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Research on the influencing factors of carbon emissions in the power industry under the "dual carbon" goal

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Abstract: *In order to promote the achievement of the "double carbon" target, a log-average weighting decomposition method was used to analyze the factors influencing carbon emissions in the power sector, which accounts for the highest carbon emissions in China. The main factors in the power sector, namely the share of energy, coal consumption in power generation, the ratio of thermal power generation to total power generation, the ratio of electricity generation to electricity consumption and total power consumption, were analyzed by the modified Kaya constant equation and the Divisia decomposition method, and the positive driving effect of total power consumption on carbon emissions in the power sector was found to be the strongest. The negative driving effect of coal consumption and the proportion of thermal power generation to total power generation on carbon emissions in the power sector is obvious, and the negative driving effect of the energy share and the proportion of power generation to power consumption on carbon emissions in the power sector is very weak.*

Keywords: *"dual carbon" goal, power industry, carbon emissions, Log-average weighting decomposition method*

1. Introduction

After decades of rapid development, China's gross domestic product (GDP) has jumped to the second highest in the world, its total trade volume to the first place and its total manufacturing output to the first place in the world. However, China was also the largest emitter of carbon dioxide in 2005. emissions by 2020, accounting for approximately 30% of global CO2 emissions. In September 2020, General Secretary Xi Jinping announced at the 75th UN General Assembly General Debate that China would increase its autonomous contribution to the fight against climate change, so that with stronger measures and policies, China will strive to reach a peak in CO2 emissions by 2030 and work towards a peak by 2060. emissions to peak by 2030 and strive to achieve carbon neutrality by 2060. Based on the above background, this paper studies the impact of the carbon trading market on the electricity market under the background of "double carbon". Firstly, the LMDI decomposition method is used to analyze the power generation side and the power consumption side that need to be managed in order to achieve China's carbon emission reduction target, and it is concluded that vigorously developing low-carbon emission energy and clean energy on the power supply side, reducing the proportion of coal-fired power generation, accelerating the flexible transformation of coal-fired power generation, and building a diversified clean energy power generation system are still powerful graspers for achieving "double carbon".

2. "Dual Carbon" targets and the current status of China's carbon emissions

2.1 The introduction of the 'dual carbon' target at China

In September 2020, China formally proposed the "dual carbon" target, promoting the realization of the "dual carbon" target has become a national strategy, green and low carbon development has been the current era of development undertones [1], a comprehensive and objective understanding and promotion of carbon peaking and carbon neutral work is essential. This is in line with the concept of sustainable development in China, which is both an environmental issue and a quality development issue, and will

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be a systemic change for the environment and the economy. "The 14th Five-Year Plan" period is a period in which China's economy is entering a phase of high-quality development, where the industrial structure continues to be optimized, the industrial base is advanced and the level of modernization of the industrial chain is rising, and the future will also see steady growth in the long term. As can be seen from Figure 1, in 2020, China's power sector accounts for 40% of total carbon emissions, making it the largest sector, and the power sector will be the first sector to be included in the national carbon market [2,3]. In this new phase of the "dual carbon" target, new requirements and challenges have been put forward for the development of the power industry[4] , which requires strong measures and more effective policies in the areas of energy production and energy use in the power industry[5] .

