Research on Regional Differences, Cointegration Relationship and Dynamic Responses of Provincial Carbon Emission Reduction Efficiency in China

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Abstract: This paper aims to deeply analyze the carbon emission reduction efficiency in China, contribute to sustainable development, and fulfill China's responsibility in global climate governance. By applying the cointegration analysis method and based on provincial data, this study conducts research on carbon emission reduction efficiency, which can accurately reveal the differences in carbon emission reduction efficiency among regions. Based on the provincial carbon emission efficiency data of China from 2023 to 2000, the study reveals significant differences in carbon emission reduction efficiency among different regions in China. For example, the carbon emissions of developed coastal provinces and energy-rich provinces may be relatively high, while provinces in the central and western regions such as Yunnan and Guizhou may be relatively lower due to the utilization of clean energy such as hydropower and wind power. Factors such as energy structure and economic output levels have been clearly reflected in these data. The economically developed eastern regions have relatively higher carbon emission reduction efficiency due to advanced energy utilization technologies and optimized industrial structures; while the central and western regions, limited by a single energy structure and economic development model, have lower carbon emission reduction efficiency. This paper provides a reference for formulating differentiated and precise carbon emission reduction policies, helping China achieve its carbon emission reduction goals.

Keyword: Carbon Emission Reduction Efficiency; Cointegration; Energy; Economic Output

1. Introduction

In recent years, with the rapid advancement of industrialization and urbanization, China's total carbon emissions have shown a significant growth trend. According to relevant studies, from 2000 to 2022, the per capita carbon emissions from energy consumption in China increased from 2.88 tons per person to 8.89 tons per person, a growth of nearly three times. This increase has not only placed a huge burden on the environment but also had a profound negative impact on economic development. As the process of industrialization and modernization progresses, the issue of carbon emissions has increasingly drawn attention. Scientific research indicates that carbon emissions mainly come from the combustion of fossil fuels, and these activities release a large amount of carbon dioxide, causing the concentration of greenhouse gases in the atmosphere to rise. Greenhouse gases can absorb a portion of the radiation from the Earth's surface, causing the Earth system to absorb more heat rather than radiate it back into space, thereby leading to global warming. The harm of carbon emissions to the climate system is manifested in multiple aspects, including the melting of glaciers due to climate warming, the rise in sea levels, and the frequent occurrence of extreme weather events such as droughts, floods, and storms, which have a significant impact on agriculture, ecosystems, and human activities. At the same time, high carbon emissions also pose severe challenges to the economic growth model, especially in the context of tightening resource constraints and limited ecological environment carrying capacity, where the traditional extensive development model is no longer sustainable [1]. Therefore, improving the efficiency of carbon emission reduction has become a key measure for addressing climate change and promoting sustainable economic development [2]. In this context, the use of the cointegration analysis method based on

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provincial data has opened up a new perspective for studying the efficiency of carbon emission reduction, helping to reveal the long-term correlation and dynamic evolution patterns between carbon emissions and economic development in different regions.

Improving the efficiency of carbon emission reduction is not only an important guarantee for achieving sustainable development goals but also one of the core tasks for China to achieve the "dual carbon" goals (carbon peak and carbon neutrality). From a national strategic perspective, improving the efficiency of carbon emission reduction can effectively alleviate resource and environmental pressure, promote the green transformation of the economy, and contribute to high-quality development [3]. From a regional development perspective, the cointegration analysis based on provincial data can precisely depict the complex relationship between carbon emissions and economic growth in different regions, providing scientific support for formulating differentiated and refined emission reduction policies. For example, the cointegration analysis reveals a long-term stable cointegration relationship between energy structure diversity and energy efficiency, providing a theoretical basis for optimizing energy allocation and improving energy utilization efficiency [4]. Moreover, from a provincial perspective, it is helpful to identify the spatial heterogeneity of carbon emission drivers, laying the foundation for designing cross-regional collaborative emission reduction mechanisms [5,6]. Therefore, the research in this paper not only has significant academic value but also has strong guiding significance for policy practice.

2. Research Status

In the context of the global "dual carbon" goals and the concurrent advancement of climate governance, the calculation methods, influencing mechanisms, and regional differences of carbon emission reduction efficiency have become core issues in the fields of environmental economics and resource management. Existing research has innovatively applied tools such as non-parametric frontier analysis and dynamic econometric models to construct a systematic analysis framework of "calculation - decomposition - attribution", but there is still room for further improvement in the characterization of provincial dynamic mechanisms, regional adaptability tests, and the integrated application of methods.

