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China's power industry's carbon emission intensity in the context of carbon peaking and carbon neutrality: measurement and regional difference

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Abstract

Purpose – To cope with the severe situation of the global climate, China proposed the "30 60" dual-carbon strategic goal. Based on this background, the purpose of this paper is to investigate scientifically and reasonably the interprovincial pattern of China's power carbon emission intensity and further explore the causes of differences on this basis.

Design/methodology/approach – Considering the principle of "shared but differentiated responsibilities," this study measures the carbon emissions within the power industry from 1997 to 2019 scientifically, via the panel data of 30 provinces in China. The power carbon emission intensity is chosen as the indicator. Using the Dagum Gini coefficient to explore regional differences and their causes.

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Findings – The results of this paper show that, first, China's carbon emission intensity from the power industry overall is significantly different. From the perspective of geospatial distribution, the three regions have unbalanced characteristics. Second, according to the decomposition results of the Gini coefficient, the overall difference in power carbon emission intensity is generally expanding. The geospatial and economic development levels are examined separately. The gaps between the eastern and economically developed regions are the smallest, and the regional differences are the source of the overall disparity.

Research limitations/implications – Further exploring the causes of differences on this basis is crucial for relevant departments to formulate differentiated energy conservation and emission reduction policies. This study provides direction for analyzing the green and low carbon development of China's power industry.

Practical implications – As an economic indicator of green and low-carbon development, CO_2 intensity of power industry can directly reflect the dependence of economic growth on the high emission of electricity and energy. and further exploring the causes of differences on this basis is crucial for relevant departments to formulate differentiated energy conservation and emission reduction policies.

Social implications – For a long time, with the rapid economic development, resulting in the unresolved contradiction between low energy efficiency and high carbon emissions. To this end, scientifically and reasonably investigating the interprovincial pattern of China's power carbon emission intensity, and further exploring the causes of differences on this basis, is crucial for relevant departments to formulate differentiated energy conservation and emission reduction policies.

Originality/value – Third, considering the influence of spatial factors on the convergence of power carbon emission intensity, a variety of different spatial weight matrices are selected. Based on the β-convergence theory from both absolute and conditional perspectives, we dig deeper into the spatial convergence of electricity carbon emission intensity across the country and the three regions.

Keywords Power industry, CO_2 intensity, Dagum Gini coefficient, Regional difference

Paper type Research paper

1. Introduction

The attention of countries around the world on climate change has risen to the level of economic and political games, and low-carbon green development has gradually become the main theme of addressing climate issues. As the world's largest energy consumer and carbon emitter, China's total CO_2 emissions in 2020 reached 9.894 billion tons, accounting for 33% of the global total (IEA, 2020). Such a high amount of carbon emissions has caused my country to face enormous pressure to reduce emissions. For a long time, the rapid development of my country's economy has led to the unresolved contradiction between low energy efficiency and high carbon emissions. Therefore, maintaining stable economic development in the short term still requires a large supply of fossil energy, which in turn will put pressure on emission reductions (Chen *et al.*, 2018). To this end, in 2020, the Chinese Government proposed the strategic goal of achieving "carbon peaking" in 2030 and "carbon neutrality" in 2060.

As the basic pillar industry of the national economy, the power industry is also the main field of carbon emissions, and its production activities are one of the main sources of carbon emissions (Wang *et al.*, 2013). In 2020, China's electricity carbon emissions will account for about 38% of my country's total carbon emissions. With the rapid progress of urbanization and industrialization, the power industry will still provide a source of power for social and economic development in the future (Xie *et al.*, 2021). Because of the constraints of resource endowment and power generation structure, coal consumption will still be the main power generation. It will inevitably have a serious impact on the environment, making it difficult to meet the needs of low-carbon green development. To this end, for carbon emission control, the central government plays an important role in it (Pan *et al.*, 2022). Under the background of the new normal, energy conservation and emission reduction will become the only way for my country's low-carbon economy and green energy transformation.

As an economic indicator of green and low-carbon development, CO_2 intensity of power industry can directly reflect the dependence of economic growth on the high emission of electricity and energy. China's vast territory and the dislocation of regional economy and energy structure determine that the power industry needs to allocate each other to maintain its supply and demand balance. In addition, differences in resource endowments and technical levels result in significant differences in the carbon emission intensity of electricity between provinces (Hu, 2019). To this end, scientifically and reasonably investigating the interprovincial pattern of China's power carbon emission intensity, and further exploring the causes of differences on this basis, is crucial for relevant departments to formulate differentiated energy conservation and emission reduction policies.

