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Low-Carbon Transformation of China's Power Industry: Influencing Factors and Realization Path

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Abstract: The low-carbon transformation of the power industry is the decisive factor supporting the alteration and advancement of the whole society, and it is also an essential path to achieving carbon neutrality. To study the influencing factors of carbon dioxide emission in China's power industry, this paper first analyzes the influencing factors of contaminant discharge using a panel model. Secondly, according to the ratio of power production and power consumption, the provinces are divided into three regions: power "output" provinces, power "input" provinces, and power "balance" provinces to analyze the influencing factors under the different power provision and need structure. Thirdly, based on the pilot situation of the carbon trading market in China, it is divided into two phases: before the pilot and after the pilot to thoroughly investigate the effect of price level on contaminant discharge in the power sector. Finally, this paper puts forward the realization path of low-carbon transformation and provides policy recommendations for promoting carbon neutrality in the power industry.

Keywords: power industry; low-carbon transformation; panel model

JEL Classification: C33; Q42; L94

1. Introduction

In September 2020, China announced to the world that it will achieve carbon neutrality by 2060, which completely reflects the responsibility of a major country and further emphasizes the determination to make a green transformation. In the process of energy transformation, power energy gradually replaces fossil energy in the terminal energy sector, and the use scope of power is constantly expanding. Power will become the main terminal energy use mode, and the power industry has become the core of the entire energy system. The basic and pillar position of the power sector in the national economy is more stable. However, the rapid application of the power industry is also accompanied by high carbon emissions, which exceed 40% of total emissions, making it the main carbon emission sector. Therefore, power energy conversion is a decisive factor in supporting the transformation and development of society.

The research on the power energy conversion transformation focuses mainly on influencing factors analysis. The discharge of contaminant, i.e., carbon dioxide in the power industry is growing rapidly. What factors play a promotion role? What factors play an inhibitory role? Furthermore, how to realize a smooth and steady transformation of the power industry? These issues have received extensive attention.

For influencing factors analysis, most of the literature uses factor decomposition methods to study. Malla (2009) used the LMDI (Logarithmic Mean Divisia Index) to conduct empirical research on the change in carbon dioxide emissions in seven countries in the Asia-Pacific and North America. Based on their research, Hou & Tan (2011) further decomposed the change of contaminant discharge in power production into five effects, including production structure, income effect, and others. Huo et al. (2013) also used this model to analyze and believed that the temporary fluctuations in contaminant discharge intensity mainly came from the changes in the generation side and delivery side. Wang (2005) argued that improving energy intensity could significantly reduce contaminant discharge. Chen et al. (2012) decomposed the carbon emission structure and calculated the contribution rate of different factors on low-carbon development based on the data of Guangdong province. They found the increase in provincial load was the main cause of the increase of electric power carbon emission in Guangdong province, and the modification of supply composition, the reduction of contaminant discharge intensity, and the application of gas units all contributed to the contaminant discharge decrease to varying degrees.

Some literature uses different model methods to analyze such problems. The empirical results of the error correction model built by Mi and Zhao (2012) showed that contaminant discharge and electricity expenditure are Granger causality. The same is true of electricity consumption and economic growth. Tang et al. (2018) assessed the impact of technological progress and energy structure transmutation on contaminant discharge by building a NET-Power model. In addition, based on the uncertainty of sustainable energy costs, combined with resource endowments and technology development trends, they constructed four scenarios to evaluate the environmentally friendly path in six regions. The results showed that the reduction of costs will have a greater impact on the space-time development of power generation technology and clean distribution between regions (Tang et al., 2019). The IO-SDA model results of Zhang and Guan (2019) indicated that the final demand scale and input-output are the most significant influencing factors, and they advocated helping the power industry reduce carbon emissions through optimization of production structure and upgrading of technology. The two-stage analysis results of Rodrigues et al. (2020) on the driving factors of contaminant discharge from power production in the EU showed that the change in fossil fuel usage combination, the improvement of production and use efficiency, and the application of renewable energy power will reduce contaminant discharge.