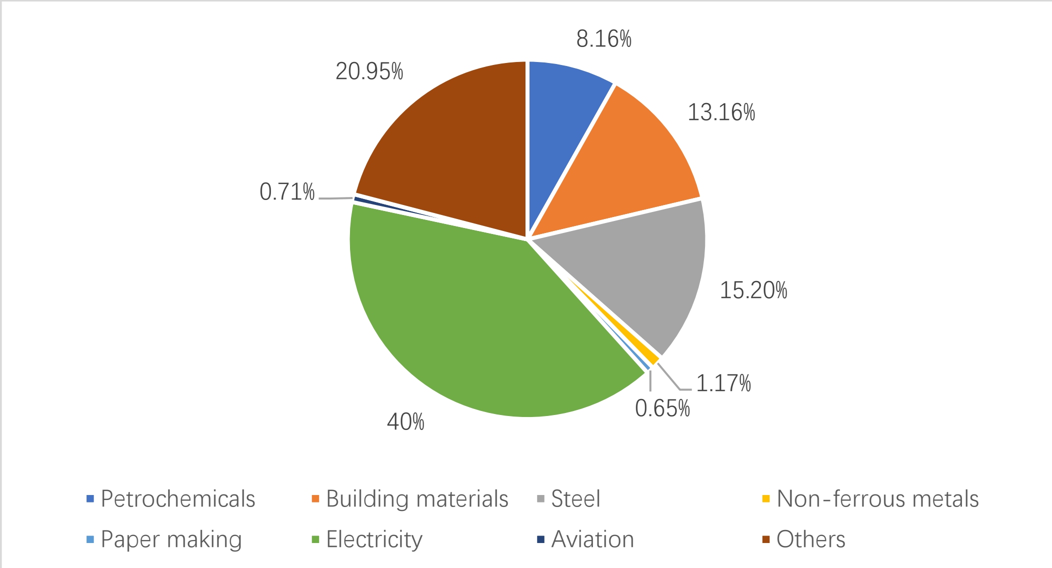

Figure 1 Total carbon emissions from the eight sectors in 2020

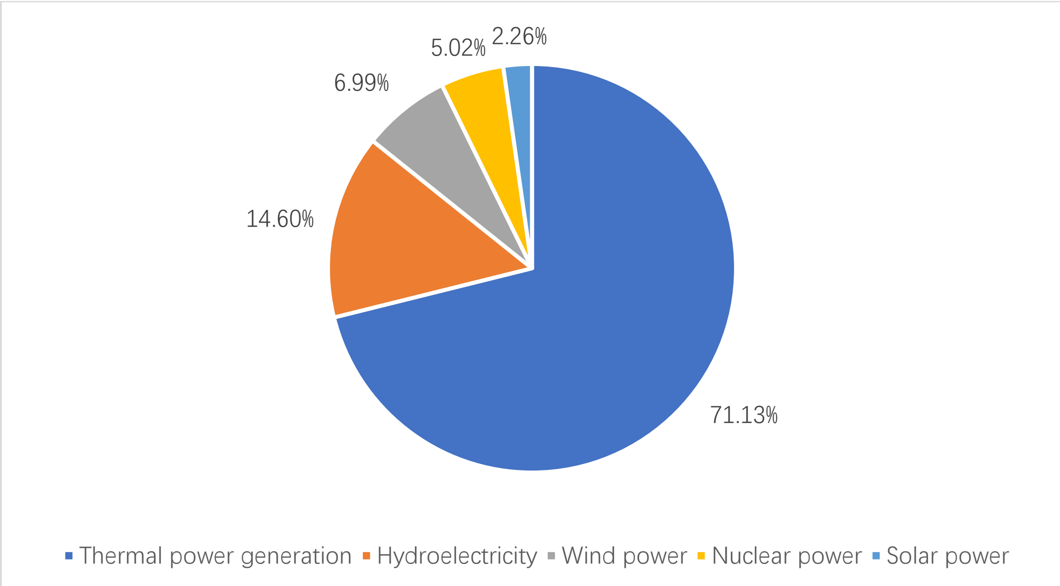

Figure 2 China's electricity generation mix in 2021

As can be seen from Figure 2, thermal power generation in China will account for 71.13% in 2021, much higher than hydroelectric power generation (14.6%), wind power generation (6.99%), nuclear power generation (5.02%) and solar power generation (2.26%). It can be seen that thermal power generation is still the main form of power generation in China, and the installed capacity of coal power generation in China is large, and its service time is relatively short, and the carbon dioxide emissions from power generation are high. The power sector accounts for the highest proportion of China's total carbon emissions, and to promote the "double carbon" target, it will be necessary to fundamentally promote the energy transition, actively encourage cleaner electricity production, and increase the installed capacity of photovoltaic and wind power [6,7]. The study of the factors influencing CO2 emissions in the power sector is of great theoretical and practical importance for the formulation of targeted carbon reduction policies.

