

Research Article

Research on the Relationship Between Carbon Emissions and Economic Growth in China Under the Environmental Kuznets Curve Theory

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Abstract

Context: The coordination between carbon emissions and economic growth is of great significance for actively and prudently promoting carbon peak and carbon neutrality. **Objectives** The paper takes Qinghai Province, an economically underdeveloped region in China, and Zhejiang Province, an economically developed region, as comparative cases. Starting from the environmental Kuznets curve theory, based on the decoupling model and factor decomposition method, it analyzes the EKC curve, decoupling trend, and driving factors of provincial carbon emissions and economic growth from 1997 to 2023. **Results:** Research has shown that the EKC curve in economically underdeveloped areas and developed areas do not conform to the traditional inverted U-shaped curve, both of which experience two inflection points. Developed areas have an N-shaped EKC curve, with inflection point years around 2007 and 2014, while economically underdeveloped areas have a weak inverted N-shaped EKC curve, with inflection point years around 1998 and 2013. **Conclusions:** The decoupling of carbon emissions in economically developed regions is shifting from expansion negative decoupling to strong decoupling and weak decoupling, while in economically underdeveloped areas, weak decoupling is the main trend. The energy structure and intensity effects have a significant promoting effect on the decoupling of carbon emissions in economically developed areas, while economic growth and energy structure effects have a negative effect on the decoupling of carbon emissions in economically underdeveloped areas.

Keywords

Carbon Emissions, Economic Growth, Environmental Kuznets Curve, Decoupling Analysis, Lmdi Factor Decomposition Method

1. Introduction

The greenhouse gas emissions, mainly caused by carbon dioxide, have exacerbated climate change, which goes against China's economic development goals of developing a green economy and achieving sustainable development. Extreme weather events such as sustained high temperatures, droughts, and floods occur frequently in many provinces, bringing

multiple negative effects on stable food production, life and health, and electricity supply. According to the latest report released by the Intergovernmental Panel on Climate Change (IPCC) in 2022, China's total carbon dioxide emissions are nearly 10 billion tons, accounting for over 28% of global emissions [1]. As a responsible major country, China has

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proposed the strategic goals of peaking carbon emissions by 2030 and achieving carbon neutrality by 2060, and has included controlling total energy consumption and energy intensity in its national development plan.

The report of the 20th National Congress of the Communist Party of China pointed out that we should actively and steadily promote carbon peaking and carbon neutrality. To anchor the carbon peaking and carbon neutrality goals, General Secretary Xi Jinping stressed that the relationship between development and emission reduction should be properly handled. In October 2021, the State Council issued the Action Plan for Carbon Peak before 2030 [2]. At the provincial level, it is required that all regions incorporate the reduction of carbon emissions and energy consumption intensity into their economic development plans, promoting coordinated development between carbon emissions and economic growth. Faced with complex carbon reduction issues and high-quality development requirements, major economic provinces should maintain sustained and stable economic growth while controlling and reducing total carbon emissions, and achieve coordinated and sustainable carbon emission governance and economic growth. Based on this, how to balance the relationship between carbon emissions and economic growth is an important issue worth studying.

Actively and prudently promoting carbon peaking and carbon neutrality is not a sports style that lacks overall planning, but rather promotes the coordination between carbon emissions and economic growth [3]. There are significant differences in economic structure, development stage, emission status, and carbon reduction potential between the first-mover and latecomer provinces, which determines that they have different Environmental Kuznets curve relationships, and the same province will also be in the position of the environmental Kuznets curve at different stages of economic and social development [4]. The relationship between carbon emissions and economic growth should be coordinated, and the most ideal state should be to cross the inflection point of environmental Kuznets curve, that is, the curve changes from increasing to decreasing, achieve economic growth while reducing carbon emissions, and achieve decoupling between carbon emissions and economic growth. Crossing the point of inflection and achieving decoupling is a complex, long-term, and systematic project that requires tailored and precise policies. Firstly, we should clarify the environmental Kuznets curve relationship between carbon emissions and economic growth, conduct theoretical tests, inflection point inference, and curve analysis, with a focus on exploring the underlying impact mechanism; Secondly, it'll be encouraged to focus on decoupling and analyze the degree of coordination between provincial carbon emissions and economic growth; Finally, centre on the driving factors of carbon decoupling, we will focus on studying the leading driving factors and promote precise carbon reduction strategies.

The research on the spatiotemporal pattern evolution of carbon emissions reflects that China's carbon emissions have significant spatial agglomeration characteristics, with high

carbon emission areas mainly distributed in the eastern regions with high population density and economic development levels [5]. This also leads to the selection of central and eastern regions of China as the research focus at the county level, such as the in-depth discussions conducted by Qi et al. [6] on Zhejiang Province, Chen et al. [7] on Fujian Province, based on the overall changes, regional differences, spatiotemporal patterns, and agglomeration characteristics of carbon emissions at the county level. There are various differences between the eastern and central regions, as well as between the pioneer and late-comer provinces in terms of economic structure, industrialization stage, and emission status, but they all face the practical issue of balancing carbon reduction goals and economic performance. If we aim to promote the decoupling of carbon emissions from economic growth and cross the inflection point of environmental Kuznets curve, we must focus on the main research on the relationship between carbon emissions and economic growth. We need to recognize that economically developed regions are drivers of domestic economic growth, while economically underdeveloped regions are important areas for ecological governance reform in China. Based on this, this study attempts to focus on three core issues from a comparative research perspective: (1) the Environmental Kuznets curve relationship between carbon emissions and economic growth in economically developed and underdeveloped regions; (2) The degree of decoupling and coordination between carbon emissions and economic growth in economically developed and underdeveloped regions; (3) The dominant driving factors for carbon decoupling in economically developed and economically underdeveloped regions.

To investigate the correlation between carbon emissions and economic growth, this study comprises the following three research stages. Firstly, data from economically developed and underdeveloped regions from 1997 to 2023 are selected to further optimize the regression model of carbon emissions and economic growth. The Environmental Kuznets Curve is re-examined to ascertain its compliance with the traditional inverted U-shaped, and a comparative analysis is conducted to study the characteristics and inflection points of the EKC in the two provinces. Secondly, this study uses the elasticity coefficients in the Tapio decoupling model of carbon emissions to determine the annual decoupling status, in order to compare and analyze the coordinated relationship between carbon emissions and economic growth. Finally, combined with Kaya's identity, the LMDI (Logarithmic Mean Divisia Index) factor decomposition method is applied to decompose the decoupling coefficients of carbon emissions. Based on empirical research, scientific policy recommendations can be provided for promoting the coordinated and sustainable development of carbon emission control and economic stability and growth.

