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The current situation, development aims and policy recommendation of China's electric power industry

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Abstract

Purpose – Although the tasks of managing carbon peaks and achieving carbon neutrality in China are arduous, they are also of great significance, which highlights China's determination and courage in dealing with climate change. The power industry is not only a major source of carbon emissions but also an important area for carbon emission reduction. Thus, against the backdrop of carbon neutrality, understanding the development status of China's power industry guided by the carbon neutrality background is important because it largely determines the completeness of China's carbon reduction promises to the world. This study aims to review China's achievements in carbon reduction in the electric industry, its causes and future policy highlights.

Design/methodology/approach – The methods used in this study include descriptive analyses based on official statistics, government documents and reports.

Findings – The research results show that, after years of development, the power industry has achieved positive results in low-carbon provisions and in the electrification of consumption, and carbon emission intensity has continued to decline. Policy initiatives play a key role in this process, including, but not limited to, technology innovations, low-carbon power replacement and supported policies for low-carbon transformation toward low-carbon economies.

Originality/value – This study provides a full picture of China's power industry against the backdrop of low-carbon development, which could be used as a benchmark for other countries engaging in the same processes. Moreover, a careful review of China's development status may offer profound implications for policymaking both for China and for other governments across the globe.

Keywords Carbon peak, Carbon neutrality, Power industry, Low-carbon development

Paper type Research paper

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1. Introduction

With the rapid increase in the global population and fast-growing industries, carbon dioxide emissions into the atmosphere are rising, and problems such as the greenhouse effect, ocean storms, land desertification and climate extremes are becoming increasingly serious (Mora *et al.*, 2018; Jia *et al.*, 2021; Sun and Li, 2021). Therefore, the question of how to reduce carbon dioxide emissions has become a key concern for the international community and relevant governments (Zhang and Da, 2015; Zhao *et al.*, 2021). The report "Global Energy Review: CO_2 Emissions in 2021" released by the International Energy Agency (IEA) states that global CO_2 emissions from the energy sector reached 36.3 billion tons in 2021, growing at a 6% year-on-year pace (IEA, 2021). At the 75th UN General Assembly, the Chinese Government also proposed significant improvements to energy use efficiency in key sectors by 2025, which laid a solid foundation for achieving carbon peak and carbon neutrality. By 2030, carbon dioxide emissions per unit of gross development product (GDP) will drop by more than 65% compared to 2005, the share of non-fossil energy consumption will reach about 25%, and carbon dioxide emissions will reach a peak and achieve a steady decline. By 2060, the proportion of non-fossil energy consumption will reach more than 80%, the goal of carbon neutrality will be successfully achieved and a new era of harmonious coexistence between humans and nature will be created. In addition, the IPCC Sixth Assessment Report emphasizes that the concentration of greenhouse gases (GHG) in the atmosphere has risen to unprecedented levels, which means that it is urgent to implement definitive emissions reduction activities in all sectors (IPCC, 2014). If global warming is to be controlled to within 1.5°C of pre-industrial levels, global GHG emissions need to peak by 2025, with CO_2 emissions decreasing by approximately 45% in 2030 compared to 2010, and achieving "zero emissions" by around 2050 (Rogelj *et al.*, 2018).

In the context of an increasingly severe global climate, people are gradually embracing low-carbon lifestyles and pay more attention to a low-carbon sustainable choices (Mathews and Tan, 2016). China's carbon emissions have been ranked first in the world since 2005 (Hao *et al.*, 2015; Wang *et al.*, 2020), while the power industry is the sector with the highest carbon emissions in China, accounting for about 40% of CO_2 emissions from energy activities. Therefore, innovating business models and encouraging the decarbonization of the power industry are the main means to promote the low-carbon transformation of the energy system and long-term GHG emission reduction (Sieminski, 2014). Considering the urgency and necessity of energy conservation and emission reduction in the power industry, China's National Development and Reform Commission officially issued "The 13th Five-Year Plan for power development (2016–2020)". The policy includes a five-year development goal for the power industry, as well as ways to actively prevent excess capacity of coal and electricity and improve the utilization efficiency of thermal power energy, to significantly promote the green and low-carbon transformation of the power industry.