2. Literature reviews

Accurate accounting of carbon emissions is the primary basis for formulating emission reduction strategies and achieving low-carbon development (Shan *et al.*, 2018). At present, scholars' accounting for electricity carbon emissions mainly includes the following three aspects: The first type is the accounting method based on the principle of responsibility on the production side, that is, from the perspective of electricity production, it is believed that all carbon emissions come from the original power supply side (Zhang *et al.*, 2013; Yang and Lin, 2016; Zhou *et al.*, 2019). This accounting method mainly applies the accounting method compiled by the Intergovernmental Panel on Climate Change, and has the characteristics of fewer data required and easy calculation, and has been widely used. For example, Qu *et al.* (2019), Shan *et al.* (2018), Jin (2011), Li *et al.* (2014, 2015) and even the research of China Emission Accounts and Databases and the International Energy Agency (2018) (IEA). The second category is the accounting method based on the principle of consumer responsibility, that is, from the perspective of power consumption, it is believed that the consumption mainly originates from the user side. This accounting method considers the interprovincial power transaction and improves the accuracy and reliability of the data, such as the research of Tao *et al.* (2016) and Wang *et al.* (2019). The third category is the shared responsibility-sharing accounting method. Starting from the two ends of electricity production and consumption, and sharing the emission according to a reasonable proportion, it can effectively avoid the double calculation of electricity emissions. Chen *et al.* (2018) studied the regional decomposition of electricity carbon emissions in my country based on the production side and the consumption side. Although this method considers both the power production and consumption sides, it does not apply the principle of "shared responsibility between the production side and the consumption side" to the measurement of power carbon emissions. However, Fu and Qi (2014) and Zhao *et al.* (2019) considered the reality of "production and consumption are the same but different," and based on the principle of "shared responsibility," they studied my country's electricity carbon emissions in 2011 condition. The economic level, technological level and energy structure of different regions in China are different. If we study only China's overall power carbon emissions from a time scale, we will not be able to examine the actual emissions in each region, which is not conducive to the promotion and implementation of emission reduction work in each region. To this end, scholars have conducted a more in-depth study of the carbon emissions or intensity of electricity in each province based on panel data. Wang *et al.* (2019) studied the regional spatiotemporal characteristics based on the carbon emissions of electricity on the production side in my country. However, Su *et al.* (2016) and Hou and Hou (2018) considered the cross-regional dispatch and transaction of electricity and studied the carbon emission characteristics of electricity in my country based on the consumption side. The cross-sectional data of a certain year used in the above studies ignores the differences in the time scale of each region. It will make it impossible to accurately examine the dynamic evolution of carbon emissions from electricity, thus making it impossible to formulate reasonable emission reduction policies in the long run.

At the same time, some scholars have also analyzed the influencing factors of electricity carbon emissions through models such as econometrics (Wen and Yan, 2018), input–output method (Wiedmen, 2009) and factor decomposition method (Xie *et al.*, 2019). For example, Wang and Xie (2015), Yan *et al.* (2019), Chen *et al.* (2018), Pan *et al.* (2022) and Cao and Jiang (2018) used logarithmic mean divisia index to decompose the driving factors of electricity carbon emissions. Xie *et al.* (2020) used Topia decomposition analysis, autoregressive distributed lag, and error correction model to study the influencing factors of CO_2 emissions from electricity in China and their decoupling relationship with economic development. However, the above studies lacked in-depth consideration of the regional differences and their causes mentioned above. A review of the literature shows that most studies on regional differences are still at the level of overall carbon emissions, and methods such as coefficient of variation, Gini coefficient and Theil index are usually used to measure regional differences (Li and Li, 2010; Clarke *et al.*, 2011; Yang and Liu, 2012; Dong *et al.*, 2014). However, the above literature all focus on carbon emission data, and a few pieces of literature focus on the power industry. In addition, Zhou *et al.* (2019) and Liu *et al.* (2019) used the Dagum Gini coefficient method to further clarify the source of regional differences in carbon emissions, to seek a more reasonable and effective regional carbon reduction path. To this end, this paper draws on the above ideas and conducts an in-depth analysis of regional differences in carbon emissions from electricity (Li and Wang, 2019).

The above literature lays a good foundation for our research on carbon emissions from electricity and provides new ideas for subsequent in-depth research. To this end, this paper calculates the panel data of electricity carbon emissions from 1997 to 2019 in 30 provinces in Mainland China based on the principle of "shared responsibility between the production side and the consumption side," and uses CO_2 intensity of power industry as an indicator to analyze its regional differences and its causes. The main contributions or innovations of this paper are as follows: first, based on the principle of "shared responsibility between the production side and the consumer side," the total amount of electricity carbon emissions from 1997 to 2019 was completely measured, and the carbon emission intensity of electricity was used as an indicator to study. Second, the Gini coefficient method is based on subgroup decomposition proposed by Dagum. It not only depicts the overall regional differences in CO_2 intensity of power industry, but also decomposes regional differences into three parts: interregional, intra-regional and hyper-variable density, to deeply study the causes of regional differences. Third, considering the influence of spatial factors on the convergence of power carbon emission intensity, a variety of different spatial weight matrices are selected. Based on the β-convergence theory from both absolute and conditional perspectives, we dig deeper into the spatial convergence of electricity carbon emission intensity across the country and the three regions.