2. Environmental Kuznets Curve

The Environmental Kuznets Curve (EKC) theory suggests an inverted U-shaped relationship between environmental

pollution and economic growth. In the early stages of economic growth, environmental pollution increases and environmental quality decreases. But if the per capita income exceeds a certain level, it will reach the inflection point of the EKC and the trend will reverse. Therefore, at high income levels, economic growth leads to environmental improvement, achieving decoupling between economic growth and environmental pollution [8].

The EKC theory is widely applied in empirical research in various regions. Existing literature has focused on EKC theory testing and inflection point inference. Since the early environmental indicator data primarily focused on air pollution concentrations and industrial pollution emissions in China, the provincial EKC theoretical tests primarily selected pollution indicators such as industrial wastewater, industrial exhaust gas, solid waste, SO_2 , and PM_{10} . In some regions, the inverted U-shaped relationship between these indicators and economic growth has been confirmed [9-11]. However, with the increase of case areas, longer time series, and more empirical methods, the traditional types of EKC theory have been further developed. The inverted U-shaped cannot be proven in some provinces, and some types of EKC curves such as N-shaped, inverted N-shaped, and U-shaped have been discovered and empirically tested (Figure 1). For example, Shen and Xu [12] conducted an EKC analysis on the per capita economic total, industrial waste gas, wastewater, waste residue, and their per capita amounts in economically developed provinces from 1991 to 1998, and found a wavy environmental Kuznets curve. Ling et al. [13] discovered and tested that there is an increasing linear relationship between industrial waste gas and economic development level in Guang-

dong Province. Industrial wastewater and solid waste respectively conform to the EKC curve characteristics of N and inverted N types. In summary, previous studies have examined and analyzed the EKC relationship of major pollutants. However, further research on the EKC relationship of carbon emissions is urgently needed. Based on this, this study will conduct theoretical testing and in-depth analysis of the carbon emission environment Kuznets curve in combination with the actual economic development.

3. Decoupling Theory

In the process of ecological civilization construction in different regions, the evolution of the environmental Kuznets curve relationship is inevitably related to the process of decoupling their carbon emissions [14]. The process of crossing the EKC inflection point is not only the process of the curve going from decreasing to decreasing, but also reflects the change in the relationship between environmental pollution and economic growth, i.e., from non-decoupling to decoupling, and the relationship from uncoordinated to coordinated [15]. In terms of direct carbon emissions, input-side carbon emissions, and consumption-side carbon emissions, economically developed provinces such as Jiangsu, Zhejiang, Shanghai, Beijing-Tianjin-Hebei, and Guangdong have much higher levels of these three types of carbon emissions compared to inland provinces such as Qinghai, Gansu, and Xinjiang. There is a significant regional difference in carbon emissions in the logistics industry [16].

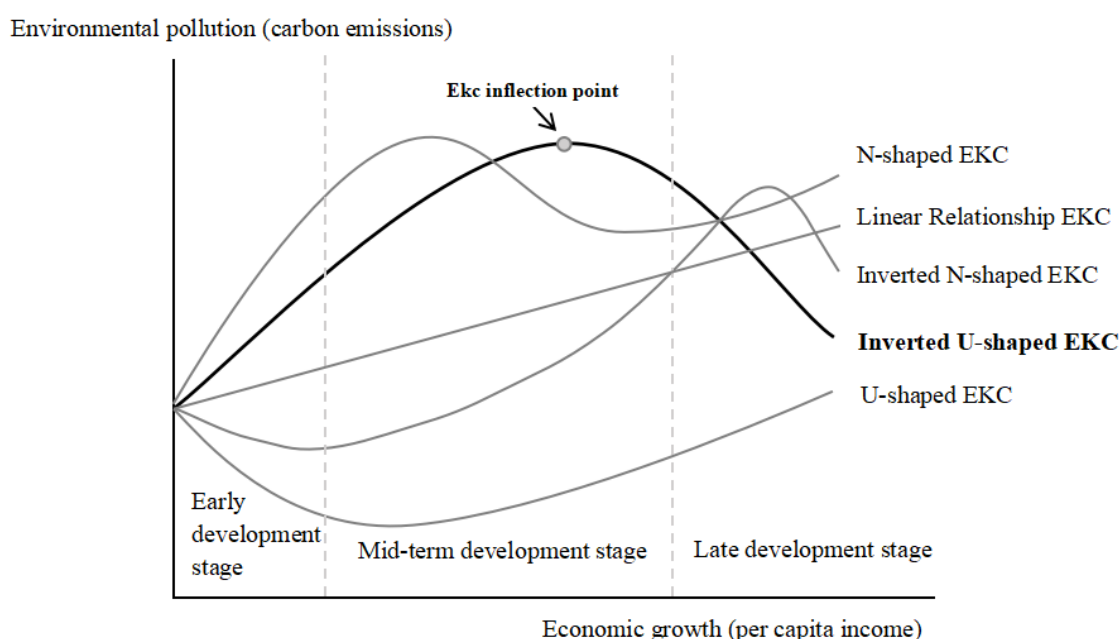


Figure 1. Traditional inverted U-shaped and other types of EKC.

