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Short Communication

Measurement of Carbon Emissions in China and Analysis of Decoupling Relationship with Economic Development

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Abstract

[Purpose] Our study delves into temporal and spatial disparities of carbon emissions within China and delineates the characteristics of decoupling, with the overarching goal of furnishing decision-making insights for China's low-carbon economic trajectory and the advancement of high-quality economic policies. [Methods] Employing the IPCC carbon emission coefficient method, our study quantifies carbon emissions across 30 provinces in China spanning the period from 2017 to 2021. The Tapio model is subsequently leveraged to elucidate the decoupling dynamics between carbon emissions and economic development in China. [Results] Over the period from 2017 to 2021, both the total carbon emissions and GDP exhibited a discernible upward trajectory nationwide. The eastern region sustained its position as the principal locus of economic expansion and carbon emissions within China. Concurrently, there was a marked reduction in carbon emissions per ten thousand yuan of GDP output across all provinces. Despite the simultaneous augmentation of economic development and carbon emissions, the pace of economic growth outpaces that of carbon emissions, indicative of a relatively favorable scenario. [Conclusions] Adherence to technological innovation and structural optimization emerges as imperative, underscoring the need for tailored strategies and targeted interventions. Emphasis should be placed on enhancing quality and efficiency and fostering green development to steer China towards the dual objectives of low-carbon and high-quality economic development.

Keywords: China, economy, carbon emissions, Tapio

Introduction

In light of the increasingly urgent global climate change crisis, carbon emissions have emerged as a central concern due to their role in exacerbating greenhouse effects [1, 2]. As the world's largest developing nation, China's total carbon emissions and their correlation with economic growth wield significant influence over global climate governance and the formulation of domestic sustainable development strategies [3, 4]. Therefore, it is imperative to undertake a comprehensive analysis to accurately measure China's total carbon emissions and assess their decoupling from economic development, bearing paramount theoretical and practical significance.

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In recent decades, China's economy has undergone rapid expansion [5, 6], accompanied by substantial increases in energy consumption and carbon emissions [7]. While this growth trajectory has fostered economic prosperity, it has also placed a considerable strain on the environment [8-10]. To confront this challenge, the Chinese government has implemented a series of policies and measures aimed at conserving energy, reducing emissions, and promoting green development to facilitate the optimization and transformation of the economic structure [11-13]. However, effective implementation of these policies necessitates a clear understanding of China's carbon emissions in terms of both total volume and characteristics. Presently, domestic and international scholars have conducted extensive research on China's carbon emissions, yet challenges persist [11, 14-18]. On one hand, disparities in data sources and statistical methodologies lead to variations in reported total carbon emission figures, thereby affecting the accurate assessment of emission trends and characteristics [Ref]. On the other hand, although some studies have attempted decoupling analysis between carbon emissions and economic development, they often lack in-depth theoretical exploration and empirical verification [Ref]. Hence, this paper aims to employ scientific econometric methods to collect and analyze the latest data, accurately measure China's total carbon emissions, and conduct an in-depth analysis of their decoupling from economic development.

Research Methods and Data Sources

Objective and Scope of the Research

The research object is the total carbon emissions and gross domestic product (GDP) of 30 provinces (municipalities directly under the central government and autonomous regions) in China from 2017 to 2021. Due to data availability, Tibet, Hong Kong, Macao, and Taiwan were not included in the study.

Research Area Classification

According to the division methodology of the Development Research Centre of the State Council of China, China can be divided into four major economic regions, namely, the eastern, central, western, and north-eastern regions (Fig. 1). Among them, the eastern region includes 10 provinces or municipalities directly under the central government, namely Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong and Hainan; the central region includes 6 provinces, namely Shanxi, Anhui, Jiangxi, Henan, Hubei and Hunan; and the western region includes 11 provinces, municipalities directly under the central government or autonomous regions, namely Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang; The north-eastern region includes three provinces, namely Liaoning, Jilin and Heilongjiang.