3. Methodology

3.1 Calculation method of CO_2 in power industry

3.1.1 Calculation method of CO_2 emissions in power industry. Based on the principle of "shared responsibility between production and consumption" to measure the carbon emissions of provincial electricity, the determination of the shared proportion of carbon emissions at the production end between production and consumption is the key. According to previous research, some scholars take the ratio of added value to net output (Lenzen *et al.*,2007), and some scholars take half of each according to the symmetry theory (Rodrigues *et al.*, 2006). This paper considers the technical differences between regional power generation and the operability of actual calculation, so the sharing ratio is determined by considering the power generation efficiency and power consumption efficiency of each province. Given the availability of data, this paper simplifies the transaction and dispatch of electricity between regions. The specific calculation equation is as follows:

$$\begin{cases} \theta_n = \frac{1}{2}(1 - K_n) + \frac{1}{2}S_n \\ K_n = \frac{ECV}{EEV_n} \\ EEV = \frac{\sum_i FC_{i,n} * R_i}{TP_n} \\ S_n = \frac{GDP_n / YP_n}{B_n} \end{cases} \tag{1}$$

Among them, K_n represents the power generation efficiency of the production end in the nth year, that is, the ratio of the electric power equivalent value to the equivalent value. S_n represents the power consumption efficiency of the consumer in the nth year, which is the greater the proportion of the consumer end in the region where the unit power consumption produces a larger gross domestic product (GDP) value. θ_n represents the proportion of carbon emissions borne by the power production side of each province in the nth year. ECV represents the equivalent value of electricity, which is generally 0.1229 kgcc/kWh. EEV_n represents the equivalent value of electricity in each province in the nth year. $FC_{i,n}$ represents the consumption of fossil fuel i in the thermal power generation structure of each province in the nth year. R_i represents the converted standard coal coefficient of this type of fossil fuel i. TP_n represents the thermal power generation of each province in the nth year. GDP_n and YP_n represent the GDP and electricity consumption of each province in the nth year, respectively. B_n is the maximum value of GDP_n/YP_n among the 30 provinces in the nth year.

Given the situation of external transmission and transfer of provincial power, it is necessary to consider the carbon emissions borne by the provincial power producers and the carbon emissions borne by the consumers. Therefore, the calculation equation of provincial electricity CO_2 emissions is:

$$PC = EP + EC \tag{2}$$

Among them, EP represents the carbon emissions borne by the provincial power producers and EC represents the carbon emissions borne by the provincial power consumers.

The carbon emission borne by the provincial power production side is obtained by multiplying the direct carbon emission of electricity by the proportion of the production side:

$$EP_n = \theta_n * EM_n \tag{3}$$

Among them, EP_n represents the carbon emission borne by the power generation end in the nth year, EM_n represents the direct carbon emission of the power in the nth year and θ_n is the same as equation (1). Calculated by the following equation:

$$EM_n = \sum_i AC_i * EF_i \tag{4}$$

Among them, AC_i represents the consumption of fuel i in the process of electricity-to-fuel production, and EF_i represents the CO_2 emission factor of fuel i.

The carbon emission borne by the provincial power consumption end consists of two parts: the carbon emission of power consumption of the power grid and the carbon emission of the power consumption of other provincial power grids:

$$EC_n = ECI_n + ECO_n \tag{5}$$

Among them, EC_n represents the carbon emissions borne by the power consumer in the nth year. ECI_n represents the carbon emissions from consumption of electricity produced in the province in the nth year. ECO_n represents the carbon emissions from the consumption of other provincial power grids net transferred to the province in the nth year.

- Accounting of carbon emissions from consumption of electricity produced in the province.

Based on the law of conservation of production and consumption, the total power generation of the provincial power grid is equal to the power consumption in the provincial power grid plus the power consumption transferred out to other provincial power grids. (Constrained by data availability, this paper ignores network loss.) Therefore, the carbon emission factor of the power consumption of the provincial power grid is equal to the carbon emission borne by the consumers of the provincial power grid divided by the total power generation of the provincial power grid (including the total power generation of all power generation methods):

$$EFIC_{nk} = \frac{(1 - \theta_{nk}) * EM_{nk}}{GE_{nk}} \tag{6}$$

Among them, $EFIC_{nk}$ represents the carbon emission factor of electricity consumption in province k in the nth year. $(1 - \theta_{nk})$ represents the emission share of the electricity consumption side of province k in the nth year. EM_{nk} represents the direct emissions from electricity in province k in the nth year. GE_{nk} represents the total power generation in province k in the nth year.

The consumer end consumes the province's electricity production carbon emissions, which is the province's electricity generation minus the product of the electricity consumption exported to other electricity provinces and the electricity consumption carbon emission factor:

$$ECI_{nk} = EFIC_{nk} * (GE_{nk} - EO_{nk}) \tag{7}$$

Among them, EO_{nk} represents the total amount of electricity net transferred from province k to other provincial power grids in the nth year; $(GE_{nk} - EO_{nk})$ represents the total electricity consumption of province k in the nth year.

- Calculation of carbon emissions from consumption of net transfer into power grids in other provinces.

In the nth year, the carbon emission consumption ECO_{nk} of the province k from other provincial power grids transferred to the province's electricity is calculated as follows:

$$ECO_{nk} = \frac{\sum_{g \neq k} \left((1 - \theta_{ng}) * EM_{ng}\right)}{\sum_{g \neq k} GE_{ng}} * ER_{nk} \tag{8}$$

Among them, $\sum_{g \neq k} GE_{nk}$ represents the total power generation of other provinces except province k, and ER_{nk} represents the net electricity transferred from other provinces to province k in the nth year.