In the 1990s, the academic community introduced the concept of "decoupling" into environmental research. Initially, "decoupling" was defined as the process of breaking the link between economic growth and environmental pollution. After 2000, the Organization for Economic Cooperation and Development established a decoupling model, quantitatively dividing environmental pollution decoupling into relative decoupling and absolute decoupling, in order to evaluate the degree of coordination between regional economic growth and environmental pollution. With the development of decoupling theory, decoupling models are gradually being applied to the coordinated analysis of economic development and carbon emissions. Sun et al. [17] conducted a decoupling analysis between carbon emissions and economic growth in various provinces of China from 1999 to 2008, and found that the vast majority of provinces were in a weak decoupling state. Ren et al. [18] established a decoupling model, and after research, they found that the industrial growth and industrial air pollution status in Jilin Province are mainly absolute decoupling. In 2005, the Tapio decoupling model was proposed, bringing carbon decoupling research to a new stage. TAPIO [19] broke through dimensional limitations and subdivided decoupling states into eight categories, analyzing the decoupling relationship between transportation carbon emissions and economic growth in EU countries from 1997 to 2001. Compared with early decoupling models, the Tapio model is more widely used for decoupling analysis of provincial carbon emissions and economic growth. Based on the 2017 time series, Liu [20] applied Tapio decoupling analysis and found that the carbon emission decoupling status of 30 provinces in China can be divided into four categories, which are strong decoupling, weak decoupling, expansive negative decoupling, and expansive decoupling. Moreover, Tapio introduced the concept of decoupling elasticity in the process of determining the decoupling state [21]. When analyzing the relationship between carbon dioxide emissions and economic growth, research often revolves around the Tapio decoupling model [22].

The decoupling model quantitatively evaluates the coordination between carbon emissions and economic growth, but its explanatory power on the driving factors of carbon decoupling is limited. Therefore, in order to effectively analyze the carbon emission impact mechanism of the carbon decoupling process, the academic community usually combines the decoupling model with the decomposition of carbon emission factors. Researchers have optimized the Laspeyres index method and Divisia index method based on Kaya's identity, and proposed the LMDI factor decomposition method [23, 24]. This method achieves full decomposition of multiplication and addition with no residuals, and has stronger universality. It has been widely applied in decomposing the driving factors of carbon emissions at the provincial level in China. Zhao et al. [25] used LMDI to decompose the carbon emission factors in Jiangsu Province and found that technological progress and energy consumption structure are negative influencing factors. Song [26] used the LMDI

method to decompose the carbon emissions of energy consumption in Shandong, and the results showed that the economic growth effect was the dominant driving factor. Peng et al. [27] decomposed the factors of energy carbon footprint in the Pearl River Delta based on the LMDI method and proposed policy recommendations for developing low-carbon industries and improving energy efficiency. However, most LMDI decomposition objects are carbon emission changes over a certain period of time, rather than direct carbon emission decoupling coefficients, which limits their explanatory power for the driving factors of carbon decoupling. Therefore, some scholars have focused their research on direct decoupling coefficients decomposition. Wang et al. [28] found that the decrease in energy intensity at the global scale plays a dominant role in promoting the process of carbon decoupling by combining the Kaya identity and LMDI decomposition equation. MOUTINHO et al. [29] decomposed the decoupling coefficients of energy carbon emissions in Latin America using the LMDI method and found that the energy intensity and changes in total domestic investment are the most important factors accelerating the process of carbon decoupling.

In September 2020, the Chinese President announced to the world on behalf of the Chinese government at the United Nations General Assembly, "China will increase its national independent contribution, adopt more powerful policies and measures, strive to peak CO₂ emissions before 2030, and strive to achieve carbon neutrality before 2060 [30].". The achievement of the carbon peak target indicates that the industrial, social, and economic development of the region no longer causes CO₂ emissions. At the national level, carbon neutrality refers to achieving net zero carbon emissions by balancing overall economic emissions through carbon sequestration and carbon offsetting [31].

Driven by the the goals of carbon peaking and carbon neutrality, the EKC analysis of carbon emissions and economic growth has become a research focus. Firstly, this article integrates the EKC theory with the Tapio decoupling model and LMDI factor decomposition, and conducts in-depth analysis from a comparative perspective of different economic regions. Secondly, this article utilizes the latest data from the China Carbon Accounting Database (CEADs) to improve the scientific and accurate nature of the data.

4. Theoretical Models and Data Sources

4.1. Theoretical Models

4.1.1. EKC Test Model

Based on existing empirical studies on the environmental Kuznets curve [32, 39, 40], this paper focuses on the relationship between carbon emissions and economic growth. Taking into account the impact of environmental policy intensity, an optimized EKC test model is established as follows:

$$\ln CO_{2pct} = \beta_0 + \beta_1 \ln GDP_{pct} + \beta_2 \ln GDP_{pct}^2 + \beta_3 \ln GDP_{pct}^3 + \beta_4 X_t + \varepsilon_t \quad (1)$$

where β_0 represents the cross-sectional effect; CO_{2pct} refers to the per capita carbon emissions of the province in year t ; GDP_{pct} stands for the per capita gross domestic product of the province in year t ; X_t represents control variables, including the proportion of the secondary industry, total fiscal expenditure, R&D expenditure, direct investment from foreign and Hong Kong, Macao, and Taiwan regions, urban green coverage area, electricity consumption, total trade import and export, primary school enrollment rate, and environmental policy intensity. The intensity of environmental policies is represented by the removal rates of sulfur dioxide and smoke, with higher removal rates indicating greater environmental policy intensity [41]. In the formula, β_1 , β_2 and β_3 are the coefficients of the explanatory variable, β_4 is the coefficient of the control variable.

After t-test and p-test, the coefficients can be analyzed to determine the environmental Kuznets curve relationship between carbon emissions and economic growth. Therefore, the assumptions of this article are as follows:

if $\beta_1 \neq 0$ and $\beta_2=0$, $\beta_3=0$, then the two are in a linear relationship;

if $\beta_1 > 0$, $\beta_2 < 0$ and $\beta_3 > 0$, then the EKC is an N-shaped curve;

if $\beta_1 < 0$, $\beta_2 > 0$ and $\beta_3 < 0$, then the EKC is an inverted N-shaped curve;

if $\beta_1 < 0$, $\beta_2 > 0$ and $\beta_3=0$, then the EKC is a U-shaped curve;

if $\beta_1 > 0$, $\beta_2 < 0$ and $\beta_3=0$, then the EKC is an inverted U-shaped curve;

From the regression results, if it presents a U-shaped environmental Kuznets curve, i.e. a quadratic function, the inflection point of EKC is inferred as follows:

$$X^* = -\beta_1/2\beta_2$$

If the environment Kuznets presents an N-shaped curve, i.e. a cubic function, the inflection points of the EKC are extrapolated as follows:

$$X_1^* = \frac{-\beta_2 - \sqrt{\beta_2^2 - 3\beta_1\beta_3}}{3\beta_3}, \quad X_2^* = \frac{-\beta_2 + \sqrt{\beta_2^2 - 3\beta_1\beta_3}}{3\beta_3}$$