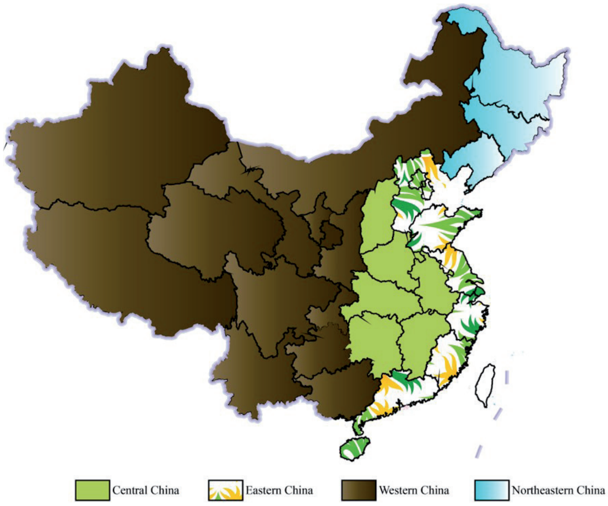

Fig. 1. Dividing China's Four Economic Regions into Sectors.

Methods

Total Carbon Emissions Accounting

Utilizing the sectoral approach outlined by IPCC (2006) [19], we computed the total carbon emissions for China and its 30 provinces from 2017 to 2021. The calculation formula is presented as follows:

$$\mathrm{CE}_{\mathrm{direct},j} = \mathrm{CE}_{\mathrm{energy-related},j} + CE_{\mathrm{process-related},j}$$

Here, j represents various industries, $\mathrm{CE}_{\mathrm{direct},j}$ denotes the aggregate of direct carbon emissions, $\mathrm{CE}_{\mathrm{energy\text{-}related},j}$ signifies the carbon emissions arising from fossil fuel combustion within industry j, and $CE_{\mathrm{process\text{-}related},j}$ indicates carbon emissions resulting from industrial processes.

The carbon emissions from the combustion of fossil fuels can be calculated using the following formula:

$$\mathrm{CE}_{\mathrm{energy-related},j} = \sum_i \mathrm{AD}_{ij} \times \mathrm{NCV}_i \times \mathrm{CC}_i \times \mathrm{O}_{ij}$$

Where AD_{ij} represents the consumption of fossil fuel i divided by department j. $\mathrm{NCV}_i \times \mathrm{CC}_i \times O_{ij}$ represents the emission coefficient of fossil fuel i burned by department j, which can be further divided into three parts: net calorific value NCV_i, carbon content CC_i of fossil fuel i, and oxidation rate O_{ij} of fossil fuel i used by department j. For industrial production processes, only cement production is considered in this study, which accounts for nearly 70% of China's processing-related carbon emissions. The calculation formula is as follows:

$$CE_{\mathrm{process-related},j} = \mathrm{AD}_{t,j} \times \mathrm{EF}_{t,j}$$

Where t represents the industrial production process, $AD_{t,j}$ represents the amount of cement consumed by industry j for industrial production, and $EF_{t,j}$ represents the emission factor.

Carbon Intensity Accounting Per Unit GDP

By calculating the carbon emissions generated per ten trillion yuan of GDP, we can gain a preliminary and simplistic understanding of the relationship between China's economic development and carbon emissions. The calculation method is as follows:

$$\mathrm{PF} = \frac{\mathrm{CE}_{\mathrm{direct,j}}}{\mathrm{GDP}}$$

Analysis of Decoupling Relationships

In this study, we employed the Tapio decoupling index to analyze the decoupling relationship between carbon emissions and GDP in China [20, 21]. The decoupling model constructed is as follows:

$$e = \frac{\Delta CE/CE}{\Delta G/G}$$

Where e stands for decoupling elasticity, CE stands for total carbon emissions, ΔCE stands for change in carbon emissions; G stands for GDP, ΔG stands for change in GDP (Table 1).

Data Sources

Data for China and provinces are sourced from the China Statistical Yearbook 2018-2022.

Table 1. Classification of the 8 decoupling states.

