341	0.377	0.422	0.481
X2	0.285	0.329	0.364	0.392	0.403
X1	0.246	0.291	0.303	0.318	0.357
X4	0.233	0.282	0.292	0.305	0.324
X6	0.225	0.271	0.283	0.294	0.305
X5	0.216	0.269	0.276	0.288	0.293
X14	0.215	0.255	0.263	0.271	0.282
X12	0.207	0.246	0.255	0.263	0.271
X13	0.203	0.241	0.246	0.253	0.265
X15	0.201	0.236	0.241	0.248	0.257
X10	0.198	0.233	0.237	0.241	0.249
X11	0.196	0.226	0.235	0.238	0.244

III. A. 3) Estimated results of the mediated effects test model

Expanding the mediating effect to the spatial econometric model, a spatial autoregressive model of regional economic growth is constructed. Model 1 is set up to explore the impact of low-carbon energy structure upgrading on regional economic growth, model 2 to explore the impact of low-carbon energy structure on industrial restructuring, and model 3 to explore the mediating role of industrial restructuring. The regression results of the mediation effect test models (1) to (3) are shown in Table 6, with "*", "**", and "***" denoting significant at the 10%, 5%, and 1%, respectively, levels. level passes the test. The Hausman test was used to identify the fixed and random effects, and the results indicated the existence of fixed effects, so the fixed effects spatial autoregressive model was used.

The test results of model (1) show that low-carbon energy structure upgrading has a significant positive impact on regional economic growth. It shows that low-carbon energy structure upgrading not only can directly reduce emissions and realize green development, but also has a driving effect on economic growth and can promote regional economic growth. The test results of model (2) show that low-carbon energy structure upgrading has a positive promotion effect on industrial restructuring, while regional population density and age structure have a significant positive effect on industrial restructuring. Although policies and market mechanisms such as mandatory emission reduction, carbon tax, and carbon trading market have caused great pressure and challenges to high-energy-consuming and high-polluting enterprises in the short term, they are still conducive to the long-term development of the enterprises, only that different enterprises respond to the pressure and challenges in different ways. A part of the enterprise may still choose to engage in the original industry, the original production process or production methods have been upgraded to lead the industry towards the direction of green development; another part of the enterprise may find another way to the upstream and downstream of the industrial chain or related industries, no longer engaged in high-pollution industries; there is also a part of the enterprise does not have the ability to cope with the challenges of low-carbon development will be eliminated. Such changes will naturally lead to the adjustment and optimization of the industrial structure in the low-carbon or even zero-carbon direction. The test results of model (3) show that industrial structure adjustment has a partial mediating effect. Combining models (1) to (3), low-carbon energy structure upgrading can play an indirect role in promoting economic high-quality development through industrial structure adjustment, in addition to having a direct positive impact on economic high-quality development. The test results of model (3) also show that there is a significant positive spatial spillover effect of high-quality economic development, which verifies the regional synergy effect of high-quality economic development.

Table 6: Test model of mediation effect

Variable	Model (1)	Model (2)	Model (3)
Upgrade	0.326***	1.248***	0.091**
	(14.53)	(11.42)	(2.45)
Age	0.302***	3.713***	0.022***
	(2.740)	(7.45)	(2.47)
Density	0.019***	0.123***	-0.039
	(5.38)	(5.35)	(-1.04)
Energy	0.042***	0.218***	-0.022***
	(5.61)	(5.24)	(-2.32)
Is	/	/	0.037**
			(2.13)
ρ	-0.018	0.103**	0.582***
	(-0.32)	(2.07)	(9.59)
R^2	0.775	0.834	0.826
Hausman test	91.38***	45.22***	44.73***

III. B. Low-carbon energy mix impact analysis

III. B. 1) Spatial autocorrelation analysis

In order to reflect the spatial correlation of the low-carbon energy structure of each province in detail, this paper further illustrates the local spatial correlation of the low-carbon energy structure of each province by using the Morans' I analysis, and the years 2020, 2022 and 2024 are selected for analysis, which is used to explore the local spatial autocorrelation pattern of the low-carbon energy structure of each province and its leaping process. The statistics of the local correlation patterns of low-carbon energy structure in each province in the three time periods are shown in Table 7.