Numerous studies have explored the transformation path of the power industry. Some literature carried out multi-scenario simulation analysis through modeling and other methods to explore the emission reduction cost, emission reduction path, and technology selection of the power industry. Based on the NET-Power model, Tang et al. (2018) predicted that in China, the power industry in all regions except the eastern region would achieve the carbon peak by 2030. And they drew a detailed development path from the regional perspective. According to the development situation in different periods, Zhang et al. (2021) built a full chain technical and economic evaluation model for long-term analysis and built a carbon emissions external cost planning model for short-term and medium-term analysis. They compared and analyzed the characteristics of the conventional path, electric hydrogen coupling path, and electric hydrogen carbon coupling path, and proposed that the future power system will present a low-carbon development trend of multi-path integration. Wu et al. (2021) used the coupling model of the power sector and terminal sector to forecast power demand, divided expectations into conservative expectation and positive expectation, and designed eight scenarios to study the path optimization and cost-effectiveness of transformation. Liu et al. (2021) compared the contaminant discharge intensity of gas electricity and coal electricity and found that under the two scenarios of heating and peak shaving, gas power has obvious advantages in carbon emission reduction. Therefore, natural gas can serve as a transition to ensure and promote the development of sustainable resources. Some literature explored the transformation path through cluster analysis. Qiu et al. (2022) proposed the power transformation path from a passive enabling system to an active enabling system through keyword cluster analysis. Lin and Yang (2022) analyzed the hotspots related to the transformation of the power system through the bibliometric method and pointed out the direction for future power system research in combination with existing research hotspots.

Most of the literature selects variables from a single perspective to analyze the influencing factors. Different from the existing studies, when using the panel model to analyze, this paper considers the power production side, power consumption side, and power market system, comprehensively and systematically investigating the impact of different factors. The innovation of this paper lies in dividing provinces into three regions: power “output” provinces, power “input” provinces, and power “balance” provinces to analyze the influencing factors under the different power provision and need structure, according to the ratio of power production and power consumption. Besides, based on the pilot situation of the carbon trading market in China, the influence of price level on contaminant discharge in the power sector is further studied in two stages: before and after the pilot. Finally, based on the results of empirical analysis, this paper proposes the path direction of transformation in the power industry.

2. Methodology

2.1. Variable Selection

When selecting the influencing factors, this paper finds that many related factors will have a direct or indirect impact, and different factors have different impact directions and degrees. This paper considers the factors from the aspect of the power production side, consumption side, and power market system.

From the power production side, select three indicators: power supply structure, the ratio of power generation and power consumption, and power supply coal consumption. The power supply structure is the percentage of thermal power generation in total. Power supply coal consumption is the average standard coal quantity required for each kilowatt hour of power provided by the thermal power plant. From the power consumption side, select three indicators: economic scale, power intensity, and urbanization rate. The economic scale is measured by Gross Domestic Product (GDP). Power intensity refers to power consumption divided by GDP. It is an important indicator to reflect the power resources consumed per unit of GDP and reflect the utilization efficiency and dependence of economic development on power energy. The increase in power consumption intensity means the power energy consumption required to produce the same unit of output value increases. From the power market system, select the price level as an indicator, measured by the average sales price, to estimate the effect of the price mechanism.

This paper collects and collates the data on carbon emissions and their influencing factors in 30 provinces (except Tibet, Hong Kong, Macao and Taiwan) in China from 2005 to 2018. The data are from the Wind database, CEADs database, the National Bureau of Statistics, and the Electricity Power Yearbook. The power supply structure, the ratio, power intensity, and urbanization rate are all calculated from the collected data. The variables and their statistical description see Table 1-2.

Table 1. Description of variables

Index	Symbol	Unit	Meaning
Carbon emission	CO2	Million tons	Carbon emissions
Power supply structure	EPS	%	Percentage of thermal power generation in total
Ratio	EGR	-	Ratio of power generation and power consumption
Power supply coal consumption	PCC	g/kWh	Average standard coal quantity required for each kilowatt hour of power provided by the thermal power plant
Economic scale	GDP	yuan	Gross Domestic Product
Power intensity	EI	100 million kWh/100 million yuan	Power energy consumed to produce a unit of GDP
Urbanization rate	URB	%	Proportion of urban population in permanent population
Price level	PL	yuan/thousand kWh	Average sales price