It is clear that all kinds of low-carbon economic strategies are being proposed and implemented with the ultimate goals of protecting the environment, reducing GHG emissions, balancing energy consumption and slowing down global warming. These strategies contribute to facilitating green development and promoting the harmonious coexistence of humans and nature. However, it is worth noting that there are still many problems in the implementation of the energy conservation and emission reduction model in China's power industry, which has not achieved ideal results. Therefore, taking into full consideration of the international climate and domestic environment, it is of great theoretical and practical significance to analyze the current situation of low-carbon development in China's power industry and put forward carbon emission reduction measures in the power sector. First, low-carbon development strategies in the power industry are conducive to improving the harmony between the industrial economy and the ecological environment, and thus can realize the long-term linkage between the two in the process of mitigating global warming. Second, an analysis of the current situation of carbon emission reduction in the power industry will help promote innovation in manufacturing and technology flow in industry. The technological innovation and development of the whole industry will not only reduce cost consumption but also increase the environmental protection effect. Third, due to the large scale of carbon dioxide emissions in power production, the implementation of carbon emission reduction policies in this industry will directly affect the outcome of controlling China's greenhouse effect, which will have significant consequences for the improvement of China's climate and environment.

The structure of this paper is as follows: Section 2 outlines the theoretical background and literature related to the theme of this paper and identifies the research deficiencies of existing studies. We describe the research design in Section 3, including research methods and an analysis of research data. Section 4 introduces the targets of a carbon peak and carbon neutrality in China's power industry. Section 5 summarizes the research results and puts forward relevant policy recommendations.

2. Literature review

2.1 Impact factors of carbon emissions

Regarding research into the factors that influence carbon emissions, scholars have mainly focused on industry, electricity, transportation, construction, population, energy consumption and other aspects. Among these topics, the economic and social behaviors caused by the industrialization process have been identified as the fundamental reasons for the sharp rise in carbon dioxide concentrations, which make controlling the carbon emissions of industries an important part of achieving a carbon peak and carbon neutrality (Xia *et al.*, 2011; Ren and Hu, 2012). Zhang *et al.* (2015) discussed the dynamic change and decomposition of carbon dioxide emissions from regional transportation industry in China. Yang and Lin (2016) and Li *et al.* (2019) analyzed the achievements of China's power industry in improving energy efficiency and reducing carbon dioxide emissions. He and Zhang (2017) calculated the carbon emissions of China's iron and steel industries using the IPCC empirical approach, and proposed that dissolving the contradiction of overcapacity and improving energy intensity would allow for significant control of carbon emissions. Based on the kaya factorization method, Shang *et al.* (2018) discussed the impact of energy structures on carbon emissions in the provincial construction industry and put forward relevant suggestions for the low-carbon development of this industry. Araújo *et al.* (2020) adopted the SDA method to quantify the driving factors of changes in EU carbon dioxide emissions. Liu *et al.* (2020) explored the driving factors of LCD inequality and evolution based on the extended spatial decomposition model. Pan *et al.* (2022a, 2022b, 2022c) analyzed the driving factors for carbon emissions and economic decoupling based on factor decomposition models. Pan *et al.* (2023) revealed the evolution of FDI shocks on intra- and inter-regional carbon emissions by establishing a novel panel vector autoregression model.