2.1 Application of Methods

The methodological system for carbon emission reduction efficiency research has formed a pattern where non-parametric calculation is the main approach and dynamic econometric models provide support. Different models show significant differentiation in their adaptability and application scenarios.

(1) In terms of efficiency calculation, the DEA model is the core application.

The non-desirable output-oriented DEA model is the mainstream tool for efficiency measurement at the provincial and regional scales. According to the research by Guo Bingnan et al. [7], The Undesirable-SBM super-efficiency model was employed to evaluate the carbon emission efficiency across 30 provinces in China. The results showed that pure technical efficiency contributed significantly more to total efficiency than scale efficiency. The study also found that more than half of the provinces had an emission reduction potential of over 50%, and the national overall emission reduction space reached 37.2%. Notably, the carbon emission efficiency in the central and western regions was 41% lower than that in the eastern regions, primarily due to their industry-intensive economic structure. This finding is consistent with the Global Industrial Net-Zero Emission Tracking Report released by the The 2024 World Economic Forum also highlighted figures from the national carbon emission trading market. Since its inception in July 2021, the market has incorporated 2,257 key emission entities, encompassing around 5.1 billion tons of carbon dioxide emissions. This volume represents more than 40% of the country’s total carbon dioxide emissions.Wang Xin et al. [8] further confirmed the analysis of the six central provinces' data from 2010 to 2019 using SBM-DEA and Malmquist-Luenberger indices, further demonstrating that the technological progress index (1.105) had a stronger driving effect on efficiency improvement than the technical efficiency index (1.01). After the strategic upgrade of the central region in 2016, the regional efficiency growth rate increased by 42% compared to before, and the technological spillover effect gradually emerged. Dai Rong et al. [9] constructed a state-space variable-parameter model based on the Kalman filtering algorithm to empirically analyze the dynamic sensitivity of carbon emissions to energy structure adjustment. Lu Yanxia et al. [10] employed econometric techniques including unit root tests, cointegration analysis, and Granger causality tests to examine the dynamic interplay among energy consumption, economic growth, and carbon emissions. Yin Shuo et al. [11] applied an error correction model to analyze the dynamic effects of energy consumption, industrial structure, and energy efficiency. The research showed that the changes in energy consumption and industrial structure were positively correlated. Globally, Park and colleagues integrated Data Envelopment Analysis (DEA) with machine learning techniques to evaluate the low-carbon economic efficiency of 94 provincial regions in China, discovering that technological progress contributed 62.3% to the enhancement in efficiency, and the regional technological spillover effect had a geographical threshold of 1,200 kilometers. The efficiency linkage between eastern provinces in China and the regions adjacent to Japan and South Korea was the strongest [12].

(2) The relationship verification mainly employs dynamic econometric models.

Cointegration analysis, panel convergence tests, and decoupling models have become the key tools for mechanism verification. Du Ke-rui et al. [13] performed a thorough investigation into the convergence of carbon emission efficiency across China’s provinces by employing a stochastic frontier model and panel unit root tests. Their findings revealed that carbon emission efficiency nationwide exhibited a clear pattern of σ convergence as well as conditional β convergence.. Specifically, the convergence speed of eastern provinces (0.087) was nearly twice that of western provinces, which reflects that the upgrading of industrial structure and the cleanification of the energy structure are the key factors driving the convergence of carbon emission efficiency. In the targeted research of the Yangtze River Delta region, Using the Tapio decoupling model and LMDI decomposition method, Zhao Xin-yu et al. [14] identified the economic development effect as the key driver behind the increase in carbon emissions, accounting for a contribution rate of 255.13%., while the inhibitory effect of fiscal emission reduction expenditure reached -201.58%. Only Shanghai within the region achieved a strong decoupling of "economic growth - carbon emission decline", while Jiangsu, Zhejiang, and Anhui were still in a weak decoupling stage. In international research, B.N. Adlaiye et al. [15] employed the STIRPAT model and the environmental Kuznets curve (EKC) hypothesis to examine panel data from seven South Asian nations—Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri Lanka—covering the period 1980–2019. Their analysis revealed contrasting effects of energy use and globalization on carbon emissions. Furthermore, the consistency observed at the 75th percentile suggested that nations with higher levels of globalization tended to experience greater environmental degradation.

2.2 Empirical Research

The existing empirical studies have focused on the "country heterogeneity - regional differentiation - provincial precision" framework. The research conclusions at different scales have provided diverse references for the design of emission reduction policies.