Decoupling states	$\Delta CE/CE$	$\Delta G/G$	e
Expansion negative decoupling	>0	>0	e>1.2
Strong-negative decoupling	>0	<0	e<0
Weak-negative decoupling	<0	<0	0≤e<0.8
Weakly decoupled	>0	>0	0≤e<0.8
Strong decoupled	<0	>0	e<0
Recessionary decoupling	<0	<0	e>1.2
Growth connection	>0	>0	0.8≤e<1.2
Recession connection	<0	<0	0.8≤e<1.2

Results

Changes in GDP and Carbon Emissions in 30 Chinese Provinces

As can be seen from Table 2, between 2017 and 2021, China's overall total carbon emissions and GDP show a clear upward trend. In 2021, China's total carbon emissions and GDP rose by 12.49% and 37.27%, respectively, relative to 2017. Specifically for individual provinces, in terms of total carbon emissions, five provinces achieved a decline in total carbon emissions, namely Beijing, Shanghai, Henan, Hunan, and Sichuan. The total carbon emissions of these six provinces in 2021 decreased by 6.54%, 1.06%, 3.61%, 3.95%, and 1.24% relative to 2017. The province with the largest total carbon emissions in 2021 was Shandong, with 947.16×10^6 t; the province with the smallest carbon emissions was Hainan, with 45.65×10^6 t. In terms of the growth rate of the total carbon emissions, the total carbon emissions in Ningxia decreased from 178 to 178 in 2017. Emissions grew from 178.62×10^6 t in 2017 to 235.32×10^6 t in 2021, with a growth rate of 31.74%, which is the largest growth rate among all provinces. Jilin, on the other hand, had the smallest growth rate of 0.03%, and its total carbon emissions were still decreasing in 2018 relative to 2017. In terms of GDP, all 30 provinces achieved positive growth between 2017 and 2021, with the top 5 provinces with the largest increases being Shanxi (57.90%), Jiangxi (47.58%), Yunnan (46.93%), Fujian (46.46%) and Xinjiang (46.16%). The top 5 provinces in terms of GDP were Guangdong (12.47×10^6 million yuan), Jiangsu (11.74×10^6 million yuan), Shandong (8.29×10^6 million yuan), Zhejiang (7.40×10^6 million yuan) and Henan (5.81×10^6 million yuan).

Changes in GDP and Carbon Emissions in China's Four Major Economic Regions

From 2017 to 2021, the total carbon emissions and GDP of China's four major regions show a clear upward trend (Table 3). In terms of total carbon emissions, the eastern region is still the most dominant carbon emission source region in China, with carbon emissions as high as 4,497.34×10^6 t in 2021, rising by 11.75% relative to 2017. It is followed by the western region, with carbon emissions of 3,452.66×10^6 t in 2021, up 19.61% relative to 2017. The rise in carbon emissions in the central region was relatively less pronounced, at 7.54%. The northeastern region has only three provinces, so it has the least carbon emissions, only 1017.53×10^6 t in 2021, up 4.03% relative to 2017. In terms of GDP, the eastern region accounts for most of China's GDP output, with 59.59×10^6 million yuan in 2021, accounting for 52.25% of all of China's GDP, up 36.30 percent relative to 2017. This is followed by 24.91×10^6 million yuan in the central region, accounting for 21.84% of all China's GDP, up 38.16% relative to 2017. The western region's GDP in 2021 was 23.98×10^6 million yuan, accounting for 21.03%

Table 2. Changes in GDP and carbon emissions in 30 provinces in China, 2017-2021.