2.2 Impact of the carbon emission reduction policy on economic growth

Although the imposition of carbon taxes can reduce carbon dioxide emissions, we are also discovering that it has a certain impact on a country's economy. For this reason, some scholars have explored the relationship between carbon emission reduction policies and the macro-economy. Zakeri *et al.* (2015) presented an analytical supply chain planning model to examine the nonlinear effects of carbon taxes on the macro-economy. Li *et al.* (2019) took the Beijing–Tianjin–Hebei region as the research scope and used the computable general equilibrium (CGE) model to assess the impact of air pollution abatement policies on both the economy and the environment. Hadfield and Cook (2019) pointed out that the government can use financial means to promote sustainable development, such as purchasing low-carbon products, providing funds for the early stage of clean energy and funding low-carbon technology pilot projects. Li *et al.* (2020) established a CGE model to reveal the transmission path of the impact of carbon tax on employment. Through the scenario simulation, Fan *et al.* (2021) found that the tax policy can encourage enterprises to pay attention to the social cost of pollution emissions and thus push them to invest in pollution control. Pan *et al.* (2022a, 2022b, 2022c) investigated the impact of the carbon emission trading scheme on total factor productivity of enterprises and tested the intermediary role of government participation and carbon trading market efficiency.

2.3 Carbon emission reduction in power industry

In the research that focuses on the theme of carbon emissions reduction in the power industry, scholars have mainly measured carbon emissions or carbon emission efficiency on the macro level of the nation or region (Zhou *et al.*, 2013; Lin and Yang, 2014; Yao *et al.*, 2015; Roh and Tae, 2017; Yi, 2017). For example, Erickson *et al.* (2012) compared the IPCC method with the method based on consumption to calculate the carbon emissions of a state in the USA and concluded that the carbon emissions calculated based on consumption were large. Yan *et al.* (2017) used the IPCC method to calculate the carbon emissions of the power industry in 30 provinces of China and analyzed the driving factors of carbon emission efficiency. In addition, some scholars predicted the path of low-carbon transformation in the power industry. For example, Stua (2013) proposed that the plot development mechanism plays the most significant positive role in the process of the low-carbon transformation of China's power industry. Shen *et al.* (2018) compared the two carbon emission models of power system transformation planning from the perspective of central planners and predicted two paths to complete the carbon emission reduction target by 2030. Rogge *et al.* (2020) summarized the combination of social technologies and policies suitable for different paths based on the low-carbon transformation path of the German power system. Duan *et al.* (2021) combined the research results of AIM, GCAM, IMAGE, POLES and other teams to predict the carbon emissions that China should reduce to achieve the global temperature control target of 1.5°C. Yao *et al.* (2021) argued that the power industry is the main source of China's carbon emissions, and that the transformation of its supply structure has a key role to play in China's low-carbon development. As such, they adopted the MARKAL-EFOM System (TIMES) model to set different scenarios for carbon emission reductions in the power industry and calculated optimal regional power supply structure under various carbon emission constraints.

In view of this, by combing the trends of some indicators in power production, power consumption and power technology, and calculating the carbon emissions of the power industry, this paper assesses the carbon emissions achievements of China's power industry in recent years. The findings and conclusions of this paper have significant theoretical significance for the subdivision of carbon emission reduction policies in China's power industry.

3. Research design

3.1 Methodology

3.1.1 Data. The purpose of this paper is to analyze the reasons for carbon emission reduction activities in the power industry, the development status of carbon emission reductions and the achievements in carbon emission reduction in the context of carbon neutrality. This information enables us to put forward relevant policy recommendations for the development of carbon emission reduction in the power industry. Therefore, following the principles of the reliability and availability of data, this study collects data that reflect China's power production capacity, power consumption level and power technology innovation from official documents, such as "China Statistical Yearbook on Environmental" and "China Statistical Yearbook on Electric Power", as well as some related government reports. These data can help to elucidate the development of carbon emission reduction in China's power industry.