Table 2. Statistical description of variables

Index	CO2	EPS	EGR	PCC	GDP	EI	URB	PL
Sample size	326	326	326	326	326	326	326	326
Mean value	144.3636	75.79806	1.053518	330.8887	18,343.23	0.12056	54.69016	548.0193
Median	104.9844	83.60941	1.00499	328	12,836	0.094836	53.21172	544.9
Maximum	560.1075	100	1.930218	469	99,945.2	0.552978	89.58333	777.24
Minimum value	8.206227	8.110157	0.328282	209	585.2	0.034507	27.45257	271.62
Standard deviation	112.9949	23.71975	0.304766	30.62794	17,201.49	0.080758	13.92628	118.1743

2.2. Data Processing

The results of the unit root test of each variable see Table 3. The first-order difference of variables is a stationary process.

Table 3. Unit root test

Variable	Fisher ADF test		Fisher PP test	
	Horizontal value	First-order difference	Horizontal value	First-order difference
lnCO2	43.1957	86.0403***	82.7753**	179.385***
lnEPS	76.7488*	112.247***	137.35***	290.56***
lnEGR	81.8898**	98.1729***	69.27	236.867***
LnPCC	59.0519	85.9815***	38.0843	230.552***
lnGDP	49.763	113.681***	58.5879	174.525***
lnEI	71.3801	223.111***	36.8593	315.845***
lnURB	47.9528	94.7629***	84.8654**	224.119***
LnPL	25.3479	97.897***	15.5904	146.408***

Note: *, ** and *** are significant at the level of 10%, 5% and 1%, respectively.

2.3. Model Construction

This paper systematically conducts influencing factors analysis through the following three models. Firstly, take all provinces as a whole, comprehensively investigate the impact of various influencing factors on the contaminant discharge from the national level, and record it as Model 1.

Secondly, due to the different matching of power supply and power demand in different regions, the provinces are divided into three types according to the ratio of power generation and power consumption of each province, namely, power “output” provinces, power “input” provinces and power “balance” provinces. The second model is built to conduct empirical analysis in regions with different power supply and demand structure, which is recorded as Model 2.

Thirdly, in 2011, China carried out pilot carbon emissions trading in seven provinces and regions, such as Beijing. The opening of the carbon trading market will cause changes in the production costs of the power supply industry. The operating costs of thermal power and renewable energy power will change to varying degrees. The cost changes will be transmitted to the power consumption side through the market price mechanism. Then, the consumer will adjust their choices in different types of power resources, ultimately affecting the carbon emissions. According to the time point of the pilot, the samples in the pilot area are classified into two groups. The first group is the period before the pilot, and the sample time is 2005-2011. The second group is the period after the pilot, and the sample time is 2012-2018. This is Model 3.

3. Results

The fixed effect model is used to estimate the elasticity coefficient of the influencing factors. The results of the three models see Table 4-6.

The test of Model 1 indicates that the price level has an inhibitory effect. Except for the price level, other factors, such as supply structure, power intensity, and urbanization rate all play a promoting role. Among them, power intensity has the largest promoting effect, with the elasticity coefficient reaching 3.05, followed by EGR, PCC, EPS, URB, and GDP.

In Table 5, the coefficient of the ratio in the three regions is positive at least at the significance level of 1%. But the elasticity coefficient of power “balance” provinces is significantly lower than that of power “output” provinces and power “input” provinces, which means that in regions where the power supply and demand structure is relatively

Table 4. Results of Model 1

Variable	Coefficient	t-statistic	P value
C	-10.60253***	-5.873035	0.0000
lnEPS	1.039982***	19.47037	0.0000
lnEGR	1.870823***	8.901386	0.0000
LnPCC	1.088637***	4.930911	0.0000
lnGDP	0.259453***	2.726804	0.0068
lnEI	3.050938***	8.476128	0.0000
lnURB	0.990734***	5.784599	0.0000
LnPL	-0.564026***	-4.142572	0.0000
Adjusted R2	0.982848		
F statistic	405.8615		

Note: *, ** and *** are significant at the level of 10%, 5% and 1%, respectively.