4.1.2. Tapio Decoupling Model

The Tapio decoupling model was originally a physical concept that described the separation or disconnection between two objects [33]. Tapio decoupling model can quantify the relationship between two or more asynchronous developmental variables [34]. The Tapio decoupling model, based on the perspective of velocity decoupling, is an analytical tool used to evaluate the relationship between economic growth and environmental pressure. Its main application is to study the decoupling status between economic activities and environmental indicators [35]. As a universal model for studying

decoupling status in the environmental field [36], the Tapio decoupling model focuses on the environmental domain and measures the decoupling elasticity relationships between variables. This article applies the Tapio decoupling model to calculate the decoupling elasticity to assess the decoupling status and coordination degree between carbon emissions and economic growth.

$$T = \frac{\Delta C/C_{t-1}}{\Delta G/G_{t-1}} = \frac{(C_t - C_{t-1})/C_{t-1}}{(G_t - G_{t-1})/G_{t-1}} \quad (2)$$

Where T represents the decoupling index between carbon emissions and economic growth, ΔC refers to the growth rate of carbon emissions, ΔG stands for the growth rate of GDP, C_t represents the target year's carbon emissions, C_{t-1} represents the baseline year's carbon emissions, G_t represents the target year's GDP, and G_{t-1} refers to the baseline year's GDP.

The Tapio decoupling model divides carbon emissions and economic growth into eight decoupling states, which namely strong decoupling, weak decoupling, recession decoupling, growth connection, recession connection, expansion negative decoupling, weak negative decoupling, and strong negative decoupling. Strong decoupling of growth is a highly coordinated state of development, where greater economic growth is achieved with minimal carbon emissions. Meanwhile, strong negative decoupling indicates that economic growth is highly dependent on carbon emissions. The specific decoupling standards are shown in Table 1.

4.2. LMDI Decoupling Decomposition

The LMDI factor decomposition method sets the decomposition formula as a continuous differentiable function, and then re integrates the differentiation over time to obtain the form of exponential decomposition. The LMDI model (Logarithmic Mean Divisia Index) refers to a statistical analysis method that uses a statistical index system to analyze the degree of influence of various factors [37]. This method has the advantages of no residual terms after decomposition, being able to achieve complete decomposition, and being able to convert additive decomposition and multiplicative decomposition into each other, so it is widely used [38]. This article combines Kaya's identity and LMDI factor decomposition method to decompose Tapio decoupling elasticity into energy structure effect, energy intensity effect, population size effect, and economic structure effect. Kaya's identity is as follows:

$$C = \frac{C}{E} \cdot \frac{E}{G} \cdot \frac{G}{P} \cdot P \quad (3)$$

Where C refers to the provincial carbon emissions, E represents the provincial energy consumption, G stands for the provincial GDP, and P stands for the total population of the province. Then variables can be defined as follows:

$$\frac{C}{E} = F, \frac{E}{G} = I, \frac{G}{P} = S$$

In this way, the above formula is simplified into the following equation:

$$C = F \cdot I \cdot S \cdot P. \quad (4)$$

F represents the carbon emissions per unit of energy output, which is a factor in energy structure; I stands for the energy consumption per unit of economic output, which is a factor in energy intensity; S represents the per capita economic aggregate, which is a factor in economic structural; P represents the total population of the province, which is a factor in population size.

ΔC represents the change in carbon emissions from year t-1 (base year) to year t (target year). The formula is as follows:

$$\Delta C = C_t - C_{t-1} = F_t \cdot I_t \cdot S_t \cdot P_t - F_{t-1} \cdot I_{t-1} \cdot S_{t-1} \cdot P_{t-1} \quad (5)$$

Through LMDI factor decomposition, the sum form is as follows:

$$\Delta C = \Delta F + \Delta I + \Delta S + \Delta P \quad (6)$$

Combining the Tapio decoupling model, the following variable relationships can be obtained:

$$T = \frac{G_{t-1} \cdot (\Delta F + \Delta I + \Delta S + \Delta P)}{C_{t-1} \cdot \Delta G} \quad (7)$$

The quadruple effect that affects decoupling can be obtained from the above equation:

$$T = D_F + D_I + D_S + D_P \quad (8)$$

$$D_F = \frac{G_{t-1} \cdot \Delta F}{C_{t-1} \cdot \Delta G}, D_I = \frac{G_{t-1} \cdot \Delta I}{C_{t-1} \cdot \Delta G}, D_S = \frac{G_{t-1} \cdot \Delta S}{C_{t-1} \cdot \Delta G}, D_P = \frac{G_{t-1} \cdot \Delta P}{C_{t-1} \cdot \Delta G} \quad (9)$$

Where D_F represents the energy structure effect, D_I represents the energy intensity effect, D_S represents the economic growth effect, and D_P represents the population size effect.

5. Data Sources

Table 1. Standard for decoupling carbon emissions from economic growth.

Sorting of the advantages and disadvantages of decoupling status	Economic growth rate	Carbon emission growth rate	Decoupling elasticity coefficient	Decoupling state
1	$\Delta G > 0$	$\Delta C < 0$	$T < 0$	Strong decoupling
2	$\Delta G > 0$	$\Delta C > 0$	$0 < T < 0.8$	Weak decoupling of growth
3	$\Delta G < 0$	$\Delta C < 0$	$T > 1.2$	Recessive decoupling
4	$\Delta G > 0$	$\Delta C > 0$	$0.8 < T < 1.2$	Growth Connection
5	$\Delta G < 0$	$\Delta C < 0$	$0.8 < T < 1.2$	Decay Connection
6	$\Delta G > 0$	$\Delta C > 0$	$T > 1.2$	Expansion negative decoupling
7	$\Delta G < 0$	$\Delta C < 0$	$0 < T < 0.8$	Weak negative decoupling
8	$\Delta G < 0$	$\Delta C > 0$	$T < 0$	Strong negative decoupling

The carbon dioxide emissions data is sourced from the China Carbon Accounting Database (CEADs). The data on regional GDP, fiscal expenditure, proportion of the secondary industry, total energy consumption, total population, the direct investment in foreign and Hong Kong, Macao and Tai-

wan regions of China are mainly sourced from the China Statistical Yearbook. The removal rates of sulfur dioxide and smoke are sourced from the China Environmental Statistical Yearbook and the China Environmental Yearbook.

