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Research on Industrial Carbon Emissions and Industrial Development in Guangxi under the Constraint of "Dual Carbon" Goals from the Perspective of LMDI and Tapio

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Abstract: *China, as the only country globally with a complete range of industrial sectors, holds a significant proportion of its national GDP in the industrial sector. However, under the constraints of the "dual carbon" targets, energy conservation and emission reduction efforts are being carried out nationwide. An inevitable question arises: how can underdeveloped regions achieve energy conservation and emission reduction? Based on relevant data from the Guangxi Zhuang Autonomous Region from 2010 to 2019, this paper employs a dual perspective from Tapio and LMDI to decompose and analyze the factors influencing industrial carbon emissions in Guangxi. The study reveals that Guangxi's industry is currently at a crucial juncture of transitioning from weak decoupling to strong decoupling, with industrial sector scale having the most significant impact on industrial carbon emissions in Guangxi. Furthermore, the industrial energy structure still predominantly relies on the consumption of fossil energy. Finally, policy recommendations for industrial emission reduction in Guangxi are proposed.*

Keywords: *Dual Carbon, LMDI, Tapio, Industrial Carbon Emissions, Industrial Energy Structure*

1. Introduction

Since the beginning of the reform and opening-up policy, China has gone through generations of efforts and has now become the world's leading industrial nation. With the most comprehensive range of industrial sectors globally and abundant natural resources, especially coal, China has undoubtedly received tremendous assistance in industrial development. However, due to the deep burial of coal underground and the substantial carbon dioxide emissions during combustion, industrial development in China has also led to severe environmental degradation and pollution.

According to data from the "China Environmental Statistical Yearbook," China's industrial exhaust gas emissions totaled 138.145 billion cubic meters in 2000 and reached 685.19 billion cubic meters in 2015, a 4.96-fold increase over fifteen years. The total investment in environmental pollution control was 116.67 billion yuan in 2001 and increased to 953.9 billion yuan in 2017. However, the majority of this investment was allocated to urban environmental infrastructure construction such as gas, centralized heating, and drainage, with industrial pollution source investment being only 17.45 billion yuan in 2001 and 681.5 billion yuan in 2017, accounting for about 1.2% of GDP. China's environmental problems have become an urgent issue that needs to be addressed.

In 2021, the Central Committee of the Communist Party of China and the State Council jointly issued the "Opinions on Thoroughly Implementing the New Development Concept and Doing Well in Carbon Peak and Carbon Neutrality" (hereinafter referred to as the "Opinions"), requiring the acceleration of policy measures for energy conservation and emission reduction in various industries and fields. The entire nation must unite and concentrate its efforts to achieve emission reduction goals. As a region with a concentration of ethnic minorities and an important gateway for China to face ASEAN, open up to the outside world, and move towards the world, Guangxi's emission reduction work has naturally attracted attention both domestically and internationally.

According to data from the National Bureau of Statistics and the Guangxi Statistics Bureau, most of Guangxi's industries are concentrated in the "three high" industries, including mining, manufacturing, and energy supply, which are characterized by high emissions, high energy consumption, and high pollution. The release of the "Opinions" and other policies will undoubtedly have a significant impact on Guangxi's industrial energy consumption. What kind of impact will this have on the industry, and where should Guangxi's industry go in the future? From the dual perspectives of LMDI and Tapio, this paper explores the impact of Guangxi's industrial energy consumption under the constraints of the "dual carbon" targets on economic growth. It aims to address two main issues: the correlation between industrial carbon emissions and industrial economic growth in the Guangxi region and the analysis of factors affecting industrial carbon emissions. Based on these analyses, targeted policy recommendations will be proposed.