3.1.2 Calculation method of CO_2 intensity of power industry. CO_2 intensity of power industry EI_g refers to the carbon emissions generated by the electricity consumed per unit of GDP, that is, the ratio of electricity carbon emissions PC_n to GDP. As an economic indicator of green electricity consumption and low-carbon development, it can comprehensively reflect the relationship between economic growth, power energy and the ecological environment. Its calculation equation is:

$$EI_g = \frac{PC_n}{GDP} \tag{9}$$

3.2 Dagum Gini coefficient and its decomposition method

In 1997, Dagum proposed the decomposition method of the Gini coefficient to study regional differences, which reflected relatively more information and brought many conveniences to scholars, so it has been widely used in many fields (Dagum, 1997; Liu *et al.*, 2013). The equation for calculating the total Gini coefficient is shown in (10):

$$G = \frac{\sum_{j=1}^{k}\sum_{h=1}^{k}\sum_{i=1}^{n_j}\sum_{r=1}^{n_h}|y_{ji} - y_{hr}|}{2\overline{Y}n^2} \tag{10}$$

Among them, y_{ji} and y_{hr} represent the carbon emission intensity level of electricity in the j region and h region, respectively, n is the number of 30 provinces, n_j and n_h represent the number of provinces within the j region and h region, respectively, k represents the number of divided regions and $\overline{Y}$ represents the national electricity. The overall average level of carbon emission intensity, $\overline{Y_i}$ represents the average carbon emission intensity of electricity in region i.

The Dagum Gini coefficient can be decomposed into the contribution of intra-regional differences G_w, the contribution of interregional differences G_{nb} and the Intensity of Trans variation between subgroup G_t according to the subgroup decomposition method. These three represent the intra-regional gap, the interregional gap and the degree of cross-group crossover of variables (Liu *et al.*, 2019):

$$\overline{Y_1} \leq \overline{Y_h} \leq \ldots \overline{Y_j} \leq \ldots \overline{Y_k} \tag{11}$$

$$G = G_w + G_{nb} + G_t \tag{12}$$

$$G_{jj} = \frac{1}{2\overline{Y}n_j^2}\sum_{i=1}^{n_j}\sum_{r=1}^{n_j}|y_{ji} - y_{jr}| \tag{13}$$

$$G_w = \sum_{j=1}^{k} G_{jj}p_js_j \tag{14}$$

$$G_{jh} = \frac{\sum_{i=1}^{n_j} \sum_{r=1}^{n_h} |y_{ji} - y_{hr}|}{n_j n_h \left(\overline{Y_j} + \overline{Y_h} \right)} \tag{15}$$

$$G_{nb} = \sum_{j=2}^{k} \sum_{h=1}^{j-1} G_{jh}(p_j s_h + p_h s_j) D_{jh} \tag{16}$$

$$G_t = \sum_{j=2}^{k} \sum_{h=1}^{j-1} G_{jh}(p_j s_h + p_h s_j) \left(1 - D_{jh} \right) \tag{17}$$

$$D_{jh} = \frac{d_{jh} - p_{jh}}{d_{jh} + p_{jh}} \tag{18}$$

$$d_{jh} = \int_0^{\infty} dF_j(y) \int_0^{y} (y - x) dF_h(x) \tag{19}$$

$$p_{jh} = \int_0^{\infty} dF_h(y) \int_0^{y} (y - x) dF_j(x) \tag{20}$$

In the above equation, G_{jj} represents the Gini coefficient within the j region, and G_{jh} represents the Gini coefficient between the j and h regions. Among them, $p_j = n_j/n$, $s_j = n_j \overline{Y}_j / n\overline{Y}$, $j = 1, 2, 3, \ldots, k$, D_{jh} represents the relative influence degree of relative CO_2 intensity of power industry among $j(h)$ regions. d_{jh} represents the difference in the contribution rate of CO_2 intensity of power industry among regions $j(h)$. p_{jh} represents the hypervariable first moment. In other words, d_{jh} and p_{jh} denote the mathematical expectation of all sample values of $y_{ji} - y_{hr} > 0$ and $y_{hr} - y_{ji} > 0$ in regions j and h, respectively.

4. Data processing and empirical analysis

4.1 Data Source and variable selection

When calculating the carbon emissions of interprovincial electricity, the equation for calculating the CO_2 emission factor EF_i of the ith fuel is:

$$EF_i = NVC_i \times CC_i \times O_i \times 44/12 \tag{21}$$

Among them, NCV_i, CC_i and O_i represent the average low-level calorific value, carbon content per unit calorific value and carbon oxidation rate of the ith fuel, respectively. In the calculation, we adopted the latest research results of Shan *et al.* (2018) and simplified the fuel types with reference to the above fuel parameters:

- The briquette and coal gangue are classified into one category, represented by coal gangue.
- Blast furnace gas, converter gas and coke oven gas are grouped into one category and represented by coke oven gas.

- Petroleum coke and other petroleum products are uniformly represented by other petroleum products.

Table 1 presents the different fuel parameters and CO_2 emission factors.

Based on the availability of data, this paper estimates the electricity carbon emissions and electricity carbon emissions intensity of 30 provinces in China (excluding Tibet, Hong Kong, Macau and Taiwan) from 1997 to 2019. To ensure the uniformity and accuracy of the data, the relevant data in the energy balance sheets of each province and the GDP of each province used in the calculation process are all from the easy professional superior data platform (www.epsnet.com.cn), and the GDP is adjusted to the real GDP with 2000 as the base period.