6. Empirical Results and Analysis Discussion

6.1. Comparison of Economic Growth and Carbon Emission Differences

6.1.1. Provincial Comparison of Total Quantity

From the perspective of overall trends, from 1997 to 2012, the high economic growth of economically developed and underdeveloped regions in China was accompanied by an overall increase in carbon emissions, while their carbon emission intensity showed an overall downward trend. Since 2012, carbon emissions have entered a plateau period, with limited increments and even reductions. High carbon emissions in economically developed regions are accompanied by high quotas, in contrast to low carbon emissions and low quotas in economically underdeveloped regions. The initial spatial balance of carbon emission rights shows a mild deficiency, indicating a strong ability to reduce carbon emissions [42].

From the perspective of total carbon emissions and intensity, the rate of change in total carbon emissions in economically developed regions has shifted from growth to slowdown. During the period from 2002 to 2012, the total carbon emissions in economically developed regions increased rapidly and were significantly higher than those in economically underdeveloped regions. However, in the plateau period from 2013 to 2020, the growth significantly slowed down or even declined. The total carbon emissions in economically underdeveloped areas grew slowly from 2001 to 2007, but entered a high-speed growth from 2008 to 2012 and surpassed those in economically developed areas from 2013 to 2015. The carbon intensity in economically underdeveloped areas is significantly higher than that in economically developed areas, but their carbon intensity has continued to decline significantly, while the carbon emission intensity in economically developed areas has maintained a downward trend after fluctuating from 1997 to 2001.

In terms of economic aggregates and growth rate, economically developed regions have a leading position in economic aggregates compared to economically underdeveloped regions, and their economic growth rate has begun to shift from high to medium high. From 1999 to 2007, the economic growth rate in economically developed areas was higher than that in economically underdeveloped areas, while from 2008 to 2020, the economic growth rate in economically developed

areas was lower than that in economically underdeveloped areas. The total economic output of economically underdeveloped areas has significantly increased since 2008, with economic growth rate gradually increasing from medium to high, and finally decreasing to medium. After experiencing medium speed growth from 1997 to 2007, the economic growth rate of economically underdeveloped areas returned to surpass that of economically developed areas from 2008 to 2012, entering a period of high-speed growth. However, since 2013, the economic growth rate of economically underdeveloped areas has gradually slowed down and entered a period of medium speed growth.

6.1.2. Regional Comparison of Average Quantity

From the perspective of average quantity, the per capita economic output and growth rate in economically developed areas are higher than those in economically underdeveloped areas. The per capita carbon emissions in economically developed regions fluctuated from 1997 to 2001 and increased significantly from 2002 to 2013, higher than those in economically underdeveloped regions. However, from 2013 to 2019, the per capita carbon emissions decreased and remained basically the same as those in economically underdeveloped regions. The per capita carbon emissions in economically underdeveloped areas continued to rise from 1997 to 2013, but slowly decreased from 2014 to 2020.

In summary, from the perspectives of total and average emissions, economically developed regions have a solid foundation for development, with a reasonable industrial structure and a gradual deceleration in the growth rate of total carbon emissions. While carbon intensity continues to steadily decline, they have maintained a medium to high-speed economic growth. However, economically underdeveloped areas showed a significant catch-up effect from 2002 to 2012.

In order to undertake industrial transfer, the speed of industrialization and economic development has increased rapidly, and high energy consuming and high emission projects have been concentrated and implemented. The scope of energy consumption has rapidly expanded, causing the total carbon emissions in economically underdeveloped areas to catch up with those in economically developed areas.

6.2. Environmental Kuznets Curve Analysis

$\beta_1 > 0$, $\beta_2 < 0$ and $\beta_3 > 0$, by combining t-value and p-value tests, we can determine that the EKC fitting curve in economically developed regions should be:

$$\ln \text{CO}_{2\text{pc}_t} = 11.013594 \ln \text{GDP}_{\text{pc}_t} + 6.992332 \ln \text{GDP}_{\text{pc}_t}^2 + 1.414663 \ln \text{GDP}_{\text{pc}_t}^3. \quad (10)$$

It can be inferred that the relationship between carbon emissions and economic growth in economically developed regions presents an N-shaped curve, which is a cubic function and does not conform to the traditional inverted U-shaped curve. Ac-

cording to the properties of the cubic function, the inflection points of the per capita economic total can be calculated as 36,766 yuan and 73,388 yuan, respectively (Table 2).

The economically developed regions have an N-shaped

EKC curve, which experiences two EKC inflection points, roughly corresponding to the years 2007 and 2014. In the process of rapid industrialization and urbanization, economically developed regions took the lead in promoting the construction of ecological provinces in 2003, implementing clean production in the county-level planning outline, issuing strong energy planning and emission reduction plans, promoting regional resource recycling systems, continuously promoting clean energy and environmental system improvement, and reaching the first inflection point of EKC at a per capita economic total of 36,766 yuan. The achievements of low-carbon development were initially highlighted, and the overall per capita carbon emissions slowed down, showing a downward trend.

China's economic development has entered a new normal. Economically developed regions have taken multiple measures to drive stable domestic demand growth, showing a slight upward trend. Therefore, at a per capita economic output of 73,388 yuan, there is a second inflection point of EKC. Since the 18th National Congress of the Communist Party of China, economically developed regions have vigorously promoted the construction of ecological civilization. During the 12th Five-Year Plan period, the cumulative decrease in unit economic energy consumption in economically developed regions reached 20.34%, achieving energy savings of 84 million tons of standard coal and reducing carbon dioxide emissions by 210 million tons [43].

Table 2. EKC fitting and testing in economically developed and underdeveloped regions.