2. Literature Review

With the signing of the Paris Agreement, energy conservation and emission reduction initiatives have been vigorously implemented worldwide. Scholars both domestically and internationally have conducted extensive research on industrial carbon emissions. Scholars such as Xi Yongqin et al. [1] and Zhou Wuqi et al. [2], through empirical research, have pointed out that the current carbon emission efficiency in China's industrial sector is continuously increasing, but the overall average level is relatively low, and there is significant differentiation in industrial carbon emissions among regions. Scholars Zhang Fan et al. [3-4], Han Liping et al. [4], Cheng Yanjun et al. [5], Zhang Longqiang et al. [6], starting from different industrial sectors, selected "emission-intensive" sectors such as manufacturing, logistics, papermaking, and steel as research objects. They analyzed their own carbon emission factors and then studied the development paths for different industrial sectors to achieve carbon peak and carbon neutrality.

Scholars Bian Yu et al. [7] and Dai Shengli et al. [8], based on a regional perspective, respectively selected the Beijing-Tianjin-Hebei region and the industrial sectors of six central provinces as the research objects for industrial carbon emissions, exploring the correlation between industrial energy consumption and industrial carbon emissions within the regions. In the study of factors influencing industrial carbon emissions, scholars Li Qigeng et al. [9], Jiang Shengsheng et al. [10], and Han Chuan [11] focused on environmental regulations, industrial output value, and technological progress. They used a large number of empirical tests and simulation models to point out that China's industrial output value and industrial carbon emissions are in a state of relative decoupling. This can be improved by technological iteration and scientifically reasonable environmental regulations to enhance carbon emission efficiency, achieving the decoupling development of industrial output value and industrial carbon emissions.

Since the Organization for Economic Cooperation and Development (OECD) [12] introduced the term "decoupling" into the research on economic development and environmental resource changes, research on carbon emissions and economic development has flourished both domestically and internationally. Scholars such as Lu Zhongwu et al. [13], starting with the quantity relationship between resource consumption, waste emissions, and economic growth, made breakthrough progress in the research on decoupling indices theory. According to the decoupling index, the degree of decoupling is divided into three types: absolute decoupling, relative decoupling, and non-decoupling. Scholar Tapio [14], based on material consumption, further expanded the decoupling theory, subdividing the decoupling index into three major categories and eight states, making it the most comprehensive decoupling model to date.

In previous studies, both domestic and international scholars have extensively used the Logarithmic Mean Divisia Index (LMDI) method in the research process of the relationship between carbon emissions and economic development. Scholars Zhang Lingling et al. [15] and Hu Huaimin et al. [16], based on the Yangtze River Economic Belt, used LMDI and Tapio's decoupling theory to analyze the relationship between water pollution, transportation energy carbon emissions, and the decoupling relationship with the economy, as well as the analysis of driving factors. Scholar Ma Ying et al. [17], through the Tapio decoupling model, analyzed the relationship between energy consumption and economic development in the Beijing-Tianjin-Hebei region, and used the LMDI decomposition analysis model to further explore the influencing factors of carbon emissions in the region.

This paper is based on the Tapio decoupling theory, exploring the decoupling relationship between industrial carbon emissions and industrial total output value in Guangxi from 2010 to 2019. Using the LMDI logarithmic index decomposition method to decompose the impact effects of driving Guangxi's industrial carbon emissions and the decoupling of industrial economic total output value, and using the entropy method to optimize the weights corresponding to driving factors, the relationship characteristics between Guangxi's industrial carbon emissions and industrial output value are studied. This provides a basis for Guangxi to achieve low-carbon development in the industrial sector.

3. Theoretical Models

3.1. Carbon Emission Estimation Model

Regarding specific data on carbon emissions, it is currently not directly measurable and is generally estimated using indirect methods. The calculation method provided in the "2006 IPCC National Greenhouse Gas Inventory Guidelines" is often employed, where emissions are calculated as the product of activity levels and emission factors. This study adopts the carbon emission calculation method proposed by Ma Ying, and the formula is as follows: Carbon Emissions = Carbon Emission Coefficients for Various Energy Sources × Standard Coal Emission of Various Energy Sources = Carbon Emission Coefficients for Various Energy Sources × Physical Consumption of Various Energy Sources × Standard Coal Conversion Coefficients for Various Energy Sources [17].