3.1.2 Method. The method used in this paper is descriptive statistical analysis of the collected data according to the time series. By comparing the annual change trends in various indicators in power production, power consumption, power technology, etc., we can understand the energy use and new energy substitution in China's power industry. Additionally, we can also point out the problems that exist in the process of energy conservation and emission reduction in the power industry and the links to be optimized. In addition, this paper calculates the annual carbon emissions of the power industry according to the method provided by the IPCC emission calculation guide, and discusses the carbon emission reduction achievements according to the unit coal consumption in the processes of power production and power consumption. These analyses help to highlight the contribution of the power industry to achieving China's carbon peak and carbon neutrality goals.

3.2 Data analysis

3.2.1 Optimization of the power supply energy structure. The proportion of nonfossil energy installed capacity has increased steadily. Nonfossil energy refers to energy from sources other than coal, oil, natural gas and other types of energy that allow only one-time use. It includes renewable energy sources such as wind energy, solar energy, hydropower and biomass energy, as well as new energy represented by nuclear energy. Increasing the proportion of nonfossil energy consumption can effectively reduce the emission of carbon into the environment and reduce the risks sustainable energy supply. Therefore, non-fossil energy is of great significance for China if it is to successfully achieve the carbon peak goal by 2030. The 2022 China carbon neutral forum also revealed that, in the process of working toward a carbon peak and carbon neutrality, we should increase the supply capacity and consumption level of new energy, and gradually replace traditional fossil energy. Since 2000, China's hydropower and nuclear power have experienced steady-state growth. After 2010, wind and solar power developed rapidly. By the end of 2020, the installed capacity of non-fossil energy power generation in China had reached 955.38 GW, accounting for 43.4%, which is 17.9% higher than the 81.45 GW in 2000. China's nonfossil energy consumption accounted for 15.9% of primary energy consumption in 2020, which favorably supports the carbon neutrality target of 25% nonfossil energy consumption by 2030. The installed capacity and proportion of non-fossil energy in China from 2000 to 2020 are shown in Figure 1.

Wind and solar power have achieved significant leaps in terms of development. As high-quality sources of renewable energy, the development and utilization of solar energy and wind energy are regarded as effective ways to solve the energy crisis and climate problems (Creutzig *et al.*, 2017). In 1986, China's first wind farm was connected to the grid. This became a milestone in the history of wind power in China. In 2011, China's first solar thermal power generation project completed the concession demonstration bidding, marking a firm step forward in the commercialization of China's early heat and power industry. Since the 13th Five-Year Plan, the country's determination to vigorously develop green power and adjust the energy structure has become increasingly pronounced. Since then, a series of successive policies have been issued to mark out the direction of development for the new energy industry. By the end of 2020, the grid-connected wind and solar power installed capacity in China has reached 282 and 254 GW, accounting for 12.8% and 11.5% of the total installed capacity, and with an increase of 8.4% and 11.3% compared with 2011, respectively. Over the past decade, China's installed capacity of wind power and solar power has increased significantly, accounting for 37.7% and 25.2% of the total installed capacity in 2020, respectively. Figure 2 shows the development of wind power and solar power in China from 2011 to 2020.

The fossil energy power generation method strives for cleanness and efficiency. Restricted by the endowment of energy resources, China's power supply structure has been dominated by thermal power for a long time, and coal power generation accounts for a significant proportion. According to the data released by the National Bureau of Statistics, China's thermal power generation reached 5.28 trillion kW·h in 2020, with a year-on-year increase of 1.2%, accounting for 71.16% of the national power generation. Thermal power generation has the advantages of low investment costs, fuel storage, flexibility in terms of location and stable operating conditions, but pollutant emissions and pollution control are the main constraints in its development process. At present, the development of China's energy industry has begun to follow the principle of a "strong guarantee of energy supply, and the intensity of energy consumption continues to decline" and has made remarkable