Index	Economically developed regions				Economically underdeveloped areas			
	Constant term	$\ln GDP_{pct}$	$\ln GDP_p^2_{ct}$	$\ln GDP_p^3_{ct}$	Constant term	$\ln GDP_{pct}$	$\ln GDP_p^2_{ct}$	$\ln GDP_p^3_{ct}$
Coefficient	-24.4943	11.0135*	6.9923**	1.4146*	-5.0890	0.7330*	0.1438	0.2546***
Standard Error	6.7687	0.9108	0.5795	0.1638	2.2486	0.1140	0.0510	0.0298
t value	-3.6187	12.0915	-12.0650	8.6316	-2.2632	6.4283	2.8206	-8.5419
p value	0.1716	0.0525	0.0526	0.0734	0.2648	0.0982	0.2169	0.0741
Inverted U-shaped or not	No				No			
Curve type	N-type				Inverted N-type			
First inflection point	36 766 yuan, in 2007				4 452 yuan, in 1998			
Second inflection point	73 388 yuan, in 2013				32 733 yuan, in 2013			

The increase in EKC is within a controllable and reasonable range, mainly due to the long-term optimization of energy structure in economically developed regions, sustained support for the development of clean energy, non fossil energy, and renewable energy, increased allocation of power and water supplies from other provinces, and overall coordination between carbon emissions and economic growth.

$\beta_1 < 0$, $\beta_2 > 0$ and $\beta_3 < 0$, by combining t-value and p-value tests, we can determine that the EKC fitting curve in economically undeveloped areas should be:

$$\ln \text{CCO}_{2pct} = 0.733095 \ln GDP_{pct} - 0.254656 \ln GDP_{pct}^3. \quad (11)$$

According to the data in Table 2, we can conclude that the relationship between carbon emissions and economic growth in underdeveloped areas from 1997 to 2020 presents an inverted N-shaped curve, which is a cubic function and does not strictly conform to the inverted U-shaped curve. Based on the properties of the cubic function, the inflection points can be

calculated as per capita economic output of 4,452 yuan and 23,733 yuan, respectively.

The economically underdeveloped areas have a weak inverted N-shaped EKC curve, which theoretically experiences two inflection points, roughly corresponding to 1998 and 2013. Affected by macroeconomic factors from 1997 to 1999, carbon emissions in economically underdeveloped areas continued to decline slightly, reaching the first inflection point, with a per capita economic total of 4,452 yuan. At that time, the carbon emissions and intensity in economically underdeveloped areas were at a medium to low level. From 2000 to 2012, the economy in underdeveloped areas was in a rapid development stage, with high energy consuming industrial economies continuing to develop. The total consumption of traditional energy increased, carbon emissions continued to increase, and the EKC curve between carbon emissions and economic growth increased significantly. Until around 2013, it reached the maximum value of the EKC curve, which is the second inflection point, indicating a per capita economic

output of 23,733 yuan. Since the 18th National Congress of the Communist Party of China, economically underdeveloped areas have actively promoted ecological civilization construction, set binding emission reduction targets, optimized energy supply structure, and increased environmental super-

vision intensity. From 2014 to 2016, the carbon emissions in economically underdeveloped areas decreased by about 5%, and the overall carbon emissions were controlled within a reasonable range.

6.3. Analysis of Decoupling Between Carbon Emissions and Economic Growth

6.3.1. Analysis of Decoupling Status

Table 3. Decoupling indicators of carbon emissions and economic growth in economically developed and underdeveloped regions in 1997-2020.

Regions	Decoupling effect	1997-1999	2000-2002	2003-2005	2006-2008	2009-2011	2012-2014	2015-2017	2018-2020
Economically developed regions	DF	-0.3457	1.0792	0.5038	-0.0522	-0.0299	-0.2913	-0.0952	-0.0372
	DI	-0.3803	-0.1394	-0.2008	-0.5324	-0.5320	-0.6758	-0.5826	-0.7626
	DS	0.8792	1.0391	0.9470	0.8204	0.7513	0.7075	0.7807	0.7646
	DP	0.0635	0.0860	0.0983	0.0738	0.1462	0.2151	0.1528	0.0720
	Decoupling elasticity	0.2167	2.0649	1.3482	0.3096	0.3355	-0.0445	0.2556	0.0368
	Decoupling state	Weak decoupling of growth	Expansion negative decoupling	Expansion negative decoupling	Weak decoupling of growth	Weak decoupling of growth	Strong decoupling	Weak decoupling of growth	Weak decoupling of growth
Economically underdeveloped regions	DF	0.2225	-0.8445	-0.3930	-0.2342	0.0905	1.2646	0.3982	0.3517
	DI	-1.1852	0.2881	-0.0899	-0.1028	-0.6534	-1.6564	-1.2540	-1.0660
	DS	0.8279	0.9018	0.9521	0.9200	0.9290	0.9430	0.8678	0.7858
	DP	0.0924	0.0387	-0.0236	0.0100	-0.0566	0.0148	0.0312	0.0158
	Decoupling elasticity	-0.0424	0.3840	0.4456	0.5930	0.3095	0.5660	0.0433	0.0873
	Decoupling state	Strong decoupling	Weak decoupling of growth	Weak decoupling of growth	Weak decoupling of growth	Weak decoupling of growth	Weak decoupling of growth	Weak decoupling of growth	Weak decoupling of growth

By employing the Tapio decoupling model to calculate the decoupling elasticity and determine the decoupling status. At the same time, combining Kaya's identity and LDMI factor decomposition, we can decompose the decoupling elasticity coefficients to explore the effects of energy structure, energy intensity, economic structure, and population size on carbon emission decoupling (Table 3).

Overall, from 1997 to 2020, economically developed and underdeveloped regions showed three decoupling states: weak decoupling of growth, negative decoupling of expansion, and strong decoupling. From the perspective of decoupling measurement, in most economically developed and underdeveloped regions, carbon emissions and economic growth have increased simultaneously, and the increase in carbon emissions is lower than the magnitude of economic growth. The overall decou-

pling relationships are relatively coordinated.

Since the launch of ecological civilization construction in economically developed areas in 2003, the overall carbon decoupling indexes in these areas has shown a downward trend. Between 1997 and 2011, the carbon decoupling state was divided into two states: weak decoupling and expansion weak decoupling. They are in the increasing part of the environmental Kuznets curve, with economic growth and carbon emissions increasing in parallel. Economically underdeveloped regions maintained a weak decoupling of growth from 2000 to 2017. From 2012 to 2014, under the new normal, the economic growth rate shifted to medium to high-speed growth, and the construction of ecological civilization was raised to the institutional level. In the short term, economically developed regions experienced a decrease in total carbon

emissions, and the decoupling state changed from weak growth decoupling to strong decoupling. The coordination between carbon emissions and economic growth was optimized. From 1997 to 2000, the decoupling status of carbon emissions in economically underdeveloped areas was strong decoupling. In economically underdeveloped areas, the speed of economic development driven by investment showed a rapid growth situation, and a large number of heavy industrial projects were implemented intensively in these areas, resulting in a short-term increase in the decoupling index.