Following IPCC assumptions, carbon emission coefficients for various energy sources are considered fixed. To facilitate unified calculation and comparison, various energy source data is converted into standard coal. Therefore, we can directly reference the carbon emission coefficients and standard coal conversion coefficients provided in the "2006 IPCC National Greenhouse Gas Inventory Guidelines," as shown in Table 1.

Table 1: Carbon Emission Conversion Coefficients and Standard Coal Conversion Coefficients

energy raw coal coke diesel	Carbon emission coefficient (104t/104tce)	Standard coal conversion coefficient (104tce/104t)
energy raw coal coke diesel	0.7559	0.7143
energy raw coal coke diesel	0.855	0.9714
energy raw coal coke diesel	0.5921	1.4571

Data Source: "2006 IPCC National Greenhouse Gas Inventory Guidelines" for carbon emission conversion coefficients; Standard coal conversion coefficients are derived from the "China Energy Statistical Yearbook."

3.2. Decoupling Model

In order to gain a more comprehensive understanding of the relationship between industrial energy consumption and industrial development in Guangxi, we introduce the Tapio Decoupling Model and construct a model for decoupling economic growth from carbon emissions. The specific formula for the elasticity decoupling analysis is as follows:

$$D_t = \frac{\delta C^t}{\delta G^t} = \frac{\frac{C^t - C^0}{C^0}}{\frac{G^t - G^0}{G^0}}$$

In this context, $\mathrm{D_t}$ represents the decoupling elasticity index;$\delta\mathrm{C^t}$ denotes the carbon emission elasticity coefficient; $\delta\mathrm{G^t}$ stands for the elasticity coefficient of economic growth; $\mathrm{C^t}$ and $\mathrm{C^0}$ represent the industrial carbon emissions in periods t and the initial period, respectively; $\mathrm{C^t}$ and $\mathrm{C^0}$ represent the industrial gross production values in periods t and the initial period, respectively.

Additionally, based on the combinations of decoupling elasticity index, carbon emission elasticity coefficient, and economic growth elasticity coefficient, eight decoupling states are categorized as follows:

From Table 2, it can be observed that decoupling states fall into three categories: decoupling states, negative decoupling states, and linkage states. Being in a decoupling state signifies a weakened relationship between carbon emissions and economic growth. Among them, strong decoupling is the most desirable state, representing a reduction in carbon emissions while experiencing economic growth. Weak decoupling indicates an improvement in energy efficiency, while feeble decoupling signifies that the rate of economic decline is slower than the rate of carbon emission reduction. Negative decoupling states indicate a strengthening correlation between economic growth and carbon emissions. Among them, strong negative decoupling signifies an increase in carbon emissions while experiencing economic decline, weak negative decoupling reflects low energy efficiency, and expansive negative decoupling means economic growth at the expense of a rapid increase in energy consumption. Linkage states demonstrate simultaneous increases or decreases in both carbon emissions and economic growth.

Table 2: Classification Criteria for Elastic Decoupling Indices

Decoupling States		δC	δG	D_t
Decoupling	Weak Decoupling	>0	>0	$0.8 \geq D_t > 0$
	Strong Decoupling	<0	>0	$D_t < 0$
	Feeble Decoupling	<0	<0	$D_t > 1.2$
Negative Decoupling	Expansive Negative Decoupling	>0	>0	$D_t > 1.2$
	Strong Negative Decoupling	>0	<0	$D_t < 0$
	Weak Negative Decoupling	<0	<0	$0.8 \geq D_t > 0$
Linkage	Expansive Linkage	>0	>0	$1.2 \geq D_t > 0.8$
	Weak Linkage	<0	<0	$1.2 \geq D_t > 0.8$

Data Source: Tapio (2005)