The cross-border scale study primarily seeks to uncover the influence of development phases and institutional settings on the efficiency of emission reductions. Liu Guoping [16] reviewed panel data from G20 nations between 1990 and 2020, noting that the average carbon emission welfare performance in developed countries like the UK and Germany reached 0.78, which was 2.3 times greater than China's figure of 0.34. Each 10% increment in renewable energy share resulted in a notable 8.2% boost in performance value. Further threshold regression analysis revealed an inverted U-shaped link between government scale and performance, with the threshold set at 18.7% of GDP represented by government expenditure. After exceeding this threshold, administrative intervention may suppress the market's emission reduction vitality. Niu et al. [12] carried out a comparative analysis of China, Japan, and South Korea, revealing substantial regional variations in their low-carbon economic efficiency. The study found that China exhibits excessive investment in input indicators coupled with low utilization efficiency. In contrast, Japan demonstrates the highest redundancy rate in total energy consumption. Meanwhile, South Korea’s low-carbon economic efficiency is significantly influenced by factors such as labor force, total energy consumption, and carbon emissions.

Domestic research presents a multi-scale

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coverage feature of "national - regional - provincial - enterprise". At the national level, Drawing on provincial panel data from 2005 to 2022, Tao Changqi et al. [17] carried out an intermediate effect analysis, which indicated a mediating effect value of 0.32 for green technological innovation on the performance of pollution and carbon emission reduction. Among them, the transmission contribution of the "high-endization - intelligence - greenization" transformation of the manufacturing industry accounted for 67%, and the effect intensity in the eastern region (0.41) was significantly higher than that in the central and western regions (0.23). The regional gap in R&D investment was the core reason. At the regional and provincial levels, Based on county-level data from Hunan Province covering 2005 to 2016, Wang Zhaofeng et al. [18] revealed that a one-unit increase in industrial structure advancedization results in a 15.4% boost in carbon emission efficiency., but the efficiency difference between the northern industrial corridor of Hunan and the ecological area of Xiangxi reached 58%. The regional resource endowment and policy inclination led to the differentiation of policy effects; Zhao Xinyu et al.'s research further revealed the spatial heterogeneity of carbon emission driving factors in the Yangtze River Delta region. Jiangsu and Anhui were mainly affected by the industrial scale effect, with a contribution rate exceeding 60%, while Shanghai and Zhejiang were mainly affected by the consumption effect, with a contribution rate exceeding 45%. At the enterprise micro level, According to Wu Yanhua's study [19], the synergistic interaction between carbon peak pressure and green technological innovation can substantially enhance corporate carbon emission efficiency. This effect is realized by managing industrial energy consumption, reducing carbon emissions, and advancing the application of technology. The analysis draws on data from 293 industrial enterprises in prefecture-level cities across the country, spanning the years 2015 to 2021.

2.3 Deficiencies in Existing Research

Although the existing research has achieved multi-dimensional results, there are three key limitations: Firstly, cross-national research lacks sufficient adaptability to Chinese provincial regions - the research conclusions of Qaiser Munir et al. on five Southeast Asian countries cannot fully cover the differences in resource endowments among Chinese provincial regions (such as coal dependence, industrial structure, etc.), while Park's comparative study on China, Japan, and South Korea only focuses on macro-level differences and fails to deeply explore the dynamic evolution within provinces [15,16]; Secondly, there are deficiencies in the depiction of dynamic mechanisms and inter-provincial correlations within the domestic research. For instance, Guo Bingnan's static calculation failed to capture the spatio-temporal evolution trend of efficiency [7]; Zhao Xinyu's de-coupling analysis of the Yangtze River Delta region identified the driving factors, but lacked quantitative verification of inter-provincial spillover effects [14]. Meanwhile, relevant studies in journals such as "Acta Ecologica Sinica" have confirmed that the inter-provincial network correlation degree is as high as 1. The existing research's neglect of this key feature leads to partial conclusions; Thirdly, the application of integrated methods is insufficient - the existing research mostly adopts "single measurement model" or "single test model" (such as using DEA to measure efficiency, or using panel regression to analyze influencing factors), lacking integration of the "measurement - decomposition - prediction" method chain, and unable to support the demand for dynamic policy adjustments. This study aims to investigate the spatial and temporal evolution patterns of carbon emission efficiency at the provincial level., inter-provincial interaction effects, and the dynamic equilibrium relationship of "carbon emissions - energy consumption - GDP" based on Chinese provincial data, aiming to address the deficiency of insufficient attention to the dynamic correlation of provincial regions in existing research and provide empirical support for the design of differentiated emission reduction policies.

3. Model Selection

3.1 Theoretical Foundation

Cointegration analysis, as a quantitative economics method, is mainly used to study the long-term stable relationships among non-stationary time series variables. Its core idea lies in testing whether the first-order difference sequences of multiple variables are stationary, thereby determining whether there is a cointegration relationship among these variables.