2.2 Literature review

There are currently three main types of methods for analyzing the factors influencing carbon emissions: the first is the SDA method, or structural decomposition analysis; the second is the IDA method, or Index decomposition analysis; and the third is the PDA method, or production decomposition analysis.

The SDA model of carbon emissions plays a fundamental role in the analysis and research of the decomposition of carbon emission factors. The structural decomposition analysis (SDA) is based on input-output tables, and the model is constructed by considering the input-output relationship of each industrial sector in China, taking into account the characteristics of each industry, inter-industry linkages and each trade linkage, so as to obtain the direct and indirect drivers [8-10]. This method requires a high level of data precision, and as input-output tables are generally compiled once every five years, the decomposition results obtained from this model will not be a continuous time series of drivers.

Index Decomposition Analysis (IDA) requires less data and is less dependent, and allows for a continuous decomposition of impact factors in time series and allows for decomposition of other factors such as structure, size and intensity according to time series variation [11-13]. However, the IDA method does not have the ability to decompose production processes, and production processes involving technical aspects such as technical efficiency do not have the means to be included in the carbon impact factors.

The production theory decomposition analysis (PDA) method is based on data envelopment analysis (DEA), which can incorporate environmental efficiency into the decomposition analysis model considering the input-output process, so that inefficiencies can be removed from the model run to measure changes in potential emission targets and to analyze efficient emission reduction paths under efficient operation. However, PDA has some drawbacks in that the method can only increase or decrease in the same proportion when dealing with carbon emissions and desired outputs of the same study subject, which can be very different from the reality and is not very suitable for carbon emission studies in the power sector [14,15].

Based on the analysis of the above-mentioned research methods, the research on the impact factors of carbon emissions in the power industry under the "dual carbon" target, first of all, starts from the whole industry chain of power generation side - transmission side - consumption side of the power industry, and mainly studies the quantitative indicators, so the log-average weight decomposition method is used to analyze the impact factors of carbon emissions in the power industry, which provides a good basis for the proposal of policies such as carbon emission reduction in the power industry. This will provide a good basis for proposing policies to reduce carbon emissions in the power industry, so as to promote the early realization of the "dual carbon" target.

3. Research Methodology and Model Construction

3.1 Kaya's constant equation and LMDI analysis method

As this paper studies the change in carbon dioxide emissions in China's power industry, which tends to be a quantitative indicator, it can be processed based on Kaya's constant equation and using Divisia's decomposition to calculate the weights of the influencing factors by referring to the logarithmic averaging formula, thus effectively overcoming the influence of residual values, negative values and "0" values [16-18]. The LMDI factor decomposition method is based on the Divisia decomposition and improves on the log-averaging formula by decomposing the change in the target variable into the product of several influencing factors and then assigning certain weights to them to obtain the driving degree of each influencing factor on the target variable. This method is a good basis for the formulation of policy measures under the "dual carbon" target, as it helps to grasp the direction of CO2 emissions control in the power sector at a macro level.

Firstly, the factors affecting carbon emissions in the power industry are not only limited to the power production chain, but also in the power consumption chain due to the economic growth and increase in GDP per capita, which will also have a great impact on carbon emissions. Therefore, three typical energy

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sources were selected: coal, oil and natural gas, and the consumption of each energy source, total thermal power generation energy consumption, total thermal power generation, total electricity generation and total electricity consumption were expanded by Kaya's constant equation to obtain the formula (1).

$$C=\sum_{i=1}^{3}\frac{C_i}{E_i}*\frac{E_i}{E}*\frac{E}{T}*\frac{T}{G}*\frac{G}{EC}*EC \tag{1}$$

C : Total carbon emissions from the power sector

C_i : Carbon emissions from energy type i sources in electricity production (Three fossil energy sources were selected for the article, $i=1$: coal; $i=2$: oil; $i=3$: natural gas.)