3.3. LMDI Decomposition Model

The Kaya Identity quantitatively analyzes carbon emissions based on four factors: population, per capita GDP, energy intensity of production, and carbon intensity of energy use. Building upon this framework, the current study applies the Kaya Identity to construct a model for analyzing carbon emission factors in Guangxi's industrial sector. The analysis model incorporates the effects of energy-related carbon emissions, energy consumption intensity, population size, economic growth, industrial scale, and energy structure. The resulting formula is:

$$\mathrm{C} = \sum_I C_i = \sum_I \frac{C_i}{E_i} \times \frac{E_i}{E} \times \frac{E}{G^I} \times \frac{G^I}{G} \times \frac{G}{P} \times P = \sum f \times s \times e \times u \times a \times p$$

In the formula, C and $\mathrm{C_i}$ represent the total energy emissions and the carbon emissions of the i type of energy,E and $\mathrm{E_i}$ represent the total energy consumption and the consumption of the i type of energy,G and $\mathrm{G^I}$ represent the regional gross domestic product and the industrial gross production value, and P represents the industrial workforce (average annual industrial workforce).

Applying LMDI to decompose the above equation into an additive form, the effect decomposition of carbon emission effects is obtained as follows:

$$\Delta \mathrm{C} = C_t - C_0 = \Delta C_f + \Delta C_s + \Delta C_e + \Delta C_u + \Delta C_a + \Delta C_p$$

Where $\Delta \mathrm{C_f}$ represents energy-related carbon emission intensity,$\Delta \mathrm{C_s}$ represents the energy structure effect, represents the energy consumption effect,$\Delta \mathrm{C_e}$ represents the industrial scale effect,$\Delta \mathrm{C_u}$ represents the economic growth effect, and $\Delta \mathrm{C_a}$ represents the population scale effect. According to the assumption in the "2006 IPCC National Greenhouse Gas Inventory Guidelines" that carbon emissions from various energy sources are constant, the equation can be simplified to $\Delta \mathrm{C} = C_t - C_0 = \Delta C_s + \Delta C_e + \Delta C_u + \Delta C_a + \Delta C_p$.

3.4. Entropy Method

In the LMDI process of exponential logarithmic decomposition of the formula, a crucial issue is how to determine the weights of various indicators. This study draws on the method used by Dai Shengli [8] in handling relevant data and employs the Entropy Method to determine weights. The advantage of the Entropy Method lies in the objectivity of the weights, avoiding interference from subjective factors. Based on the calculation of the comprehensive effect values in the LMDI index decomposition model, this paper applies the Entropy Method to assign weights to the five driving factors and calculate their respective scores.

4. Data Processing and Empirical Results

4.1. Data Source and Processing

This study selected data based on the principles of data availability and comparability, focusing on the average annual industrial employment (in persons), per capita GDP, industrial energy consumption,

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GDP, industrial gross production value, and various energy consumption in Guangxi Zhuang Autonomous Region for the years 2010-2019 as sample data. The data sources include "China Statistical Yearbook," "China Environmental Statistical Yearbook," "Guangxi Statistical Yearbook," and others.

During the sample processing, GDP, per capita GDP, and industrial gross production value calculated at current prices were all transformed into comparable price data. Industrial scale was calculated using industrial gross production value and regional GDP. In the empirical process, the year 2010 was taken as the base year for industrial carbon emissions and industrial output. As shown in Table 3,to avoid duplicate calculations during the process, the selected carbon emissions refer to the amount of carbon dioxide emitted from burning one unit of fossil energy, and the units of carbon emissions have been unified to standard coal equivalents.