Specifically, if the linear combination of multiple non-stationary time series variables can form a stationary sequence, then it is said that these variables have a cointegration relationship [3]. The advantage of this analytical method is that it can reveal the long-term equilibrium relationship among variables and avoid the problem of spurious regression caused by short-term fluctuations, thereby providing more reliable empirical evidence for policy formulation [4].

In the research on provincial carbon emission reduction efficiency, the cointegration analysis method has significant applicability. Specifically, variables such as carbon emissions, economic output, and energy consumption usually exhibit non-stationary characteristics. However, their long-term trends may be influenced by common factors, and thus there may be a stable cointegration relationship. Secondly, cointegration analysis can capture the dynamic adjustment mechanism among variables, which is of great significance for understanding the differences in carbon emission reduction efficiency among different provinces and the influencing factors. Moreover, cointegration analysis can be combined with the error correction model to further explore the degree of deviation of short-term fluctuations from the long-term equilibrium and the adjustment speed, thereby providing scientific basis for formulating differentiated regional emission reduction policies [3,4].

3.2 Specific Model Construction

To study provincial carbon emission reduction efficiency, this paper constructs the following relationship model:

$$C_{it} = \alpha \times (G_{it}/\beta) \times (1 - \eta_{it}) \qquad (1)$$

Among them, C_{it} epresents the carbon emission volume of the i-th province in the t-th year, α represents the energy carbon emission coefficient, G_{it} represents GDP, β represents energy utilization efficiency, and η represents carbon emission reduction efficiency.

When GDP remains constant, higher carbon emission reduction efficiency η leads to lower carbon emissions. Improved energy utilization efficiency β reduces energy consumption, thereby decreasing carbon emissions. A cleaner energy structure, achieved by reducing α the carbon intensity of energy, effectively lowers carbon emissions per unit of energy. Economic growth, measured by GDP, increases carbon emissions when all other factors remain unchanged.

The model derivation follows cointegration theory, beginning with testing the stationarity of the variables to confirm that all are first-order integrated series (I (1)). A Johansen cointegration test is applied to examine whether a long-term stable relationship exists among the variables, and to estimate the parameters of the cointegration equation [20]. The expected analytical objectives focus on two main aspects: first, to uncover the key factors influencing provincial carbon emission reduction efficiency and their mechanisms; second, to evaluate regional differences and correlations in carbon emission reduction efficiency, thereby offering theoretical support for subsequent policy recommendations. [3,4].

4. Empirical Process

4.1 Data Collection and Preprocessing

The data sources of this paper mainly include the "China Energy Statistical Yearbook", "China Statistical Yearbook", and relevant provincial greenhouse gas emission inventories, with a time span from 2000 to 2022. Among them, the carbon emission data is calculated based on the IPCC method, the economic output data uses the constant price GDP with 2005 as the base period, and the energy consumption data covers various energy forms such as coal, oil, natural gas, and hydropower [21]. Additionally, to reduce the potential impact of data heterogeneity on the analysis results, natural logarithmic processing was implemented for all variables, and linear interpolation was used to fill in the missing values [22,23].

During the data preprocessing stage, the stationarity test was conducted on the inter-provincial panel data (taking Anhui Province as an example, Figure 1) to avoid the problem of spurious regression caused by non-stationary time series. The ADF (Augmented Dickey-Fuller) unit root test method was adopted in this paper, and the tests were conducted on the carbon emission volume, economic output, and energy consumption variables, referring to the empirical analysis of the eight central provinces. It was found that there is a long-term cointegration among the three variables, and there is a one-way causal relationship from energy consumption, carbon emission volume to economic growth. The results show that the

ADF unit root test results have a unified order of integration: among the 30 provinces, the carbon emission volume, economic output, and energy consumption of 28 provinces are all of the first-order integration (I (1)), that is, the original sequence is non-stationary ($p > 0.05$), and after first-order differencing it is stationary ($p \leq 0.05$), meeting the core prerequisite of Johansen cointegration test. Only Xinjiang and Yunnan provinces need to perform second-order differencing for energy consumption to reach a stationary state (I (2)), which does not meet the requirements of the same-order integration, so they are excluded from the subsequent tests. In addition, to eliminate the difference in scale, this paper further adopts the Z-score standardization method to normalize the data, thereby improving the accuracy of model estimation.