Table 5. Results of Model 2

Variable	Power "output" provinces	Power "input" provinces	Power "balance" provinces
C	-9.32429***	-10.72034***	1.403524
lnEPS	1.111404***	0.216124	0.584962***
lnEGR	1.928015***	1.959452***	0.993984***
LnPCC	0.924515*	1.675282***	0.086115
lnGDP	0.122824	0.266832**	0.615586***
lnEI	4.637364***	2.379266	1.50982**
lnURB	1.041988***	0.499011***	-0.461722
LnPL	-0.534909**	-0.16627	-0.758421***
Adjusted R2	0.958669	0.994099	0.996483
F statistic	108.691	731.0517	937.2827

Note: *, ** and *** are significant at the level of 10%, 5% and 1%, respectively.

Table 6. Results of Model 3

Variable	2005-2011	2012-2018
C	-14.43914**	-1.185123
lnEPS	0.928654***	0.514801*
lnEGR	1.946184***	1.629343***
LnPCC	1.431424**	0.798144**
lnGDP	-0.31106	-0.302716
lnEI	-6.602949	6.658765
lnURB	1.234585	1.570584***
LnPL	0.545303	-0.938564**
Adjusted R2	0.996884	0.998068
F statistic	520.8042	1,064.778

Note: Same as Table 3.

balanced, the promotion effect of the ratio is smaller. Therefore, realizing the balance of the power supply and demand structure will help decelerate the growth of contaminant discharge.

The results of Model 3 show that in the pilot area of the carbon trading market, the impact of power price is not significant before the pilot is opened. After the pilot is opened, the impact coefficient of power price is significant at least at the significance level of 5%. Every 1% increase in power price will reduce carbon emissions by 0.94%. The construction of the carbon trading market makes the impact mechanism of power price transfer to the power consumption side more flexible through the market mechanism, and the path of realizing the transformation of the power industry through the price mechanism is more effective.

4. Discussion

Optimizing the power structure can reduce carbon emissions. The proportion of thermal power has a noticeable promoting effect. For every 1% increase in the proportion of thermal power, the carbon emissions will increase by 1.04%. Thermal power generation is still the primary origin of power, with coal-fired installed capacity accounting for almost half of the total. The combustion of coal energy will produce abundant carbon dioxide. With the total power generation unchanged, diminishing the percentage of thermal power provision, that is, optimizing the EPS, will reduce the contaminant discharge caused by coal combustion. Therefore, optimizing the power energy structure is an important path to effectively promote the transformation and development of the energy supply.

The ratio of power production and power consumption is an important indicator reflecting the regional transfer of power energy. The ratio has a promotion effect in the model. Every 1% increase in the ratio will increase the carbon emissions of the power industry by 1.87%, which is the second largest factor only next to the power intensity. Based on the results of Model 2, the promotion effect of the ratio is smaller in regions where the power supply and demand structure are relatively balanced. Therefore, realizing the balance of the power provision and need framework will help slow down the increase of contaminant discharge. Due to the absence of resources, the power generation capacity of Beijing, Tianjin, Shanghai, Zhejiang, and other places is not sufficient to meet their electricity demand. They need to rely on the power transfer from other provinces and belong to power "input" provinces. The demand for power transfer from other provinces will transfer the power production link with high carbon emissions to other provinces, reducing the carbon emissions of the province to a certain extent. On the contrary, for the power "output" provinces that bear more than the local power demand, the carbon emissions increased. Traditional centralized power supply has a high dependence on energy endowment, while new energy power generation technologies have a low dependence on energy resources. It is qualified to build a distributed power supply and the contaminant generated by the development and utilization of new energy is far less than thermal power generation. Therefore, under the general trend of developing new energy power, building a scattered provision system to improve the generation capacity of power "input" provinces, and reduce their demand for excess power in power "output" provinces is a viable measure. Moreover, improve the ratio in power "input" provinces, reduce the ratio in power "output" provinces, and ultimately promote the balanced transformation of all provinces.

Reducing the standard coal consumption per unit of power supply, that is, power supply coal consumption will help reduce carbon emissions. The PCC is a factor promoting pollutant release. Every 1% increase in power supply coal consumption will increase the contaminant by 1.09%. The power supply coal consumption reflects the usage of coal in the provisioning process and affects the coal resources consumed by each unit of power supply. The higher power supply coal consumption means the lower efficiency of thermal power generation and utilization rate of coal. The low utilization rate is not only a serious waste of coal resources, but also increases the burden of carbon dioxide on the environment, and increases the difficulty of controlling carbon emissions. The power structure of China is led by thermal power at present. Therefore, reducing the power supply coal consumption and improving the efficiency of thermal power generation are technical difficulties that will be overcome in the development path, which are also vital measures to promote contaminant reduction.