E_i : Consumption of energy i in power production

E : Total thermal power generation energy consumption

T : Thermal power generation capacity

G : Total electricity production

EC : Total electricity consumption

The following decomposition of the carbon emission factors of the power sector is carried out using the additive decomposition in the LMDI decomposition method, in which the idea of the time factor of CO2 emissions from the power sector is introduced, and the amount of change in CO2 emissions from the chosen base year t to the target year T of the power sector is completely decomposed by equation (2).

$$\Delta C=\Delta C_{(C_i/E)}+\Delta C_{(E_i/E)}+\Delta C_{(E/T)}+\Delta C_{(T/G)}+\Delta C_{(G/EC)}+\Delta C_{(EC)} \tag{2}$$

ΔC : Total change in carbon emissions over time interval [t,T].

$\Delta C_{(C_i/E)}$: The amount of change in carbon emissions due to changes in fossil energy carbon emission factors over the time interval [t,T].

$\Delta C_{(E_i/E)}$: Changes in carbon emissions due to changes in the proportion of electricity generated by each energy source in the time interval [t,T].

$\Delta C_{(E/T)}$: Changes in carbon emissions due to changes in coal consumption for power generation in the time interval [t,T].

$\Delta C_{(T/G)}$: Changes in carbon emissions due to changes in the share of thermal power generation in total electricity generation over the time interval [t,T].

$\Delta C_{(G/EC)}$: Changes in carbon emissions due to changes in the ratio of electricity generation to consumption in the time interval [t,T].

$\Delta C_{(EC)}$: Changes in carbon emissions due to changes in total electricity consumption over time [t,T].

Based on the LMDI decomposition principle, the driving effects of each influencing factor on carbon emissions in the power sector can be derived from equations (3) to (8).

$$\Delta C_{(C_i/E)}=\sum_{i=1}^{3}\left(C_{i,T}-C_{i,t}\right)\Big/\left(\ln C_{i,T}-\ln C_{i,t}\right)*\ln\left(C_iE_i^{\,T}\Big/C_iE_i^{\,t}\right) \tag{3}$$

$$\Delta C_{(E_i/E)} = \sum_{i=1}^{3} \left(C_{i,T} - C_{i,t} \right) / \left(\ln C_{i,T} - \ln C_{i,t} \right) * \ln \left(E_i E^T / E_i E^t \right) \tag{4}$$

$$\Delta C_{(E/T)} = \sum_{i=1}^{3} \left(C_{i,T} - C_{i,t} \right) / \left(\ln C_{i,T} - \ln C_{i,t} \right) * \ln \left(ET^T / ET^t \right) \tag{5}$$

$$\Delta C_{(T/G)} = \sum_{i=1}^{3} \left(C_{i,T} - C_{i,t} \right) / \left(\ln C_{i,T} - \ln C_{i,t} \right) * \ln \left(TG^T / TG^t \right) \tag{6}$$

$$\Delta C_{(G/EC)} = \sum_{i=1}^{3} \left(C_{i,T} - C_{i,t} \right) / \left(\ln C_{i,T} - \ln C_{i,t} \right) * \ln \left(GEC^T / GEC^t \right) \tag{7}$$

$$\Delta C_{(EC)} = \sum_{i=1}^{3} \left(C_{i,T} - C_{i,t} \right) / \left(\ln C_{i,T} - \ln C_{i,t} \right) * \ln \left(EC^T / EC^t \right) \tag{8}$$

If the amount of change in one of the influencing factors is positive, it is a positive driver, which means that the influencing factor is contributing to the power sector's carbon emissions; if the influencing factor is negative, it is a negative driver, which means that the influencing factor is inhibiting the power sector's carbon emissions.