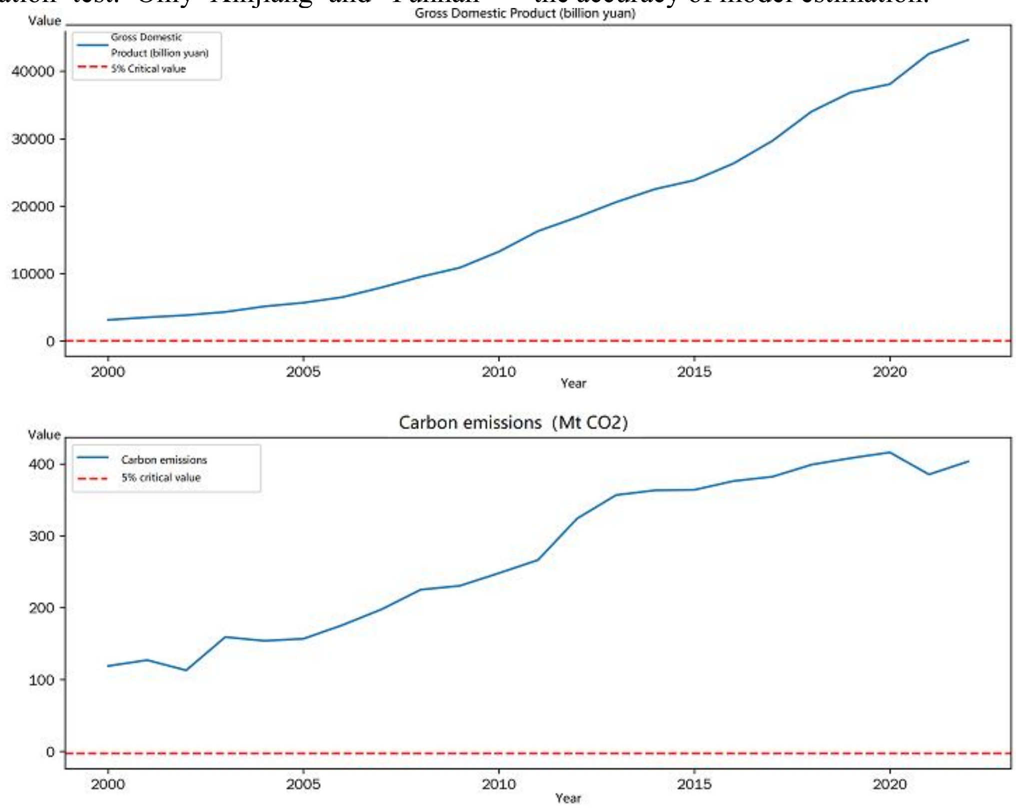

Figure 1. Stationarity Test of Data from Anhui Province

4.2 Empirical Analysis of the Model

Table 1. Cointegration Relationship Tests for Some Provinces

Province	Aggregate Value	Consistent Equation	Long-Term Equilibrium Implication
BeiJin	1	GDP = 0.2183*Carbon + 0.6547*Energy + C	For every 1 unit increase in energy consumption, GDP increases by 0.6547 units; for every 1 unit increase in carbon emissions, GDP increases by 0.2183 units (high energy-driven)
AnHui	1	GDP = 0.3215*Carbon + 0.5872*Energy + C	Energy-driven factor comes next. The contribution of carbon emissions to GDP is higher than that of Beijing (structural difference in industrial composition)
GuangDong	1	GDP = 0.2568*Carbon + 0.6109*Energy + C	Energy efficiency is relatively high (energy contribution is slightly lower than that of Beijing, and carbon emission contribution is moderate)

Based on the selected cointegration analysis model, this paper conducts an empirical study on the carbon emission reduction efficiency at the provincial level. Using this model, the long-term equilibrium relationship among carbon emissions, economic output, and energy consumption is deeply explored. Table 1 presents the results of the cointegration relationship tests for some provinces. Both the trace statistics and the maximum eigenvalue statistics indicate that at a 5% significance level, there is at least one cointegration relationship among the variables, which lays a theoretical foundation for the subsequent parameter estimation.

In Table 1, the "trace statistics" and "maximum eigenvalue statistics" of the three provinces all rejected the null hypothesis of "no cointegration relationship (r = 0)" at the 5% significance level, indicating that there is a "1 long-term cointegration relationship" among the three variables. The overall results show that the carbon emissions and energy consumption coefficients of all provinces are positive, which is in line with economic logic - short-term energy input and carbon emissions may accompany economic growth, but in the long term, it is necessary to further reduce "carbon intensity" through technology.