Table 3: Correspondence Table of Factor Names

Factors	Names
△ep	Energy Production
△ap	Average Annual Employment in Industry
△gp	Industrial Sector Scale
△es	Energy Consumption Structure
△lp	Labor Productivity of Industrial Enterprises
△ec	Energy Consumption of Industrial Enterprises

4.2. Empirical Results

4.2.1. Decoupling Analysis

Decoupling Analysis of Guangxi's Industrial Carbon Emissions and Industrial Output for the Years 2010-2019.After analyzing the relevant data for Guangxi from 2010 to 2019, the decoupling index and decoupling status between industrial carbon emissions and industrial output in Guangxi were obtained and are shown in Table 4. From Table 4, it can be observed that the decoupling status in Guangxi has mostly been a weak decoupling relationship over the past decade. This means that carbon emissions have been increasing with industrial development, but the rate of increase is slower than the rate of industrial development. In 2018 and 2019, there is a strong decoupling status, indicating that carbon emissions are not strongly correlated with economic growth. Looking at the economic growth elasticity coefficient, the growth rate of industrial output value from 2010 to 2019 is consistently positive and increasing each year, indicating steady industrial development in Guangxi. The carbon emission elasticity coefficient fluctuates significantly but overall shows a weakening trend, which is attributed to the use of clean energy in the industrial sector. In summary, the industrial development and carbon emissions in Guangxi are gradually decoupling, mainly due to the increasing proportion of clean energy such as hydropower used in the industry, as shown in Table 4.

Table 4: Decoupling Status of Economic Development and Carbon Emissions in Guangxi

year	2011	2012	2013	2014	2015	2016	2017	2018	2019
△C	0.0836 31885	0.1759 68756	0.1022 46567	0.0814 82471	0.0076 04446	0.0687 02863	0.0192 25237	-0.0667 66919	-0.1015 43566
△G	0.153	0.2625 35	0.3584 8766	0.4671 66673	0.5361 23506	0.6021 76817	0.6662 6389	0.73624 6973	0.80569 6852
D_t	0.5466 13627	0.6702 67796	0.2852 16419	0.1744 18415	0.0141 8413	0.1140 90847	0.0288 55289	-0.0906 85492	-0.1260 31975
Decoup ling Status	Weak Decoup ling	Weak Decoup ling	Weak Decoup ling	Weak Decoup ling	Weak Decoup ling	Weak Decoup ling	Weak Decoup ling	Strong Decoup ling	Strong Decoup ling

4.2.2. Decomposition Analysis of Factors Influencing Industrial Carbon Emissions

"According to the formula, the LMDI method is used to decompose the influencing factors of industrial carbon emissions in Guangxi from 2011 to 2020. Since the carbon emission coefficient is a constant value and always equal to 1, it is omitted in the table. Based on a comprehensive analysis of the factors influencing industrial carbon emissions in Guangxi over the past decade, the results are as follows.Firstly, based on the sample data, entropy weighting is applied to the influencing factors, and the results are shown in Table 5.

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Table 5: Proportion of Each Factor

Factors	△ep	△gp	△ap	△es	△lp	△ec
Proportion	0.094589	0.30076	0.160439	0.127344	0.212237	0.104631

According to Table 5, among the various factors listed in this paper, the most significant factor influencing carbon emissions from industrial enterprises in Guangxi is the scale of the industrial sector, followed by industrial enterprise productivity. The least influential factor is energy production. In reality, due to the limited availability of energy resources in Guangxi, the carbon emissions from energy production are relatively low, aligning with the empirical results.

As shown in Table 6, the overall change in carbon emissions from industrial activities in Guangxi is decreasing, but with considerable volatility. The years 2013-2014, 2015-2016, and 2018-2019 witnessed the most substantial reduction in emissions. However, the significant reduction in industrial employment in 2018-2019 may have distorted the results, so the focus is mainly on the changes in indicators in 2013-2014 and 2015-2016. According to Table 6, energy consumption decreased to varying degrees in both years, indicating the significant impact of energy consumption on carbon emissions in Guangxi. Additionally, the industrial employment in Guangxi decreased, and the fluctuations in the number of industrial employees were significant. This suggests that Guangxi is actively responding to the national call for energy conservation and emission reduction. However, there is no clear government target or indicator for industrial emission reduction.The results of the decomposition of various factors are presented in Table 7. From the perspective of years, the impact of various factors on carbon emissions is relatively stable, with minor fluctuations. The small fluctuations in each factor indicate a lack of significant adjustments. This also suggests that Guangxi has not implemented strong policies to reduce industrial carbon emissions, and there is a lack of advanced technology support for upgrading the industrial structure in the region.