As there is no complete data on the carbon emissions of each energy source, this was calculated by using the carbon emission factors for each energy source and assuming that the fuels are fully combusted, and then using the amount of carbon generated from the combustion of each fossil energy source, as calculated by equations (9) to (11).

$$C_1 = 0.7476 * \frac{44}{12} * Consumption\ of\ coal\ power\ generation \tag{9}$$

$$C_2 = 0.5857 * \frac{44}{12} * Consumption\ of\ petroleum\ power\ generation \tag{10}$$

$$C_3 = 0.4483 * \frac{44}{12} * Consumption\ of\ natural\ power\ generation \tag{11}$$

Therefore, the carbon emission factors of the three selected energy sources can be considered constant at the selected time. $\Delta C_{(C_i/E)} = 0$. In the model of carbon emission influencing factors for the power industry constructed in this paper, the influencing factors involved are: the proportion of electricity generated by each energy source, coal consumption for power generation, the proportion of thermal power generation to total power generation, the proportion of power generation and consumption, and total power consumption.

4. Data and analysis

4.1 Data sources

This paper selects data on coal, oil and natural gas power generation consumption, total energy consumption, total national electricity production and total electricity consumption from 2005 to 2020, which are obtained from the China Energy Statistical Yearbook [19].

As can be seen from Figure 3, the carbon dioxide emissions from fossil energy in China's power sector, calculated from three typical fossil energy sources: coal, oil and natural gas, showed a steady increase from 2005 to 2013, during which time the economy grew rapidly and the rapid economic growth inevitably led to an increase in the amount of electricity generated. In recent years, China's economic growth rate has continued to increase, which means that the increase in the amount of energy is still putting pressure on the power sector's carbon emissions. It can be seen that from 2013 to 2015 there will be a small, but not significant, decline in carbon emissions from the power sector, after which there will also be an upward trend. After the "dual carbon" target was proposed, although the power generation structure has been adjusted, China's economic development is still very dependent on coal, coal power generation still accounts for a large part of China's power generation. China's high-carbon coal consumption is well above the world average, accounting for oil, natural gas, non-fossil energy and other low-carbon energy consumption. The share of low-carbon energy consumption, such as oil, natural gas and non-fossil energy, is well below the average of developed countries. Driven by China's "dual carbon" target, the adjustment of China's energy structure is imminent, and the adjustment of the energy structure will be of great significance to the impact of carbon emissions in the power industry. Between 2015 and 2020, the rise in fossil energy emissions from China's power sector will level off, reach a peak and decline quickly, led by low-carbon policies.