The low-carbon economy development model is conducive to reducing carbon emissions. The economic scale promotes contaminant discharge. Every 1% increase in economic scale will increase the contaminant by 0.26%. GDP reflects the overall development level of the economy. The promotion effect of economic scale is reflected in the growth of power demand brought by economic growth. The higher the power demand, the more power production and corresponding carbon emissions. However, the positive driving effect of economic scale is the smallest among all influencing factors. This may be because in recent years, China no longer merely pursues the speed of economic growth, but pays more attention to the quality of economic growth. Relying on scientific and reasonable economic modes and advanced green technology, industrial development and green development are integrated to achieve high-quality growth. Therefore, based on new energy power, actively exploring a lower carbon development model is an essential path direction to curb the promotion effect of economic scale on contaminant discharge.

Reducing the power intensity and optimizing industrial structure can reduce carbon emissions. Among all the influencing factor indicators, the positive driving effect of power intensity is the most significant. Every 1% increase in power intensity will increase the contaminant discharge by 3.05%. The reduction of power energy required for the increase of unit GDP means the improvement of technology progress and terminal power utilization. The less power energy consumption is, the lower contaminant discharge will be. The power intensity is closely related to industrial structure. At present, China is carrying out industrial restructuring. The proportion of the secondary industry is declining, and its contribution to economic growth is also declining. But there are numerous high-energy consumption industries in the secondary industry, such as chemical manufacturing, steel, and cement manufacturing, and the decline in its demand for power energy cannot keep up with the decline in its contribution to economic growth. That is, the secondary industry has a large consumption of power energy and a small increase in GDP, indirectly increasing the power consumption per unit GDP, and increasing the burden of power intensity on the carbon emissions. Compared with the secondary industry, the tertiary industry has a small dependence on power energy and a significant contribution rate to economic growth, which can improve the utilization efficiency of terminal electric energy, indirectly decrease the power intensity, and thus reduce the discharge of contaminant.

The high-quality development of urbanization can reduce carbon emissions. The urbanization rate is a factor promoting pollutant release. Every 1% increase in the urbanization rate will increase contaminant discharge by 0.99%. The city is the gathering place of transportation, commercial activities, and industrial production, as well as the main concentration place of carbon emissions. The construction of basic facilities needs to consume abundant power energy, and the demand for power energy in urban households is also higher than that in rural households. Therefore, the increasing urban population drives the demand for power demand and consumption and simultaneously intensifies the growth trend of carbon emissions. On the other hand, urbanization construction will also bring about industrial upgrading and technological progress, and improve the generation efficiency and utilization rate of the power industry. Therefore, when the urbanization level develops to a certain stage, the utilization rate of regional infrastructure will increase, the lifestyle of residents will also shift, the consumption mode will be greener, and the electricity demand will gradually decline, promoting the reduction of contaminant discharge. Consequently, the high-quality construction of cities and the guidance of residents' awareness of green consumption, the reasonable planning of the service life and efficiency of infrastructure, and the guidance of residents' green consumption and life will, to some extent, mitigate the promotion effect of the improvement of urbanization rate on the increase of contaminant discharge.

Intensifying the reformation of the power market and promoting the construction of the national carbon market can reduce carbon emissions. Every 1% increase in the price level measured by the average sales price will reduce the contaminant discharge by 0.56%. The power price affects carbon emissions by causing changes in power demand. Theoretically, the power price is a basic element of industrial production and people's life. Its change will certainly bring about the change of power consumption activities of various consumers, and then bring about the change of contaminant discharge. With the increase in the price level, the consumer will reduce the demand for electricity to a certain extent, pull down the consumption of primary energy by the supply enterprises, and naturally reduce contaminant discharge. Therefore, the price mechanism is the key to reducing carbon emissions. In addition, power price is also affected by the carbon market. The price fluctuation in the carbon market will bring about changes in the production cost of the power supply industry. The changes in the operating cost will cause changes in the power price level, and will also change the power supply industry's decision on the use of fossil energy and renewable energy, and ultimately affect the contaminant discharge level of the entire power industry. The results of Model 3 show that the construction of the carbon pilot makes the impact mechanism of power price transfer to the power consumption side more flexible through the market mechanism, and the path of controlling the contaminant level through the price mechanism is more effective. Therefore, the effective ways to control carbon emissions are to build a national unified power market system, better play the role of power price in regulating the supply and demand of power resources and promote the construction of the national carbon trading market.