In 1996, the State Council issued the *Decision of the State Council on Strengthening Environmental Protection*, aiming to control the total amount of pollutant emissions, establish a national system of major pollutant emissions indicators and a system for regular publication. During the Ninth Five-Year Plan period, a group of backward enterprises with outdated technology, severe pollution, and low efficiency were greatly eliminated and closed. At the same time, due to the impact of the 1997 Asian financial crisis and the lagged reactions (Chai 2020), the decoupling elasticity decreased to negative values, resulting in a strong decoupling state.

From 2000 to 2005, economically developed and underdeveloped regions continued to expand their investment scope, with concentrated energy consumption in industrial infrastructure projects and significant economic growth effects accompanied by a significant increase in carbon emissions, resulting in a significant increase in decoupling elasticity coefficients. Economically developed regions experienced two consecutive expansionary negative decoupling, and the decoupling index in economically underdeveloped regions increased by about 0.5. During the 11th Five-Year Plan period from 2006 to 2017, economically developed regions actively promoted energy conservation and consumption reduction in the industrial sector, adjusted and optimized industrial structure, and focused on improving energy efficiency [44], resulting in a significant decrease in carbon emission growth rate and an improvement in decoupling status.

6.3.2. Analysis of Decoupling Effect

To study the driving factors of carbon emission decoupling in economically developed and underdeveloped regions, combined with Kaya's identity and LMDI factor decomposition, the Tapio decoupling coefficients are decomposed into energy structure effect, energy intensity effect, economic growth effect, and population size effect.

The economic growth effect has a negative effect on decoupling carbon emissions in economically developed and underdeveloped regions. From 1997 to 2002, the economic growth effect of economically developed regions was stronger than that of economically underdeveloped regions. As a pioneer region, economically developed regions had higher levels of industrialization, urbanization, and foreign trade scale than economically underdeveloped regions, and their total economic output and growth rate were higher than those of economically underdeveloped regions. From 2003 to 2020,

the hindering effect of economic growth on carbon decoupling in economically underdeveloped areas exceeded that in economically developed areas. On the one hand, economically developed regions focused on ecological civilization strategies from 2003 to 2020, gradually promoting the green and low-carbon transformation of high energy consuming industries, and promoting collaborative innovation in pollution reduction and carbon reduction. As a result, the inhibitory effect of economic growth on carbon decoupling was weakened. On the other hand, economically underdeveloped regions focused on the strategy of strengthening their provinces through industries, with a focus on developing heavy industries such as high-end equipment manufacturing and energy materials. High economic growth was accompanied by an increase in carbon decoupling coefficients. Data shows that during this period, the average annual growth rate of economically underdeveloped areas was 9.3%, and the total industrial output value increased from 91.2 billion yuan to 147.8 billion yuan, with an average annual growth rate of 10.3%, far higher than the national average. Especially during the 12th Five-Year Plan period, the average annual growth rate of fixed assets investment in economically underdeveloped areas reached 18.4%.

Generally speaking, the higher the population density, the more frequent the activities, and the more resource consumption, the greater the carbon emissions [45]. The population size effect in economically developed areas significantly drives carbon emissions, which has a negative impact on the decoupling between carbon emissions and economic growth. Since 2000, the inflow of population from other provinces in economically developed areas has significantly increased, and the labor force has gathered. By the end of 2019, the net inflow of population from economically developed areas was 841,000, ranking first in the country [46]. The expansion of population size and changes in population structure have led to an increase in energy demand and production consumption. In economically developed areas, the majority of migrant population is young and middle-aged, which is in line with the labor demand for industrialization and urbanization. Population is an important factor driving carbon emissions in economically developed areas. Compared to economically developed regions, economically underdeveloped regions have lower population size effects and weaker driving effects on carbon emissions. As a latecomer region, although economically underdeveloped areas have a relatively fast pace of economic development, there are still gaps in industrial economy, wages and benefits, education and medical care compared to developed areas. Economically underdeveloped areas are still the main provinces for population outflow. In 2019, the population flowing from economically underdeveloped areas to outside the province was 110,000 people, accounting for 18.9% of the permanent population. Among them, the main flow was to developed areas. Compared with the sixth national population census, the outflow population increased by 320,000 people, an increase of 11.0% [47].

Few studies have combined the current energy structure of provinces with carbon decoupling. Therefore, based on the research of other scholars [48-52], this article believes that the energy structure and energy intensity effects in economically developed regions have a significant promoting effect on carbon decoupling. The energy structure and energy intensity effects in economically developed regions have a significant promoting effect on carbon decoupling. During the 15th and 11th Five-Year Plans period, economically developed regions took the lead in proposing to shrink coal production, accelerate the continuous optimization of energy structure, promote the transformation of economic growth mode, optimize energy-saving and emission reduction technologies, and continuously reduce energy intensity effects. Since 2012, the energy structure effect and energy intensity effect in economically developed regions have played a significant role in decoupling carbon emissions. During the 12th Five-Year Plan period, economically developed regions explicitly proposed energy strategy, which plan that the development amount of renewable energy would be 8.85 million tons of standard coal, accounting for 4.0% of the total energy consumption in the province. Based on this plan, economically developed regions vigorously promoted clean energy such as hydropower, wind power, and solar power generation, optimized the energy structure, and improved energy utilization efficiency [53]. At the same time, economically developed regions were focusing on eliminating high energy consumption and high pollution outdated production capacity, promoting industrial restructuring, increasing energy consumption with limited output value, and enhancing energy intensity effects. From 2015 to 2017, the carbon emissions increment in economically developed regions was controlled within a reasonable range, the energy structure continued to optimize, and the energy consumption per unit of economic growth decreased. During the 13th Five-Year Plan period in economically developed regions, the total energy consumption in the province was controlled within 220 million tons of standard coal. Non fossil energy accounted for 20% of primary energy consumption, clean energy accounted for 31.9% of primary energy consumption, and renewable energy, including hydropower imported from outside the province, accounted for 12.5% of primary energy consumption [54]. The optimization of energy structure and efficiency had promoted structural carbon control and reduction, and the synergy between economic growth and carbon emissions had achieved sustainable development.