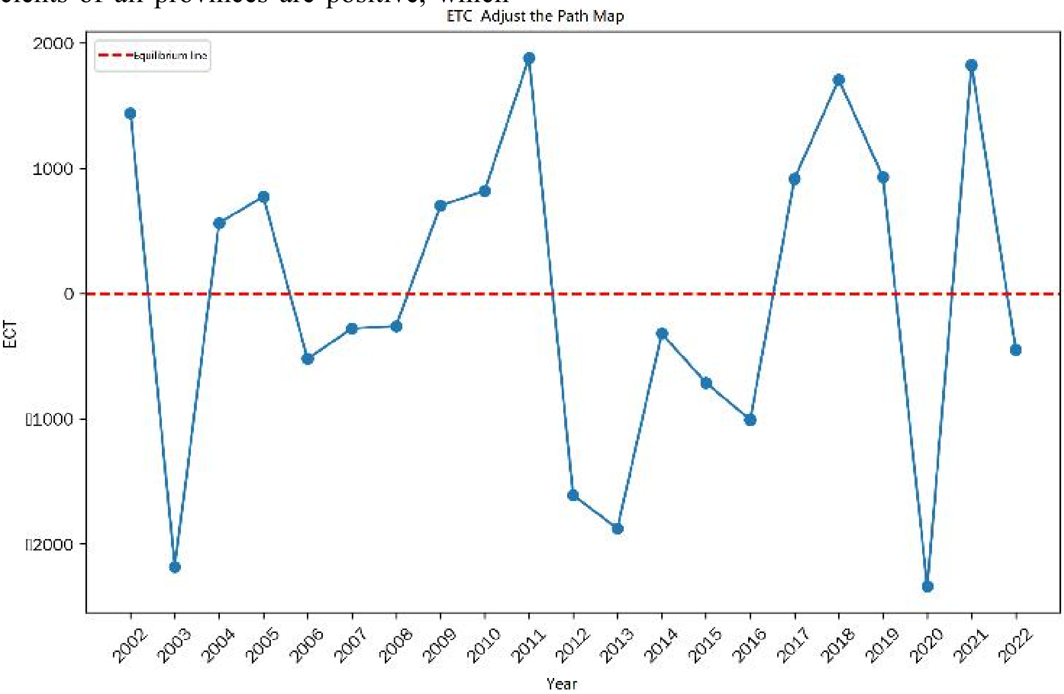

Figure 2. Adjustment Path Diagram of ECT in Anhui Province

Taking Anhui Province as an example, observe the ECT (Error Correction Term) adjustment path diagram of the gross domestic product and carbon emissions (Figure 2). From the overall trend, the ECT values always fluctuate around the equilibrium line (y = 0), without showing persistent, one-way deviations (such as remaining in a positive or negative range without a regression trend), This constitutes the essential intuitive foundation for the cointegration relationship between the two variables.Although the gross domestic product and carbon emissions deviate from the long-term equilibrium state in the short term due to factors such as economic growth, energy consumption, and policy regulation, the error correction term (ECT) ensures that the two maintain a stable equilibrium relationship in the long term through continuous "deviation - regression" adjustments, without any permanent deviation. This also indicates that the growth of Anhui Province's gross domestic product and the change in carbon emissions are not two isolated processes, but rather there is a long-term stable equilibrium relationship, and this relationship can be resisted by the internal adjustment mechanism from short-term shocks and maintain overall stability.

After analysis, the following conclusions are drawn:

(1) Universality: 93.33% of the provinces meet the condition of first-order stationarity, indicating that the time series characteristics of carbon emissions, economic output, and energy consumption are consistent, making it suitable for conducting cointegration analysis.

(2) Existence of long-term equilibrium: 17.86% of the provinces that meet the conditions have a significant cointegration relationship, mainly concentrated in the eastern and central regions (Beijing, Guangdong) and the central region (Anhui, Henan). These provinces have relatively stable industrial structures, and the long-term correlations among the variables are more closely.

(3) At the policy level, provinces demonstrating a cointegration relationship should prioritize the long-term equilibrium among energy consumption, carbon emissions, and GDP. For instance, highly energy-efficient regions such as Beijing and Guangdong can further weaken the link between carbon emissions and GDP growth by optimizing their energy mix—for example, by reducing the share of fossil fuels. Meanwhile, provinces like Anhui and Gansu, where carbon

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emissions contribute significantly, should advance industrial upgrading—such as transforming energy-intensive industries—to move away from the reliance on a "high-carbon growth" model.