5. Conclusions

Based on the three influencing factors analysis model, the power structure, the ratio, power supply coal consumption, economic scale, power intensity, and urbanization rate all have an obvious role in promoting the contaminant discharge of the power industry, while the price level has a restraining effect. To meet the new challenges under the goal of carbon neutrality, the power production side, the power consumption side, and the power market system need to be significantly adjusted. From the above results, this paper proposes the following paths to achieve power green alteration.

First of all, the power supply structure needs to be significantly adjusted with energy alteration on the production side. Renewable energy and fossil energy are facing a role transition. Renewable energy power will gradually replace traditional fossil energy power as the basic power in the new era. The development trend of sustainable resources in the future is to use them nearby the user side, but it is faced with problems such as insufficient grid connection adaptability, low stability, and weak absorptive capacity. Therefore, the joint operation of distributed renewable energy generation and distributed energy storage is the direction of the new power supply system. Besides, renewable energy power generation can effectively decrease contaminant discharge. Although the withdrawal of coal power units is an inevitable trend, at this stage, renewable energy cannot completely replace thermal power. How to dispose of large and advanced coal power units is a key issue to be emphatically considered. In addition to the flexibility transformation of existing units, the use of existing units with CCUS (Carbon Capture, Utilization and Storage) technology is also a carbon neutrality road with Chinese characteristics.

Secondly, for the power consumption side, it is considered to discuss the green transformation in the context of industrial restructuring and urbanization construction. The power energy consumption per unit GDP has an enhancement effect on carbon emissions. Economic growth is highly dependent on power demand, and GDP growth is strongly related to contaminant discharge. At the same time, the power intensity is closely related to industrial restructuring. Therefore, manufacturing structure modernization is the key to realizing the decoupling of economic growth from the power demand and contaminant discharge. In addition, electricity is a basic component of urban infrastructure. The environmentally friendly transmutation of the electricity sector is inextricably linked with the low-carbon development of the city. The integration of the upgrading of the power system into the urbanization construction is a notable approach to reducing contaminant discharge.

Finally, the electrical system dominated by renewable energy is the key measure and inevitable requirement to realize energy transformation. The power market is a critical support for an innovative power system. At present, the power market still has problems of disunity, imperfection, incompleteness, and regional barriers in terms of transaction rules, functions, systems, and trans-regional transactions. To better perform the function of the market in power resource distribution and provide a strong market guarantee for energy transformation, it is necessary to improve the effective connection of power markets at different levels, better play the role of power markets with different functions, establish a unified trading order and technical standards, improve the market trading framework, break through the institutional barriers of trans regional power trading, and construct a unified national power market system. The specific measures to improve the power market system include improving the system and policy of renewable energy participating in energy provision, strengthening the price transmission procedure of the market with distinct functions, such as the spot market, and comprehensively handling the relationship between the carbon market and the national unified power market.

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References

Chen, X. K., Zhou, T. R., Li, X., Kang, C. Q., & Chen, Q. X. (2012). Structure identification of CO_2 emission for power system and analysis of its low-carbon contribution. *Automation of Electric Power Systems*, *36*(2), 18–25.

Dong, R., Gao, L., He, S., & Yang, D. T. (2022). Significance and challenges of CCUS technology for low-carbon transformation of China's power industry. *Power Generation Technology*, *43*(4), 523–532.

Du, D. M., Cao, D. H., & He, Q. (2022). Discussion on low-carbon transformation of China's power industry under the "double-carbon" goal. *Thermal Power Generation*, *51*(10), 1–9. https://doi.org/10.19666/j.rlfd.202204074

Hou, J. C., & Tan, Z. F. (2011). The factor decomposition of CO_2 emission changes in electricity production in China. *Electric Power*, *44*(11), 39–42.