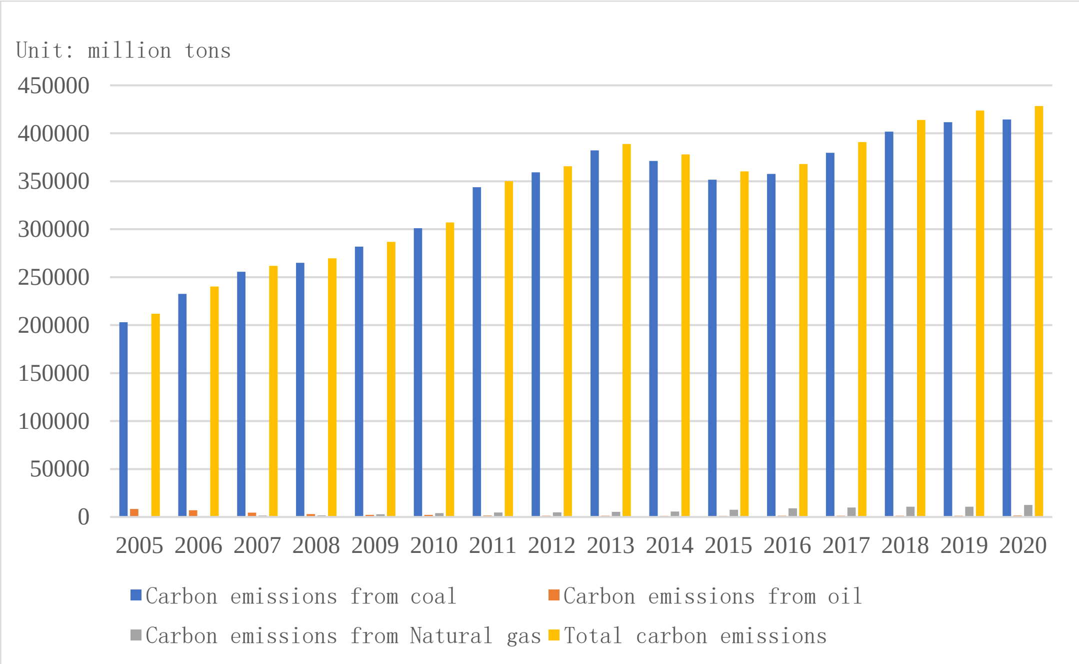

Figure 3 CO_2 emissions from fossil energy in China's power sector, 2005-2020

4.2 Data processing and analysis

Table 1 Results of year-by-year decomposition of factors influencing carbon emissions in the power sector between 2005-2020 Unit: million tons

Year	ΔC(Ei /E)	ΔC(E/T)	ΔC(T/G)	ΔC(G/EC)	ΔC(EC)	ΔC
2005-2006	529.82	-5032.97	2200.96	-16.75	30809.61	28490.67
2006-2007	316.91	-13732.52	876.05	185.62	33780.77	21426.83
2007-2008	429.02	1075.06	-8122.96	137.96	14456.75	7975.84
2008-2009	-413.97	-942.95	-624.18	-167.65	19369.29	17220.54
2009-2010	-546.29	-12135.51	-4099.31	54.83	36909.24	20182.96
2010-2011	98.55	-3185.61	8772.35	-171.04	37422.73	42936.98
2011-2012	70.06	10059.50	-14782.57	-171.35	20428.59	15604.23
2012-2013	-29.45	-9658.82	674.15	-69.25	32236.12	23152.75
2013-2014	-346.00	-12377.58	-13134.33	-9745.50	24828.41	-10775.00
2014-2015	-1401.74	-17643.86	-9282.53	9411.18	1212.47	-17704.50
2015-2016	-868.25	-4275.66	-6656.25	-36.22	19459.40	7623.02
2016-2017	-139.07	-3230.53	-1864.18	-32.92	28111.31	22844.62
2017-2018	-174.47	-4710.11	-4913.37	64.67	32764.45	23031.19
2018-2019	75.90	-265.60	-9205.51	42.64	19215.91	9863.34
2019-2020	-1117.28	-3006.00	-6479.00	-20.31	15391.98	4769.40
Total	-3516.26	-79063.16	-66640.68	-534.09	366397.03	216642.87

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Table 2 Results of year-by-year decomposition of factors influencing carbon emissions in the power sector between 2005-2020 (contribution values) Unit: %

Contribution	ΔC(Ei /E)	ΔC(E/T)	ΔC(T/G)	ΔC(G/EC)	ΔC(EC)
2005-2006	1.86%	-17.67%	7.73%	-0.06%	108.14%
2006-2007	1.48%	-64.09%	4.09%	0.87%	157.66%
2007-2008	5.38%	13.48%	-101.84%	1.73%	181.26%
2008-2009	-2.40%	-5.48%	-3.62%	-0.97%	112.48%
2009-2010	-2.71%	-60.13%	-20.31%	0.27%	182.87%
2010-2011	0.23%	-7.42%	20.43%	-0.40%	87.16%
2011-2012	0.45%	64.47%	-94.73%	-1.10%	130.92%
2012-2013	-0.13%	-41.72%	2.91%	-0.30%	139.23%
2013-2014	3.21%	114.87%	121.90%	90.45%	-230.43%
2014-2015	7.92%	99.66%	52.43%	-53.16%	-6.85%
2015-2016	-11.39%	-56.09%	-87.32%	-0.48%	255.27%
2016-2017	-0.61%	-14.14%	-8.16%	-0.14%	123.05%
2017-2018	-0.76%	-20.45%	-21.33%	0.28%	142.26%
2018-2019	0.77%	-2.69%	-93.33%	0.43%	194.82%
2019-2020	-23.43%	-63.03%	-135.85%	-0.43%	322.72%