Region	Carbon emission/10^6 t					GDP/10^6 million yuan				
	2017	2018	2019	2020	2021	2017	2018	2019	2020	2021
Beijing	85.56	88.41	88.16	76.78	79.96	2.99	3.31	3.55	3.59	4.11
Tianjin	143.99	154.34	158.47	161.87	155.55	1.25	1.34	1.41	1.40	1.57
Hebei	792.33	912.20	914.21	939.36	885.51	3.06	3.25	3.50	3.60	4.04
Shanxi	508.59	541.80	566.48	583.25	6.14	1.45	1.60	1.70	1.78	2.29
Neimenggu	656.85	723.57	794.28	839.74	843.40	1.49	1.61	1.72	1.73	2.12
Liaoning	496.83	521.00	533.39	543.87	545.67	2.17	2.35	2.49	2.50	2.76
Jilin	204.34	196.25	203.66	200.59	204.39	1.09	1.13	1.17	1.23	1.32
Heilong jiang	276.91	248.28	278.21	273.06	287.54	1.23	1.29	1.35	1.36	1.49
Shanghai	196.15	190.64	192.91	179.90	194.07	3.29	3.60	3.80	3.90	4.37
Jiangsu	757.89	764.05	804.59	773.97	817.68	8.59	9.32	9.87	10.28	11.74
Zhejiang	378.78	388.83	381.41	386.97	442.20	5.24	5.80	6.25	6.47	7.40
Anhui	382.22	398.98	408.06	416.01	433.78	2.97	3.40	3.69	3.81	4.26
Fujian	234.97	261.46	278.11	275.82	299.82	3.38	3.87	4.23	4.36	4.96
Jiangxi	228.98	236.63	242.31	241.52	245.41	2.02	2.27	2.47	2.58	2.98
Shandong	835.82	901.65	937.12	930.64	947.16	6.30	6.67	7.05	7.28	8.29
Henan	501.86	490.68	460.63	473.66	483.74	4.48	4.99	5.37	5.43	5.81
Hubei	331.61	329.08	354.75	317.49	361.05	3.72	4.20	4.54	4.30	5.01
Hunan	323.66	305.97	310.64	302.31	310.87	3.38	3.63	3.99	4.15	4.57
Guangdong	556.86	567.51	585.81	566.57	629.74	9.16	9.99	10.80	11.11	12.47
Guangxi	227.89	231.83	246.72	268.10	288.03	1.78	1.96	2.12	2.21	2.52
Hainan	42.16	42.19	43.07	40.25	45.65	0.45	0.49	0.53	0.56	0.65
Chongqing	160.55	160.60	156.25	152.86	165.28	2.01	2.16	2.36	2.50	2.81
Sichuan	318.84	296.31	315.16	307.55	314.90	3.79	4.29	4.64	4.85	5.41
Guizhou	257.66	252.99	261.13	252.80	265.86	1.36	1.54	1.68	1.79	1.95
Yunnan	199.01	212.24	185.96	235.64	234.22	1.85	2.09	2.32	2.46	2.72
Shaanxi	274.03	276.17	296.27	309.78	339.10	2.15	2.39	2.58	2.60	3.01
Gansu	151.96	162.99	164.49	175.87	189.45	0.73	0.81	0.87	0.90	1.02
Qinghai	53.49	51.94	51.75	47.93	56.38	0.25	0.27	0.29	0.30	0.34
Ningxia	178.63	191.59	212.41	225.91	235.32	0.32	0.35	0.37	0.40	0.46
Xinjiang	407.76	421.42	455.27	466.90	520.71	1.12	1.28	1.36	1.38	1.63
Total	10166.13	10521.59	10881.69	10966.98	11436.19	83.07	91.26	98.06	100.80	114.04

of all of China's GDP and rising 42.40% relative to 2017. The GDP of the Northeast region in 2021 is only 5.56×10^6 million yuan, occupying 4.88% of the whole China's GDP, up 23.83% relative to 2017.

Changes in Carbon Emissions Per Unit of GDP by Region in China

Accounting for carbon emissions per unit of GDP better reflects the relationship between economic growth and carbon emissions. Our calculations show that between 2017 and 2021, carbon emissions per 10^6 million yuan of GDP for all provinces in China declined significantly, and in 2017, China produced 1.22×10^4

Table 3. Changes in GDP and carbon emissions in China's four major economic regions, 2017-2021.

Region	Carbon emission/10^6 t					GDP/10^6 million yuan				
	2017	2018	2019	2020	2021	2017	2018	2019	2020	2021
Eastern China	4024.49	4271.27	4383.85	4332.14	4497.34	43.72	47.64	50.98	52.55	59.59
Central China	2276.91	2303.13	2342.88	2334.23	2448.59	18.03	20.10	21.75	22.05	24.91
Western China	2886.65	2981.66	3139.70	3283.08	3452.66	16.84	18.76	20.32	21.11	23.98
Northeastern China	978.08	965.53	1015.26	1017.53	1037.60	4.49	4.76	5.01	5.09	5.56