4.2 Calculation results and analysis of CO_2 intensity of power industry

Given the huge amount of data, Table 2 only lists the estimated value of electricity CO_2 intensity starting from 1997 to examine the distribution of China's CO_2 intensity of power industry from 1997 to 2019. Overall, the carbon emission intensity of electricity in most provinces and cities shows a downward trend year by year. Among them, Beijing, Tianjin, Liaoning, Jilin, Heilongjiang, Shanghai, Henan, Hubei, Chongqing, Yunnan, Qinghai and other provinces have dropped by more than 50%. This shows that in recent years, with the increase of carbon emission pressure, while the formulation and promotion of the national carbon emission reduction strategic plan, local governments actively responded to the call and formulated corresponding power emission reduction policies, thus making the power industry in most provinces have excellent emission reduction effects. Judging from the changing trend of the national average value, the carbon emission intensity of China's electricity shows an inverted "N"-shaped fluctuation, but the overall trend has dropped by 32.79%. It is not difficult to find that the peak in 2007 and the downward trend after that may be related to a series of development strategies and implementation measures formulated by China to reverse the problem of high carbon emissions. For example, in 2007, China's State Council, National Development and Reform Commission and local governments established the Leading Group on Climate Change and Energy Conservation and Emission Reduction, the

Fuel category	NCV_i ($10^{-2}J/kg$ or $10^{-2}J/m^3$)	CC_i (kgC/GJ)	O_i /	CO_2 emission factor ($kgCO_2/k$ or $kg\ CO_2/m^3$)
Raw coal	0.21	26.32	0.93	1.8865
Clean coal	0.26	26.32	0.93	2.3357
Other coal washing	0.15	26.32	0.93	1.3475
Coal gangue	0.18	26.32	0.93	1.6170
Coke	0.28	31.38	0.93	2.9989
Coke oven gas	1.61	21.49	0.99	1.2571
Other gas	0.83	21.49	0.99	6.4806
Other products	0.28	27.45	0.93	2.6233
Crude	0.43	20.08	0.98	3.1054
Gasoline	0.44	18.9	0.98	2.9909
Kerosene	0.44	19.6	0.98	3.1017
Diesel fuel	0.43	20.2	0.98	3.1240
Fuel oil	0.43	21.1	0.98	3.2632
Other petroleum products	0.51	17.2	0.98	3.1549
Liquefied petroleum gas	0.47	20	0.98	3.3808
Refinery dry gas	0.43	20.2	0.98	3.1240
Natural gas	3.89	15.32	0.99	2.1653

Table 1. Carbon emission factors (EF) and fraction of carbon oxidized (O)

Province \ Year	1997	2007	2019	Increase
Beijing	692.33	409.87	197.46	−71.47922794
Tianjin	1,221.16	933.99	552.67	−54.74230426
Hebei	1,721.36	1,616.25	1,383.31	−19.63838176
Shanxi	3,302.71	3,182.47	2,447.54	−25.89308282
Inner Mongolia	2,824.61	3,553.54	2,992.91	5.958266567
Liaoning	1,688.48	1,146.68	776.73	−53.99806841
Jilin	1,894.54	1,394.90	821.62	−56.63231196
Heilongjiang	1,990.72	1,059.09	597.95	−69.96314124
Shanghai	1,024.05	620.39	320.64	−68.68878504
Jiangsu	1,125.78	1,038.08	628.22	−44.19727503
Zhejiang	908.37	942.00	498.04	−45.17224961
Anhui	1,314.59	1,134.73	913.04	−30.54535856
Fujian	359.47	656.65	391.98	9.045109149
Jiangxi	872.47	930.82	623.01	−28.59181036
Shandong	1,121.87	1,253.66	895.11	−20.21313159
Mean	1,404.41	1,332.98	995.03	−32.7922972%
Henan	1,549.93	1,482.17	643.21	−58.50090586
Hubei	960.49	753.97	413.44	−56.95553396
Hunan	577.27	686.72	349.64	−39.43222963
Guangdong	760.12	743.94	402.65	−47.02771676
Guangxi	628.65	801.62	777.40	23.66191172
Hainan	409.41	662.83	498.70	21.80873871
Chongqing	937.22	808.58	361.42	−61.43661661
Sichuan	1,094.30	800.22	268.03	−75.5069566
Guizhou	1,758.53	2,925.83	1,201.34	−31.68525636
Yunnan	856.12	1,419.90	242.45	−71.67980327
Shaanxi	1,801.80	1,448.07	992.48	−44.91713949
Gansu	1,784.14	1,581.00	976.45	−45.27042564
Qinghai	1,906.87	1,522.66	518.61	−72.80327942
Ningxia	3,711.82	6,444.75	5,444.80	46.68799577
Xinjiang	1,333.04	1,214.46	2,719.94	104.0400542