From Tables 1 and 2, it can be seen that from 2005 to 2020, the total carbon emissions of China's power sector increased by 216,649,000 tons, of which total electricity consumption is the only positive driver, contributing 366,397,000 tons to the increase in total carbon emissions of China's power sector, while the proportion of each energy source for power generation, coal consumption for power generation, coal consumption for power generation, thermal power generation proportion to total power generation, and power generation and consumption. The proportion of coal consumption for power generation, thermal power generation as a proportion of total power generation, and power generation and consumption all played a negative role, contributing -35,162,500 tonnes, -79,063,500 tonnes, -666,406,800 tonnes and -5,340,600 tonnes respectively. The cumulative effect is shown in Figure 4, with the negative driving effect of coal consumption for power generation and the share of thermal power generation being more obvious and the negative driving effect of the share of fossil energy generation and the share of electricity generation and consumption being small.

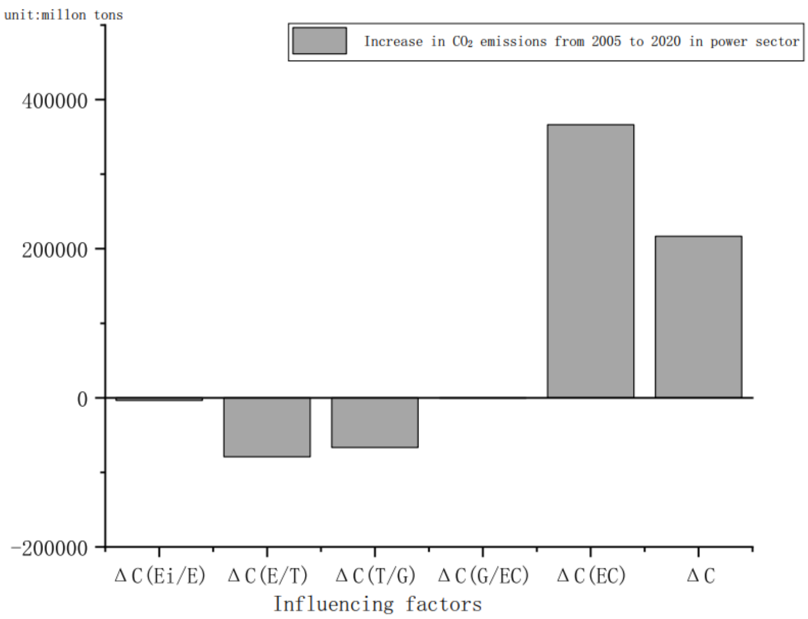

Figure 4 Cumulative effect of factors influencing carbon emissions in the power sector from 2005 to 2020

4.3 Conclusion

The following conclusions can be drawn from Tables 1 and 2 and Figure 4.