t of carbon emissions per 10^6 million yuan of GDP. By 2021, the same amount of GDP will only produce 1.00×10^4 t of carbon emissions, a year-on-year drop of 18.05%. Among the 30 provinces, Ningxia has the highest carbon emissions per unit of GDP, at 51,287.66 t/10^6 million yuan, while Beijing has the lowest, at 1,948.15 t/10^6 million yuan. In terms of the decline in carbon emissions per trillion yuan of GDP, Beijing's decline of 31.96% is the largest among the provinces. It was followed by Sichuan (30.79%), Guizhou (27.85%), Chongqing (26.43%) and Henan (25.60%). The provinces with the lowest decreases were Ningxia (8.11%), as well as Inner Mongolia (9.62%) and Guangxi (10.80%). In order to have a more intuitive look at the changes in carbon emissions per 10^6 million yuan of GDP output in each province, we have graded each province using the Chinese average as a reference (Fig. 2). It can be seen that the provinces exceeding the national average are mainly concentrated in the northeastern and western regions. In the eastern region, except for Hebei and Shandong (whose carbon emissions per 10^6 million yuan of GDP output in 2021 exceeded the national average by 218.58% and 113.97%, respectively), the rest of the provinces are below the national average, especially Beijing, Shanghai, and Guangdong, which are most obvious, with carbon emissions per 10^6 million yuan of GDP output in 2021 of these three provinces at 19.43%, 44.33% and 50.35% respectively. If we look at the four major economic regions, the Northeastern and Western regions exceed the national average by 186.12% and 143.58%, respectively, in 2021, while the Eastern and Central regions are at 75.26% and 98.01%, respectively.

Analysis of Decoupling Relationships

According to Table 4, the decoupling characteristics between economic development and carbon emissions in China from 2017 to 2021 exhibit a condition of weak decoupling. Particularly, the greatest degree of decoupling occurred in 2018-2019, with a decoupling elasticity value of 0.4589. Conversely, the period from 2019 to 2020 witnessed the lowest degree of decoupling, with a decoupling elasticity value of 0.2804, primarily attributed to the severe economic downturn resulting from the outbreak of the COVID-19 pandemic. The decoupling degrees in the remaining years remained relatively close, ranging from 0.3258 to 0.3550, with a decoupling elasticity value of 0.3352 for the entire span of 2017-2021.

Discussions and Conclusion

China has set forth ambitious plans to peak its carbon emissions at the national level by 2030, with

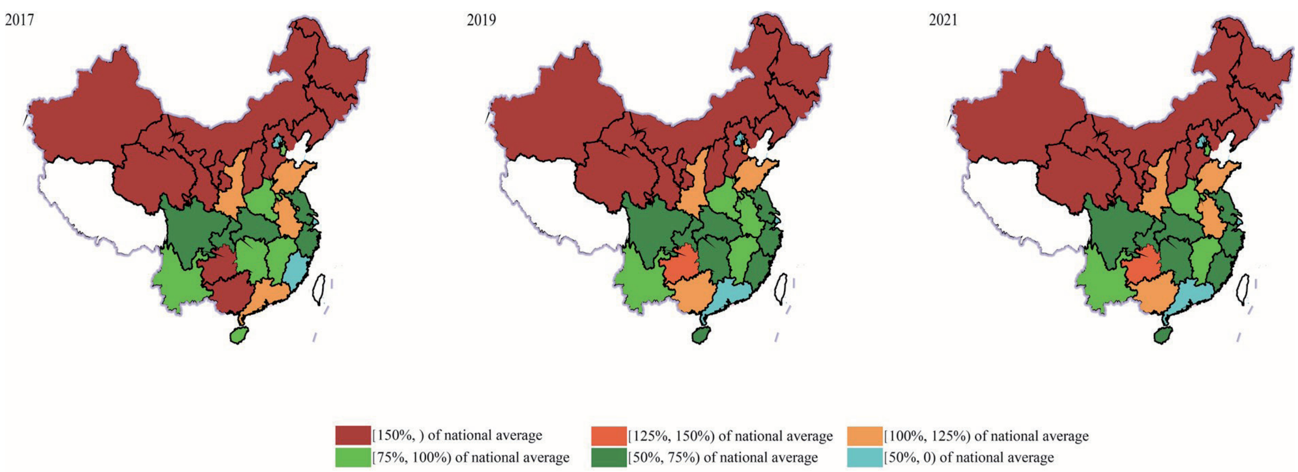

Fig. 2. Changes in carbon emissions per billion yuan of GDP generated by Chinese provinces.

Table 4. Elasticity of decoupling economic development and carbon emissions in China.