From Table 7, it can be seen that in 2020, the low-carbon energy structure of all municipalities except X12 exhibits HH agglomeration or LL agglomeration, and in 2022, the low-carbon energy structure of X3, X7, X9, X8, X2, and X6 continues to exhibit HH agglomeration, and in terms of the direction of the change of the level of development of low-carbon energy, the development of X15's low-carbon energy exhibits HL agglomeration, which indicates that the development speed of low-carbon energy is higher than that of its neighboring municipalities. development speed is higher than its neighboring municipalities.The low-carbon energy structure of X4, X1, X5, X12, X14, X10, and X13 exhibits LH agglomeration in 2022, which indicates that these seven municipalities are lagging behind the neighboring provinces in terms of their low-carbon energy development speed.In 2024, the low-carbon energy structure of X14, X10, and X13 continues to exhibit LH agglomeration, while the rest of the municipalities exhibit HH agglomeration, with X4, X1, X5 and X12 change from LH agglomeration to HH agglomeration, indicating that these four provinces continue to develop low-carbon energy at a faster rate. Taken together, municipalities with higher levels of development tend to be adjacent to municipalities with higher levels of development, while municipalities with lower levels tend to be relatively adjacent to municipalities with lower levels. There are obvious spatial correlation and dynamic development of low-carbon energy structure in each province, meanwhile, it can be seen from the type of leap of local correlation pattern in each province that the development of low-carbon energy in each province is not balanced, and the spatial dependence is significant.

Table 7: Local correlation model statistics of low-carbon energy structure

	2020			2022			2024		
Region	Z	W·Z	Type	Z	W·Z	Type	Z	W·Z	Type
X3	1.338	0.938	HH	1.392	0.648	HH	1.408	0.794	HH
X7	1.207	0.902	HH	1.311	0.584	HH	1.352	0.736	HH
X9	1.202	0.837	HH	1.303	0.568	HH	1.249	0.685	HH
X8	1.105	0.822	HH	1.211	0.503	HH	1.208	0.637	HH
X2	1.038	0.806	HH	1.183	0.485	HH	1.184	0.593	HH
X6	1.023	0.739	HH	1.137	0.422	HH	1.179	0.521	HH
X4	-0.197	-0.382	LL	-0.182	0.093	LH	0.029	0.123	HH
X1	-0.283	-0.429	LL	-0.196	0.092	LH	0.023	0.119	HH
X5	-0.375	-0.593	LL	-0.301	0.105	LH	0.032	0.115	HH
X12	-0.403	0.102	LH	-0.268	0.138	LH	0.038	0.129	HH
X14	-0.493	-0.602	LL	-0.247	0.122	LH	-0.118	0.126	LH
X10	-0.511	-0.623	LL	-0.392	0.047	LH	-0.134	0.063	LH
X15	-0.568	-0.654	LL	0.084	-0.055	HL	0.091	0.188	HH
X13	-0.603	-0.668	LL	-0.425	0.073	LH	-0.293	0.137	LH

III. B. 2) Dynamic spatial panel data model estimation results

Based on the method of 2.2, a dynamic spatial panel econometric model is constructed, and the low-carbon energy structure is set as X. The parameter estimation and significance test of the model are shown in Table 8. From the regression results and significance test in Table 8, it can be seen that: as a whole, the model's decidable coefficient R^2 reaches 95.75%, the goodness of fit is very high, which indicates that the independent variables selected in this paper can explain the dependent variable of low-carbon energy structure well, and the value of the joint LM test is obtained as 12.237, which is smaller than the corresponding χ^2 threshold, and the model does not have heteroskedasticity.

From the regression coefficients of each variable and their significance: each variable passed the significance test at 1% level or 5% level. In the low-carbon energy structure, the proportion of renewable energy power generation passed the significance test at the 1% level, indicating that the proportion of renewable energy power generation has a significant impact on energy economic efficiency, and that for every percentage point increase in the proportion of renewable energy power generation, the low-carbon energy structure is upgraded by 0.6873 percentage points.

Table 8: Estimation results of dynamic spatial panel model

Variable	Coefficient	t-statistic
lnX	-0.2186***	-0.2085

LnX1	-0.4386***	-2.4978
LnX2	0.3953**	-1.4586
LnX3	0.2470***	2.6477
LnX4	-0.5583**	0.1743
LnX5	0.1386***	2.9475
LnX6	-0.6873***	2.2048
λ	0.2947***	
R^2	0.9575	
σ^2	0.2486	
LogL	246.6978	
LM(χ^2)	12.237(20.595)	

III. C. Analysis of synergies between low-carbon energy restructuring and regional economic growth

III. C. 1) Determination of indicator weights

In the application of entropy assignment method, the raw data are first standardized, and the information entropy value, information utility value and weight value are calculated, and the weights of the coupled coordination analysis index system are shown in Table 9. In the low carbon energy subsystem, the weight of renewable energy power generation is 0.28, and the smallest weight is the per capita CO2 emission, which is 0.05. In the regional economy subsystem, the weight of green GDP is 0.26.