4.3.1 Positive driver: total electricity consumption

Total electricity consumption is the only positive driver among the selected influencing factors, which indicates that if carbon emissions from the power sector need to be reduced, a balance between economic development and carbon emissions needs to be found, and carbon emission reduction in the power sector should also be achieved under rapid economic development to achieve a coordinated and sustainable development of the economy and the environment. As can be seen from Figure 4, the trend of carbon emissions in the power sector is greatly influenced by the trend of total electricity consumption, which is roughly the same. The increase in population size and GDP per capita has led to a rise in total electricity consumption, which has promoted a rise in electricity generation and has led to an increase in carbon emissions as high carbon emission traditional energy sources remain the main energy source for electricity generation. In terms of electricity consumption, industrial electricity consumption accounts for the majority of the electricity industry's consumption and is the main part of the electricity industry's final consumption, and industrial electricity consumption contributes to carbon dioxide emissions, so it is clear that adjusting China's industrial structure and reducing the proportion of industrial electricity consumption can reduce carbon dioxide emissions from the electricity industry.

4.3.2 Negative drivers: fossil energy generation structure, coal consumption, thermal power generation ratio, electricity generation to consumption ratio

Among the negative drivers of carbon emissions in the power sector, the driving effect of coal consumption for power generation and the share of thermal power generation is more obvious, while the driving effect of the proportion of fossil energy generation and the proportion of electricity generation and consumption is small.

As can be seen from Figure 3, carbon emissions from coal power generation still account for more than 95% of carbon emissions from fossil energy in the power industry, while carbon emissions from oil power generation have decreased and carbon emissions from natural gas have increased slightly. China's power generation structure is dominated by thermal power generation, which still accounts for a large proportion of the high carbon emissions from coal, and the emission reduction effect of the "low carbon" shift in power generation energy structure will be further reflected in the future. The negative driving effect of coal consumption in power generation is mainly attributed to a series of energy-saving renovation measures taken by China in recent years, as well as the adoption of large-capacity, high-parameter thermal power units and the encouragement of cogeneration, which have effectively reduced coal consumption in power production and thus curbed CO2 emissions. The negative driving effect of the thermal power generation ratio is mainly due to the country's emphasis on clean energy, increasing the amount of clean energy generation, and continuing to increase the proportion of renewable energy generation is still the main trend in the development of China's power industry. The impact of the electricity generation ratio on the power industry's carbon emissions is minimal, as the power industry's production and demand will influence each other to achieve a balance, and will not fluctuate much so the impact of this factor will be minimal. The change in the plant electricity consumption rate of China's thermal power plants is relatively small, so the effect on the overall carbon emissions of the power industry is not significant. The key is to strictly control the total amount of coal power, change the energy structure, achieve the peak of coal power as soon as possible and decline as soon as possible, accelerate the planning and development of large-scale scenic water power generation bases, meet the new demand for electricity due to economic development and other reasons, improve the proportion of clean energy in primary energy, so that carbon emissions in the power industry will reach a peak by 2025.

Through the LMDI analysis method, a specific analysis of the factors influencing carbon emissions in China's power industry from the power generation side to the electricity consumption side has been conducted. In terms of energy consumption structure and, the proportion of fossil energy to primary energy consumption also has the form of steady decline, while China has abundant wind and solar power generation resources, through good development conditions and capacity, and under the "dual carbon "target" drive, power development policy guidance, primary energy carbon emissions will be effectively reduced, and has a strong potential. The focus of China's power industry's carbon peaking and carbon neutral actions should first be to reduce the proportion of fossil energy generation, build a diversified clean energy generation system by vigorously developing low carbon emission energy and clean energy on the power supply side, reduce the proportion of coal generation and accelerate the transformation of coal generation flexibility. On the power consumption side, we should also accelerate the construction of a smart grid on the grid side, support the development of distributed power sources and microgrids. On the power side, we should also accelerate the construction of smart grids on the grid side, support the development of distributed power sources and micro-power, and strengthen the unified dispatch of the grid to build a market mechanism for the consumption of new energy; in the technical field of the electricity industry, we should accelerate technological innovations including large-scale energy storage technology, high- voltage technology, solar thermal power generation technology and CCUS, BECCS, etc.; in the policy support of the electricity industry, we should provide policy support for green power certificates, carbon trading and green power trading.

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