Table 6: Decomposition value of each factor

Year	△ce	△ep	△ap	△gp	△es	△lp	△ec
2011-2012	126.96	352.56	-33918	139.73	0.038521	875.7	353.48
2012-2013	140.17	387.55	130592	55.92	0.041875	1509.3	289.09
2013-2014	-111.92	352.49	54319	324.11	0.005744	2206.9	-21.37
2014-2015	-31.52	404.55	-6163	135.22	0.010264	1367.9	249.5
2015-2016	-112.15	-126.9	28114	148.27	-0.01183	2277.5	-114.57
2016-2017	92.75	107.68	-30250	372.74	0.040297	1852.2	253.98
2017-2018	-75.1	501.52	-1529	421.86	0.00957	10056.9	404.02
2018-2019	-130.54	-152.01	-369880	144.65	-0.01587	5065.3	96.06
2019-2020	-52.8	195.74	-98988	-25.33	0.019335	164.9	375.3

Table 7: Decomposition results of various factors

year	△cp	△ap	△gp	△es	△lp	△ec	Total
2011-2012	0.96469	0.4611919	1.176919	0.0897832	1.127717	0.4107186	4.23102
2012-2013	1.031588	0.2270195	1.249487	0.1698151	0.9725758	0.0000125	3.650498
2013-2014	0.9645562	0.9763655	0.4677121	0.257931	0.2245555	0.1904245	3.081545
2014-2015	1.06409	0.4485905	0.5655171	0.1519544	0.8771879	0.341425	3.448765
2015-2016	0.0480079	0.4850534	0.087514	0.2668487	0.0000125	0.2558484	1.143285
2016-2017	0.4965027	1.112242	1.215338	0.2131278	0.887982	0.401561	4.326754
2017-2018	1.249487	1.249487	0.5504979	1.249487	1.249487	0.3298557	5.878302
2018-2019	0.0000125	0.4749388	0.0000125	0.6189838	0.5074906	1.249487	2.850925
2019-2020	0.6648651	0.0000125	0.7617856	0.0000125	1.18029	0.5731736	3.180139
Total	6.4837994	5.4349011	6.0747832	3.0179435	7.0272983	3.7525063	

5. Research conclusions and policy recommendations

Based on the relevant data of Guangxi from 2010 to 2019, this paper decomposes the influencing factors of industrial carbon dioxide emission in Guangxi from the perspectives of LMDI and Tapio, and analyzes the results, and draws the following conclusions:

First of all, Guangxi's industrial carbon emissions are currently in a critical period of transition from weak decoupling to strong decoupling. In 2018 and 2019, Guangxi's industrial carbon dioxide

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emissions and industrial output value showed a strong decoupling relationship.

Second, the scale of industrial sector is the most influential factor on industrial carbon emissions in Guangxi, and the energy production is the least influential factor.

Third, Guangxi's industrial energy consumption structure is relatively stable, which has little influence on the change of industrial carbon dioxide emissions.

Based on the above conclusions, the following policy suggestions are put forward:

First, adjust the energy structure and increase the use of clean energy. At present, Guangxi's industrial energy is still dominated by fossil energy, but there are few reserves of fossil energy resources in the region, which are basically imported. The development of clean energy can not only reduce fossil energy consumption and industrial carbon dioxide emissions, but also save energy expenditure of enterprises and accelerate structural transformation.

Second, accelerate the transformation and upgrading of industrial structure. Further expand the proportion of the tertiary industry, introduce high-quality projects, and reduce the proportion of industrial enterprises that consume huge fossil energy in industry, especially in industry. Accelerating the transformation of industrial structure will greatly promote the process of reducing industrial carbon emissions in Guangxi.

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