To further reveal the dynamic relationship between variables, a VAR (Vector Autoregression) model was established, and the impulse response function and variance decomposition were used to analyze the degree of influence of each variable on the efficiency of carbon emission reduction. Table 2 lists the parameter estimation results of the VAR model. According to the AIC information criterion, the optimal lag order for the VAR model is determined to be 2 periods. The Durbin-Watson statistics of the model residuals are all close to 2 (1.9765 - 2.0342), indicating that there is no significant first-order autocorrelation among the residuals, which is in line with the ideal situation, and indicates that the model fitting effect is good.

Table 2. Parameter estimation of the VAR model

Explanatory variables	Dependent variable: GDP	Dependent variable: Energy consumption(E)	Dependent variable: Energy consumption(C)	Dependent variable: Carbon emission reduction efficiency(η)
GDP(-1)	0.4333 (2.365)	0.2346 (1.431)	0.1735 (0.987)	0.0827 (0.578)
GDP(-2)	0.0872 (0.456)	0.1053 (0.615)	-0.0436 (-0.238)	0.0234 (0.157)
Energy consumption(-1)	-0.0521 (-0.263)	0.3872 (2.185)	0.2154 (1.133)	0.1036 (0.668)
Energy consumption (-2)	-0.0215 (-0.114)	0.0782 (0.462)	0.0547 (0.302)	-0.0183 (-0.124)
Carbon emissions (-1)	0.0347 (0.197)	-0.1243 (-0.787)	0.4265 (2.523)	0.0972 (0.709)
Carbon emissions (-2)	-0.0173 (-0.095)	0.0872 (0.532)	0.0653 (0.371)	-0.0321 (-0.224)
Carbon emission reduction efficiency(-1)	-0.0765 (-0.356)	-0.0532 (-0.275)	-0.0418 (-0.202)	0.3652 (2.174)
Carbon emission reduction efficiency((-2)	0.0432 (0.208)	-0.0317 (-0.170)	0.0285 (0.143)	0.0673 (0.415)
Constant term	-0.0124 (-0.590)	-0.0087 (-0.458)	-0.0053 (-0.265)	-0.0032 (-0.200)

(1) The impact of GDP shock on carbon emission reduction efficiency: In the initial period (periods 1-2), it shows a slight negative effect, indicating that economic growth may exert certain pressure on carbon emission reduction efficiency in the short term. From the third period onwards, this impact turns positive and gradually stabilizes. This suggests that in the long term, economic growth will promote the improvement of carbon emission reduction efficiency, which may be related to technological progress, industrial structure optimization, and increased environmental protection investment.

(2) The impact of energy consumption shock on carbon emission reduction efficiency: It always shows a significant negative effect, with the most significant impact level. After reaching the maximum negative effect in periods 2-3, it then gradually weakens and remains negative. This indicates that the increase in energy consumption continuously reduces carbon emission reduction efficiency, further verifying the close relationship between energy consumption and carbon emissions.

(3) The impact of carbon emission volume shock on carbon emission reduction efficiency: It shows a negative effect in the initial period and reaches the maximum value in period 2. Subsequently, this negative effect gradually weakens and becomes zero after the 6th period. This suggests that the short-term surge in carbon emissions will reduce emission reduction efficiency, but its long-term impact is limited.

The variance decomposition analysis reveals the contribution ratio of different variables to the fluctuation of carbon emission reduction efficiency, as shown in Table 3. In the long term, energy consumption has the most significant contribution to the fluctuation of carbon emission reduction efficiency, accounting for 31.56%, while the contribution of GDP is also reflected in its impact on carbon emission reduction efficiency. The data of 16.82% indicates that the economic development model has an important impact on emission reduction efficiency. The contribution rate of carbon emissions itself is 9.73%, and over time, the explanatory power of carbon emission reduction efficiency itself shows a gradually decreasing trend.

According to research, the eastern region outperforms the central and western regions in terms of carbon emission reduction efficiency.

This is attributed to the higher energy utilization efficiency and more diversified energy structure in this region. For instance, technological innovation in the eastern region has a significant positive spatial spillover effect on carbon emission fairness. For example, according to the latest data, the diversity index of energy structure in provinces such as Guangdong and Jiangsu is significantly higher than the national average. This is due to the decline in coal consumption proportion in these regions and the active utilization of clean energy. For instance, the coal consumption proportion in Jiangsu is relatively low and is on a downward trend, while that in Guangdong has always been low. The innovations and practices in green and low-carbon development in these provinces, such as Jiangsu's smart water system management solution and Guangdong's digital brain project for zero-waste cities, have further reduced carbon emission intensity. In contrast, taking Shanxi as an example, the growth rate of carbon emissions and the total carbon emissions in this province are higher than the national average, and are not decoupled from the growth of GDP and energy consumption. This leads to a high carbon intensity and significantly low carbon emission efficiency. Therefore, future policy-making should focus on the energy transformation and technological upgrading in these regions to promote coordinated development among regions [4].