Table 2. China's power industry carbon emission intensity from 1997 to 2019

Climate Change Department and the Climate Change Office, respectively, and subsequently issued the "*Notice on Carrying out the Pilot Work of Carbon Emissions Trading*," "*The 12th Five-Year Plan*," *Comprehensive Work Plan for Energy Conservation and Emission Reduction* and "*Interim Measures for the Administration of Voluntary Greenhouse Gas Emission Reduction Trading*" and other policy documents. It is particularly noteworthy that by 2013, China had successfully established seven pilot carbon markets in Beijing, Shanghai, Tianjin, Hubei, Guangdong, Shenzhen and Chongqing. And in 2019, it further promoted the establishment and development of the national electricity carbon market. In this way, the downward trend of CO_2 intensity of power industry will continue in the future. However, the carbon emission intensity of electricity in four provinces including Inner Mongolia, Guangxi, Xinjiang, Ningxia, Hainan and Fujian has increased. In 2019, the carbon emission intensity of electricity in Ningxia and Xinjiang was as high as 5,444.8 kg/10,000 yuan and 2,719.94 kg/10,000 yuan, with an increase of 46.69% and 104.04%. The country must pay attention to the relatively backward northwest region with high emission and high growth economy, make it a key area for emission reduction tasks and further accelerate the layout of new energy industries, introduce advanced power energy-saving technologies and transform and upgrade traditional industries with high energy consumption and low efficiency, to effectively curb the growth of CO_2 intensity of power industry.

4.3 Regional difference analysis

4.3.1 Differential description of China's CO_2 intensity of power industry. The preceding article examines the electricity emission intensity in China from 1997 to 2019, and finds that there are significant regional differences in CO_2 intensity of power industry. To further verify the above differences, this paper compares and analyzes the average carbon emission intensity of electricity in the three regions of the east, middle and west during the sample period. As is evident from Figure 1, there are significant differences between the three major regions, East, China and West. Among them, the carbon emission intensity in the eastern region (813 kg/10,000 yuan) is far lower than the national level (1,222 kg/10,000 yuan). The central and western regions are higher than the national level. It shows that significant progress has been made in the emission reduction work of the electric power industry in the eastern region, while there is still a lot of room for improvement in the emission reduction work of the electric power industry in the central and western regions. To understand the differences between regions more clearly, the average difference between the eastern and the national and central and western regions from 1997 to 2019 was plotted, as shown in Figure 2. Overall, the average difference between the eastern and the national, central and western power carbon emission intensity showed an inverted "N" shape in the sample period. Specifically,

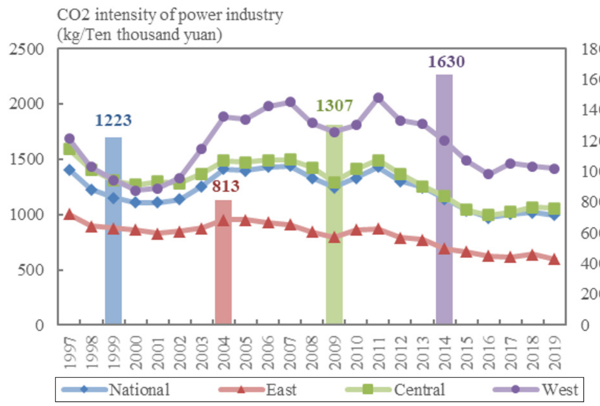

Figure 1.
Average value of CO_2 intensity of power industry in the three regions

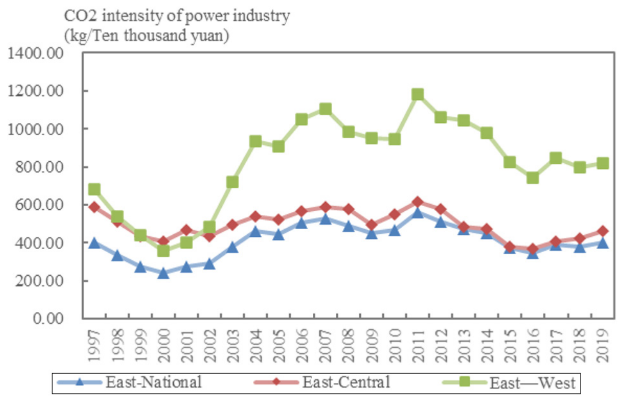

Figure 2.
Evolution of the gap in CO_2 intensity of power industry in three regions

between 1997 and 2000, the differences in all regions gradually decreased. Among them, the smallest in 2000 were 242.55, 408.06 and 355.09 kg/10,000 yuan. Then, the overall increase from 2001 to 2011. Among them, it was the largest in 2011, expanding to 561.03, 618.5 and 1182.88 kg/10,000 yuan. Then, it continued to decline from 2012 to 2019. In 2019, it reached 399.98, 462.93 and 818.9 kg/10,000 yuan, respectively. This reflects that in recent years, the difference between the central and western regions and the economically developed regions in the east has been on the decline, and the power industry in the western region has a more significant emission reduction effect. It reflects that in recent years, the difference between the central and western regions and the economically developed regions in the east has been on the decline, and the power industry in the western region has a more significant emission reduction effect.

4.3.2 Regional differences and source analysis. To measure the regional differences of China's power CO_2 intensity scientifically and comprehensively, this paper not only divides the 30 provinces into three regions according to the above geographical space but also divides them according to the level of economic development (per capita GDP)[1]. At the same time, this paper uses the Dagum Gini coefficient and its decomposition method to decompose the regional differences in CO_2 intensity of power industry in each region from 1997 to 2019. The calculation results are shown in Figure 3. It is not difficult to see that from 1997 to 2019, the total Gini coefficient of my country's CO*2* intensity of power industry increased from 0.294 to 0.458, which indicates that the overall difference in CO_2 intensity of power industry is increasing. Next, we deeply analyze the intra-regional gaps, interregional gaps and their contributions in the distribution of CO_2 intensity of power industry.