Table 9: Weight of index system of coupling coordination analysis

	Index	Information entropy	Information utility value	Weight
Low-carbon energy structure and regional economic system	X1	0.79	0.21	0.19
	X2	0.72	0.28	0.15
	X3	0.76	0.24	0.09
	X4	0.77	0.23	0.24
	X5	0.79	0.21	0.05
	X6	0.71	0.29	0.28
	Y1	0.83	0.17	0.26
	Y2	0.81	0.19	0.11
	Y3	0.87	0.13	0.07
	Y4	0.85	0.15	0.08
	Y5	0.83	0.17	0.08
	Y6	0.84	0.16	0.11
	Y7	0.83	0.17	0.17
	Y8	0.88	0.12	0.12

III. C. 2) Coupling coordination analysis

Based on the weights determined by the entropy value method, according to the calculation method of the coupling degree of coordination, we can get the integrated ordinal coefficients of China's low-carbon energy structure and regional economic growth in 2020-2024, U1 and U2, as well as the coupling degree of the "low-carbon energy structure-regional economic growth" system, C. In addition, in view of the importance of both of them in the current development, we can obtain the degree of coordination D. In addition, given the importance of the two in the current development, the coordinated development of the two is set to be equally important, i.e., a and b in the coordination formula are set to be 0.5, resulting in a degree of coordination D. The results of the integrated ordinal coefficients of the system and the coupling coordination are shown in Table 10, which is a comparative analysis of the longitudinal perspective of time, in order to explore the time-varying nature of the synergistic effect of China's low-carbon energy structure and regional economic growth.

According to the measurement results in Table 10, the integrated ordinal coefficients of the two show a growing trend, and the coupling degree is maintained at a high level of 0.89-0.99, while the degree of coordination is developed from the near-disordered recession zigzagging to the intermediate level of coupling and coordination. This suggests that both low-carbon energy structure and regional economic growth have achieved five years of rapid development, while the two also maintain a strong interaction, however, the overall situation does not form a synergistic development, especially the early imbalance situation is serious, barely reaching coordination. Of course, with the development of energy and industry, and the guidance of related policies, the two mutual promotion and mutual enhancement have been realized, and the primary coupling coordination was achieved in 2022, and the degree of coordination has been kept growing, reaching 0.79 in 2024.

Table 10: comprehensive order parameter values and coupling coordination degree

Year	U1	U2	C	D	Coupling strength and coordination degree
2020	0.33	0.29	0.89	0.46	Good horizontal coupling
					Borderline dysfunctional recession type
2021	0.22	0.25	0.99	0.47	Good horizontal coupling
					Borderline dysfunctional recession type
2022	0.68	0.45	0.97	0.66	Good horizontal coupling
					Primary coupling coordinated development type
2023	0.71	0.58	0.98	0.72	Good horizontal coupling
					Intermediate coupling coordinated development type
2024	0.66	0.52	0.99	0.79	Good horizontal coupling
					Intermediate coupling coordinated development type

IV. Conclusion

This paper constructs a coupling model of low-carbon energy structure adjustment and regional economic growth based on stochastic optimization algorithm, explores the reasonableness of subsystem indicator selection, and measures the coupling coordination of low-carbon energy structure and regional economic growth in China through actual data.

The results of the mediation effect test model show that low-carbon energy structure upgrading has a significant positive impact on regional economic growth. The decidable coefficient R^2 of the dynamic spatial panel econometric model of low-carbon energy structure reaches 95.75%, and the value of the joint LM test is 12.237, which is smaller than the corresponding χ^2 threshold, and the model does not have heteroskedasticity.

In 2020-2024, the coupling degree of China's low-carbon energy structure adjustment and regional economic growth stays at a high level stage of 0.89-0.99, while the coordination degree is developed from the near-disordered recession zigzagging to the intermediate coupling coordination, and realizes the primary coupling coordination in 2022, and the coordination degree has been kept growing and reaches 0.79 in 2024.

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