Table 3. Variance Decomposition Results

Term	GDP (%)	Energy consumption contribution (%)	Carbon emissions contribution (%)	Self contribution (%)
Term 1	2.15	3.82	1.03	93
Term 3	8.77	15.32	4.28	71.64
Term 5	12.46	23.68	6.89	56.99
Term 10	16.82	31.56	9.73	41.89

5. Conclusion

5.1 Summary of Provincial Carbon Emission Reduction Efficiency

Based on the empirical analysis results, the provincial carbon emission reduction efficiency in China shows significant regional differences and imbalances. Specifically, the carbon emission reduction efficiency in the eastern regions is generally higher than that in the central and western regions. This phenomenon is closely related to the regional economic development level, the degree of industrial structure optimization, and energy utilization efficiency. For instance, eastern coastal provinces such as Guangdong and Jiangsu, due to their more diversified economic structures and higher proportions of clean energy, exhibit relatively high stability and sustainability in carbon emission reduction efficiency. In contrast, some provinces in the central and western regions, such as Shanxi and Inner Mongolia, due to their excessive reliance on high-energy-consuming industries and coal resources, have relatively low carbon emission reduction efficiency and significant fluctuations. Moreover, the carbon emission intensity in the northern regions is generally higher than that in the southern regions, which is closely related to the energy consumption structure, climate conditions, and the spatial distribution characteristics of industrialization processes. Overall, the improvement of provincial carbon emission reduction efficiency in China still faces significant challenges, especially in economically underdeveloped regions. How to balance economic growth and carbon emission control in these regions has become an urgent problem to be solved.

5.2 Analysis of Influencing Factors

The primary factors influencing China's carbon emission reduction efficiency encompass industrial structure, energy composition, and technological advancement.

First, industrial structure substantially shapes carbon reduction performance. Research indicates that a larger share of secondary industry—particularly heavy industry—tends to increase carbon emission intensity. In contrast, expanding the tertiary industry helps lower carbon emissions per unit of GDP.

Second, optimizing the energy mix is crucial for improving emission reduction efficiency. Heavy reliance on coal not only raises carbon output but also limits gains in energy efficiency. Shifting toward cleaner sources such as natural gas and hydropower can significantly cut emissions and enhance energy utilization.

Finally, technological progress plays a central role. Innovations in green technology and the adoption of high-efficiency energy-saving measures can reduce both energy consumption intensity and carbon emission coefficients, thereby strengthening overall carbon reduction performance. Studies confirm that green technology innovation, industrial upgrading driven by foreign direct investment, and active technology markets all positively influence emission reduction efficiency.

Nevertheless, regional disparities in technology research and deployment persist in China, which exacerbates differences in carbon reduction outcomes across provinces.

5.3 Policy Suggestions

The influence of energy usage on carbon reduction efficiency is notably substantial and adverse. It is imperative to expedite the adoption of clean energy and enhance energy efficiency. To boost overall carbon emission reduction performance and foster low-carbon growth, tailored policies should be developed by refining industrial structures, reinforcing regional collaboration, and advancing energy transition. While short-term economic expansion may pose challenges to carbon reduction efficiency, from a long-term viewpoint, it contributes positively and warrants emphasis on green economic transformation. Based on varying temporal impacts, integrated short- and long-term emission reduction strategies should be crafted. In the near term, prioritize carbon emission management, while focusing on energy mix optimization and economic development model shifts over the long run. Carbon reduction efficiency is shaped by multiple factors including economy, energy, and emissions, necessitating coordinated policies across sectors to create synergistic effects. First, accelerate industrial restructuring, particularly in central and western regions, guiding traditional high-energy-consumption industries toward low-energy, high-value-added pathways, gradually reducing the secondary industry's share while increasing the tertiary sector's proportion to achieve economic and environmental synergy. Second, strengthen regional cooperation mechanisms, facilitating the transfer of advanced technologies and management practices from eastern to central and western areas, and establish a cross-regional carbon emission trading market to incentivize participation in emission reduction efforts. Additionally, diversifying the energy structure is crucial for improving carbon reduction efficiency. Governments should bolster support for clean energy development and utilization, progressively raising the share of natural gas, hydropower, wind power, and other clean sources in energy consumption, and accelerate research and deployment of clean coal technologies. Through these measures, carbon reduction pressures in China can be effectively mitigated, laying a robust foundation for achieving the "dual carbon" goals.

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