From the perspective of intra-regional Gini coefficients, according to Figure 4, the gap in the eastern region is the smallest, followed by the western region, and the Gini coefficients of the two regions remain around 0.22 and 0.33, respectively. The biggest gap is in the central region, which has a significant upward trend from 1997 to 2019, with a growth rate of 123.34%. It shows that the difference in carbon emission intensity of electricity in the eastern and western regions is relatively small and remains stable in general, while the imbalance in the western region is becoming more and more significant. Comparing the Gini coefficient of the level of economic development, the gap in developed regions is the smallest, which has an overall volatility trend similar to the eastern region. But it has slightly decreased by 15.27%. Overall, the differences within regions with relatively backward and moderate development levels showed an upward fluctuation, with an increase of 94.99% and 40.73%. Among them, the intra-regional gap in the lagging regions fluctuates the most. It shows that the improvement of the internal economic level of the developed regions is conducive to the reduction of the overall strength within them. However, how to narrow the gap between relatively backward

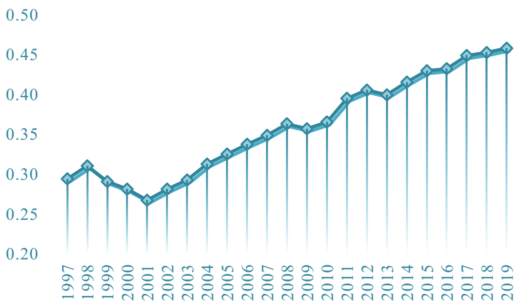

Figure 3.
Regional differences

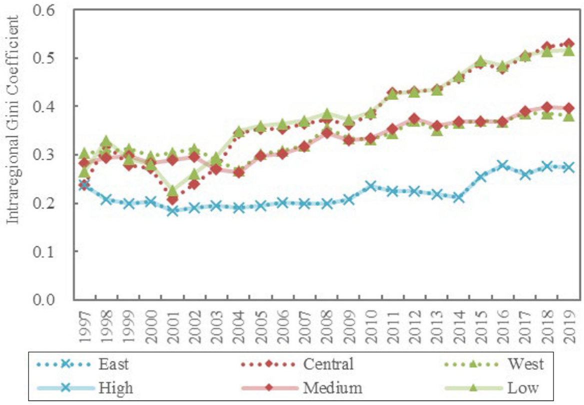

Figure 4.
Intra-regional differences

regions and regions with moderate development levels? It will be the focus in the future to shrink the overall regional differences.

Combined with Figure 5, we further analyze the differences between regions. From the Gini coefficient of geographic space, the Gini coefficient between the eastern and central regions is the smallest, and the Gini coefficient in the eastern and western regions is the largest. The former's Gini coefficient was only 18.14%, whereas the latter's increase was as high as 74.85%. Comparing the Gini coefficient of economic development level, the difference between regions with high and middle development levels is the smallest, whereas the difference between regions with high and low levels of development is the largest. The fluctuations between the two showed a significant upward trend, but the specific range was different, which were 21.41% and 70.62%, respectively. It shows that the difference between the carbon emission intensity of electricity in economically developed regions and those in relatively backward regions is slowly widening. Considering the actual situation of the power industry, with the increase of environmental constraints, industries in the developed eastern regions in the process of low-carbon green transformation and upgrading may lead to the transfer of many high-energy-consuming industries to the central and western regions.

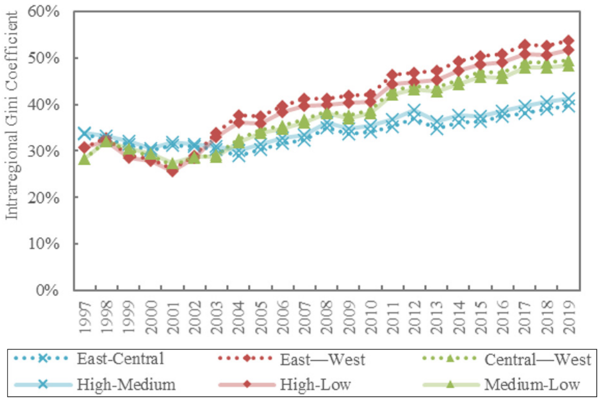

Figure 5.
Interregional differences

Figure 6 describes the contribution of regional differences in China's electricity CO_2 intensity, to find out the source and cause of the difference, and provide a theoretical basis for further narrowing the difference and formulating emission reduction policies. During the sample investigation period, the contribution rate of intra-regional differences in the three major regions of East, China and West has been stable at around 29%. However, the contribution rates of hypervariable density and inter-regional disparity fluctuated significantly, and the two trends were completely different. Specifically, the former's contribution rate first decreased and then increased, whereas the latter's contribution rate first increased and then decreased. On the whole, both of them showed an upward trend, and the contribution rate of the gap between regions was greater than that of the hypervariable density. After 2015, the contribution rate of hypervariable density and the regional disparity has stabilized at around 25% and 54%. Therefore, the intra-regional differences did not further widen, whereas the interregional gaps and cross-group crossovers increased overall. However, overall, the degree of cross-group crossover is the main source of the regional disparity in my country's electricity carbon emission intensity. Comparing the contribution rate of economic development level, the contribution rate of regional disparity and hypervariable density is consistent with the fluctuation trend of the two in geographical space, and the contribution rate of regional differences is greater than that of hypervariable density. It is worth pointing out that the contribution rate of hypervariable density continued to decline, whereas the contribution rate of regional differences continued to increase, and the change was stable after 2004. It shows that the difference between regions with different economic levels comes from the contribution of hypervariable density, that is, regions with higher CO_2 intensity of power industry appear in economically developed regions. However, regions with low levels of economic level appear regions with low levels of electricity carbon emissions, which leads to the dominance of hypervariable density.