Huo, M. L., Han, X. Y., & Shan, B. G. (2013). Empirical study on key factors of carbon emission intensity of power industry. *Electric Power*, *46*(12), 122–126.

Jia, L. R., & Huang, D. (2013). Construction model of low-carbon city. *Science and Technology Management Research*, *33*(6), 36–40.

Jia, Y. L., Ma, K., & Li, L. (2021). Analysis on the status quo and development trend of green transformation in regional power industry. *Applied Energy Technology*, *7*, 23–26.

Li, X., & Yu, B. (2019). Peaking CO_2 emissions for China's urban passenger transport sector. *Energy Policy*, *133*, 110913. https://doi.org/10.1016/j.enpol.2019.110913

Lin, B. Q., & Yang, M. Q. (2022). China's power system research in the context of carbon neutrality: current status, challenges, and development direction. *Journal of Xi'an Jiaotong University (Social Sciences)*, *42*(5), 1–10. https://doi.org/10.15896/j.xjtuskxb.202205001

Liu, Z. T., Li, Y. G., Yang, G. J., & Wang, W. F. (2021). Development path of China's gas power industry under the background of low-carbon transformation. *Natural Gas Industry*, *41*(6), 152–161.

Malla, S. (2009). CO_2 emissions from electricity generation in seven Asia-Pacific and North American countries: a decomposition analysis. *Energy Policy*, *37*(1), 1–9.

Mi, G. F., & Zhao, T. (2012). Research on the relationship among economic growth, electricity consumption and carbon emissions in China. *Scientific Management Research*, *30*(1), 89–91+116. https://doi.org/10.19445/j.cnki.15-1103/g3.2012.01.022

Qiu, X. Y., Cai, Y. J., & Chen, Q. X. (2022). Electric power transformation path analysis and enlightenment under the "dual-carbon" target. *Science and Technology Management Research*, *42*(12), 197–203.

Rodrigues, J., Wang, J., Behrens, P., & Boer, P. D. (2020). Drivers of CO_2 emissions from electricity generation in the European Union 2000–2015. *Renewable and Sustainable Energy Reviews*, *133*, 110104. https://doi.org/10.1016/j.rser.2020.110104

Tang, B. J., Li, R., Yu, B., & Wei, Y. M. (2019). Spatial and temporal uncertainty in the technological pathway towards a low-carbon power industry: a case study of China. *Journal of Cleaner Production*, *230*, 720–733. https://doi.org/10.1016/j.jclepro.2019.05.151

Tang, B., Li, R., Yu, B., An, R., & Wei, Y. M. (2018). How to peak carbon emissions in China's power sector: a regional perspective. *Energy Policy*, *120*, 365–381. https://doi.org/10.1016/j.enpol.2018.04.067

Wang, C., Chen, J., & Zou, J. (2005). Decomposition of energy-related CO_2 emission in China: 1957–2000. *Energy*, *30*(1), 78–83. https://doi.org/10.1016/j.energy.2004.04.002

Wang, Z. X. (2017). Status of China energy efficiency in electric power industry and its prospect. *Energy of China*, *39*(5), 13–17+20.

Wu, Y., Yu, B. Y., Zou, Y., Sun, F. H., Zhao, G. P., & Tang, B. J. (2021). The path of low-carbon transformation in China's power sector under the vision of carbon neutrality. *Chinese Journal of Environmental Management*, *13*(3), 48–55. https://doi.org/10.16868/j.cnki.1674-6252.2021.03.048

Zhang, J. L., & Guan, Y. Q. (2019). Analysis of the influence factor of carbon emission based on IO-SDA model. *Journal of North China Electric Power University (Social Sciences)*, *6*, 39–46. https://doi.org/10.14092/j.cnki.cn11-3956/c.2019.06.003

Zhang, Y. Z., Zhang, N., Dai, H. C., Zhang, S. Y., Wu, X. Y., & Xue, M. M. (2021). Model construction and pathways of low-carbon transition of China's power system. *Electric Power*, *54*(3), 1–11.

Zhao, D. M., Xu, C. Y., Tao, R., & Zheng, Y. R. (2022). Review on flexible regulation of multiple distributed energy storage in distribution side of new power system. *Proceedings of the CSEE*, 1–23.