From 1997 to 1999, the energy intensity effect in economically underdeveloped areas was negative, while the energy structure, economic growth, and population size effects were all positive. Faced with the impact of the Asian financial crisis and internal state-owned enterprise reforms, economically underdeveloped regions focused on expanding domestic demand and investment, implementing key projects with high energy consumption, and industrial development drove a surge in energy demand. From 2000 to 2020, the negative effects of economic growth and energy structure on carbon

decoupling were prominent. A large number of major industrial projects have been implemented in economically underdeveloped areas, with an overall increase in the proportion of high energy consuming industries and an expansion of domestic demand for fossil fuels. As a result, sustained economic growth was accompanied by an increase in carbon emissions. The increase in coal production capacity and the rapid expansion of electricity production capacity in economically underdeveloped areas had improved the guarantee of industrial energy, resulting in a shift from negative to positive energy structure effects and a shift from positive to negative contribution rates of energy intensity effects. Since the 12th Five-Year Plan period, the energy intensity in economically underdeveloped areas has continued to promote the decoupling of carbon emissions. Economically underdeveloped areas have implemented the dual control targets on total energy consumption and energy intensity, and have made green development a key focus of manufacturing strong provinces. They have strengthened energy-saving and environmental protection technologies, actively and comprehensively promoted clean production, improved resource recovery and utilization rates, built a green manufacturing system, and vigorously developed advanced manufacturing industries with low energy consumption and light pollution.

7. Research Conclusions and Policy Recommendations

7.1. Research Conclusions

By combining the EKC model, decoupling model, and LMDI decomposition method, the EKC, decoupling trend, and driving factors of carbon emissions and economic growth in economically developed and underdeveloped regions were analyzed and compared. The following conclusion has been drawn.

The EKC curve in economically developed and underdeveloped regions does not conform to the traditional inverted U-shaped curve and is a cubic function. Among them, economically developed provinces have an N-shaped EKC curve, which has gone through two EKC inflection points, with a per capita economic total of 36,766 yuan and 73,388 yuan, respectively, and is already in the final stage of the N-shaped curve. However, the slope of the carbon emission curve is relatively low, and it is estimated that under environmental policy intervention, it is difficult to see a significant rebound and increase in the curve, and carbon emissions are generally controllable. Economically underdeveloped areas have a weak inverted N-shaped EKC, experiencing two inflection points, standing for a per capita economic total of 4,452 yuan and 23,733 yuan, respectively. They have entered the final stage of the inverted N-shaped curve, entering a plateau period and showing a decreasing trend in stability.

The decoupling status of economically developed and underdeveloped regions mainly includes three states: weak decoupling of growth, negative decoupling of expansion, and strong decoupling. The overall relationship between the two is relatively coordinated and continues to be optimized. The carbon decoupling status in economically developed areas has continued to improve. From 2000 to 2014, the decoupling coefficients in economically developed areas decreased overall, and from 2012 to 2014, it shifted to a strong decoupling state. Long term environmental planning and emission control had optimized the coordination between carbon emissions and economic growth. From 2000 to 2014, the economic growth rate in underdeveloped areas increased from fast to slow, maintaining a weak decoupling state of growth. The concentration of high energy consuming projects limited the extent of carbon reduction, and it was not until 2015-2020 that the decoupling state was improved. At this time, the energy and industrial foundation accumulation stage also shifted to the adjustment and optimization stage.

The promotion effect of energy structure effect and energy intensity effect on carbon emission decoupling is particularly prominent in economically developed regions, and the continuous energy and industrial transformation weakens the negative effect of economic growth effect on carbon emission decoupling. Economically developed regions, as areas of population inflow, have a stronger population size effect on decoupling carbon emissions than economically underdeveloped regions, and will still face the problem of carbon emissions driven by population growth. As a latecomer region, economically underdeveloped areas are still in a period of rising industrialization and urbanization. From the perspective of regional industrial structure layout, economically underdeveloped areas are often transit stations or ultimate destinations for carbon emissions in economically developed areas [55]. The inhibitory effects of economic growth and energy structure on carbon emissions decoupling are obvious. Policies still need to balance low-carbon transformation and technological updates of energy and industry.

7.2. Policy Recommendations

Above all, it is recommended to strictly regulate provincial carbon emissions and strengthen data review of cities, counties, and major units. Relevant departments should optimize the carbon emission accounting system, integrate blockchain technology, implement tracking and accounting reporting, gather carbon emission data integration capabilities, establish a transparent low-carbon industry chain rating system, and encourage multiple industries and fields to introduce carbon reduction plans.

Secondly, The government should continue to promote industrial restructuring, especially in the manufacturing industry, by transferring existing traditional industries from industrial bases and introducing advanced productivity or high-end industries, in order to achieve economic transformation and industrial upgrading. It is recommended to eliminate high energy

consuming and inefficient enterprises, orderly adjust high energy consuming and high emission projects, scientifically plan the line map of industrial carbon reduction technology, strengthen the synergies between environmental policies and financial market tools, encourage the development of low-carbon innovative enterprises through market-oriented means, and improve the layout of low-carbon industrial chains.

Furthermore, We suggest strengthening provincial coordination, strengthening joint control between cities and counties, and promoting low-carbon comprehensive governance. It'll be suggested to establish a carbon emission total control and responsibility sharing mechanism to improve the laws and regulations on controlling the total amount and intensity of energy, consolidate the total emission control goals, clarify the responsibility sharing mechanism at all levels, and strictly regulate carbon emissions. Meanwhile, relevant government departments should promote the carbon emissions trading system and promote carbon emissions trading between cities and counties.

Last but not least, promoting energy structure optimization and accelerating low-carbon energy transformation are both encouraged. As a government, it should strive to reduce the proportion of fossil energy consumption, actively promote the utilization of clean energy, continue to reduce taxes and fees in the field of new energy, and strengthen research on technologies such as carbon regulation and capture, hydrogen energy storage, etc. We believe that in the process of steadily promoting the electrification of industry, transportation, and construction, we will gradually improve the energy utilization efficiency in key areas.

Abbreviations

EKC Environmental Kuznets Curve

Author Contributions

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Research Field

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