5. Research conclusions and policy recommendations

To achieve green emission reduction in the power industry under the "30·60" dual carbon goal, based on panel data from 1997 to 2019, this paper selects the power carbon emission intensity as an indicator of green and low-carbon power, uses the Dagum Gini coefficient decomposition method to investigate its regional differences and their causes and build a spatial econometric model to test the convergence of CO_2 intensity of power industry. The main conclusions are as follows:

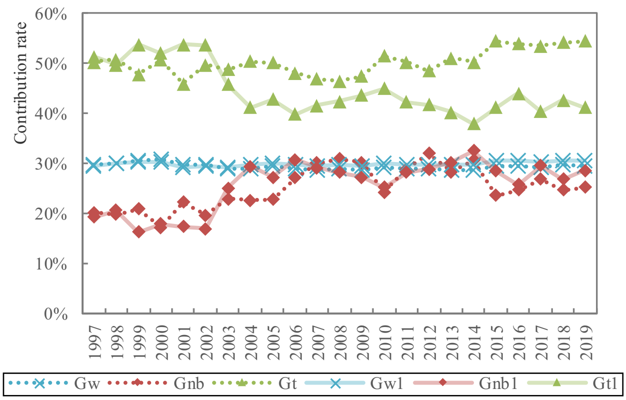

Figure 6.
Contribution of regional differences

- The overall difference in electricity emission intensity in China is significant, and most provinces and cities show a downward trend year by year. From the perspective of geographical space distribution, there is an imbalance between the three major regions, the east, the middle and the west, and the eastern region has the lowest power carbon emission intensity.
- The decomposition results of the Dagum Gini coefficient show that the difference in the carbon emission intensity of electricity shows an expanding trend. From the perspective of geographical space and economic development level, the three regions were investigated respectively. From a geospatial perspective, the difference in CO_2 intensity of power industry within the eastern region is the smallest, whereas the difference between the eastern and central regions is the smallest. And the degree of cross-group crossing is the main source of its regional disparity. From the perspective of economic development level, the differences among regions in economically developed regions are the smallest, and the differences among regions with high and medium development levels are the smallest. However, the differences among regions in the level of economic development are mainly due to the contribution of hypervariable density.

Given the above conclusions, this paper can draw the following suggestions:

First, strengthen cooperation and exchanges to achieve balanced development. The Chinese Government should speed up the green and low-carbon development of the overall power industry. Provinces with higher CO_2 intensity of power industry should strengthen cooperation with neighboring provinces with lower CO_2 intensity, and form an effective cooperation and exchange mechanism to narrow the differences between the eastern and western regions. Provinces with low CO_2 intensity of power industry should continue to maintain steady development and drive the development of their surrounding areas to reduce the carbon emission intensity of electricity across the country.

Second, improve the market mechanism and formulate differentiated policies. Facing the increasingly complex international low-carbon situation. The government needs to give full play to the role of market management and supervision and strengthen the construction of the carbon emission rights market in the power industry. By regulating the trading methods of various trading entities, the optimal allocation of carbon emission rights is promoted, thereby reducing the cost of emission reduction. In addition, according to the carbon emission levels of the power industry in each region, it is necessary to formulate different emission reduction policies according to local conditions, which will also help to achieve the green transformation of the economy in each region.

Third, clarify the main responsibilities and lead green energy use. Recently, with the large-scale integration of renewable energy into the grid, the proportion of renewable energy in electricity consumption has also increased. However, in the process of clean energy development, all provincial-level regions have neglected the system's inherent absorptive capacity and market demand. Therefore, it is necessary to subdivide the responsibilities of each market entity and guide users to use green energy while improving the local consumption capacity. At the same time, the construction of the carbon quota system should be accelerated with the guidance of climate policy tools such as electricity carbon emissions trading. On the one hand, it promotes the clean and efficient transformation of power generation enterprises in terms of both total amount and quality. On the other hand, manufacturers are encouraged and guided to participate in green certificate transactions to achieve a low-carbon energy transition.

Note

1. According to per capita GDP, it is divided into three regions: high, medium and low; developed regions: Shanghai, Tianjin, Liaoning, Beijing, Jiangsu, Zhejiang, Fujian, Guangdong, Shandong and Heilongjiang; medium developed regions: Hubei, Jilin, Hebei, Chongqing, Inner Mongolia, Hainan, Xinjiang, Hunan, Henan and Sichuan; and relatively backward areas: Anhui, Qinghai, Shaanxi, Shanxi, Jiangxi, Guangxi, Ningxia, Yunnan, Gansu and Guizhou.

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