	$\Delta CE/CE$	$\Delta G/G$	e	Decoupling characteristics
2017-2018	0.0349	0.0985	0.3550	Weakly decoupled
2018-2019	0.0342	0.0746	0.4589	Weakly decoupled
2019-2020	0.0078	0.0279	0.2804	Weakly decoupled
2020-2021	0.0428	0.1313	0.3258	Weakly decoupled
2017-2021	0.1249	0.3727	0.3352	Weakly decoupled

the overarching aim of achieving carbon neutrality [22]. It is evident that the Chinese government is steadfast in its commitment to ecological strategies while concurrently prioritizing economic vitality. In recent years, there has been a discernible emphasis on industrial upgrading and the promotion of green industries [23, 24]. Notably, among the five provinces that have attained negative carbon emissions growth, Beijing and Shanghai have historically gravitated towards high-tech industries, relegating high-pollution and high-carbon emission industries to a peripheral status [25, 26]. Concurrently, the green development initiatives within the provinces of Henan, Hunan, and Sichuan have reached significant milestones, facilitating relatively facile reductions in carbon emissions. Despite these regional advancements, at the national level, China's total carbon emissions continue to exhibit an upward trajectory. Some scholars had previously forecasted a peak in China's carbon emissions by 2025, estimating a range between 100.59×10^8 t and 148.98×10^8 t [27]. However, in 2021, mainland China's carbon emissions, excluding measurements from the Tibet Autonomous Region, amounted to 114.36×10^8 t, indicating a discrepancy of up to 34.62×10^8 t from the projected peak. While certain regions may persist with elevated carbon emissions post-2030 due to ongoing industrial transformations, an overall reduction in carbon emissions appears probable.

In the examination of China's economy, it is imperative to adopt a holistic perspective, as the nation's development paradigm is predicated on synergistic growth [28]. Thus, our study undertakes an analysis of the four officially recognized economic regions of China. From an economic standpoint, the eastern seaboard emerges as the most industrially advanced region in China, a status it has maintained since the inception of the country's reform and opening-up policies [29]. Characterized by a dense concentration of high-tech industries, exemplified by regions such as Guangdong Province, which encompasses Shanghai and Shenzhen, carbon emissions per billion yuan of GDP have consistently hovered around 50% of the national average between 2017 and 2021. This underscores the robust development of green industries in these regions, yielding commendable economic dividends, particularly evident in Guangdong Province, which has perennially ranked as the top GDP contributor among Chinese provinces. Subsequently, the central region of China, although trailing the eastern region in GDP, has effectively curbed carbon emissions. With the exception of 2017, when carbon emissions per billion yuan of GDP in the central region exceeded the national average, subsequent years witnessed this metric falling below the national average. Conversely, the Northeast and West regions have consistently surpassed the national benchmark for carbon emissions. In 2017, carbon emissions per 100 million yuan of GDP in these regions were 177.90% and 140.09% of the national average, respectively, rising to 186.12% and 143.58% by 2021. Historically, these regions have been bastions of heavy industry in China, particularly pronounced in the northeast [30]. The protracted economic downturn in the Northeast, exacerbated by challenges in industrial transformation post the 1998 reform of state-owned enterprises, has perpetuated a reliance on heavy industry, consequently driving heightened carbon emissions. To address the carbon intensity of regions with concentrated heavy industry, scholars advocate for robust interventions, emphasizing technological innovation in carbon emission reduction as paramount. Strategies encompass comprehensive digital and intelligent transformations within industrial enterprises, coupled with incentivized research and development initiatives targeting key processes and equipment. Additionally, proposals advocate for the consolidation of high carbon emission-intensive industrial enterprises into centralized industrial parks, facilitating unified management and the deployment of emission reduction facilities. Such integrated approaches aim to optimize resource utilization and harmonize carbon emission management across diverse enterprises.

The study culminates in a comparative analysis of China's foremost economic zones, with the notable omission of the Guangdong-Hong Kong-Macao Greater Bay Area due to data constraints pertaining to Hong Kong and Macao. By juxtaposing the Yangtze River Economic Belt with the Bohai Economic Circle, a discernible economic divide emerges, characterized by the adage of "strong in the south and weak in the north". Notably, the Yangtze River Economic Belt exemplifies a more pronounced trajectory toward green industry development compared to the Bohai Economic Circle. This disjuncture underscores a pressing imperative for the Chinese government to reconcile the economic and carbon emission differentials between northern and southern regions.

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Conflict of Interest

The authors declare no conflict of interest.

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