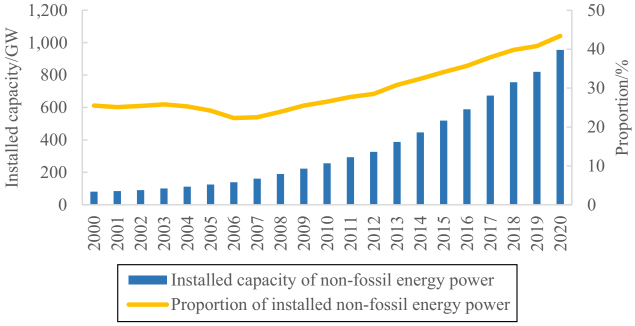

Figure 1.
Installed capacity and proportion of nonfossil energy in China from 2000 to 2020

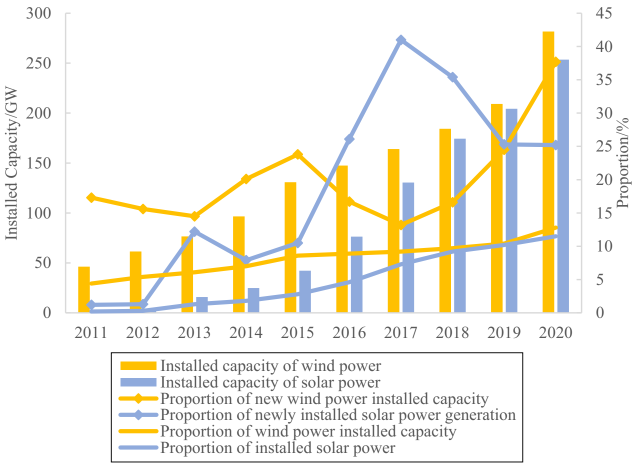

Figure 2.
Development of wind power and solar power in China from 2011 to 2020

progress. The reform of emission standards of thermal power plants in 2014, coupled with the release of the ultra-low emission and energy-saving transformation work plan for coal-fired power plants in 2015, significantly reduced the emissions and emission performance of pollutants in the national thermal power industry. In addition, thermal power units strictly control the emission of pollutants, such as smoke, SO_2 and nitrogen oxides, through improving pollution control technology, reducing the loss of coal-fired resources and optimizing the power structure, along with other measures. Meanwhile, the construction of an efficient operation system for the coal-fired thermal power industry has been promoted, on the basis of environmental protection. The emission of major pollutants from China's thermal power industry from 2011 to 2020 is shown in Figure 3.

3.2.2 Energy efficiency improvements of power consumption. In terms of the contribution rate to the growth of electricity consumption in society as a whole and the structure of electric power expenditure, the secondary industry is the main source of electricity consumption in China, but its proportion shows a downward trend on the whole. On the other hand, the ratio of power usage in the tertiary industry and by residents continues to rise. In 2020, the electricity consumption of the whole society reached 7521.4 billion kW·h, and the electric usage ratios of the primary, secondary and tertiary industries and urban and rural residents of the whole society were as follows: 1.1%, 68.2%, 16.1%, and 14.6%, respectively. At the same time, the growth rate of electricity consumption in tertiary industry, and by urban and rural residents, reached 2.0% and 6.8%, respectively. Compared with 2010, the proportion of electricity used by the tertiary industry and households increased by 5.4% and 2.4%, respectively. It can be seen that, although China's economy has significantly changed from high-speed growth to medium and high-speed growth since the period of the 13th Five-Year Plan, the power consumption of the society as a whole has continued to increase, and the growth rate has risen year by year. On the one hand, the rapid development of new business forms, such as the modern service industry, has boosted the increase in power consumption in the tertiary industry. On the other hand, the upgrading of residential consumption and the deepening of poverty alleviation have also led to rapid growth in the power consumption of urban and rural dwellers. Figure 4 shows the changes in electricity consumption and its growth rate in China from 2011 to 2020.

Electrification development is an effective way to achieve the carbon peak and carbon neutralization. At the moment, it is mainly concentrated in residential heating, industrial and agricultural production, transportation, power supply and consumption and other key areas. The continuous increase in the proportion of electricity expenditure in energy

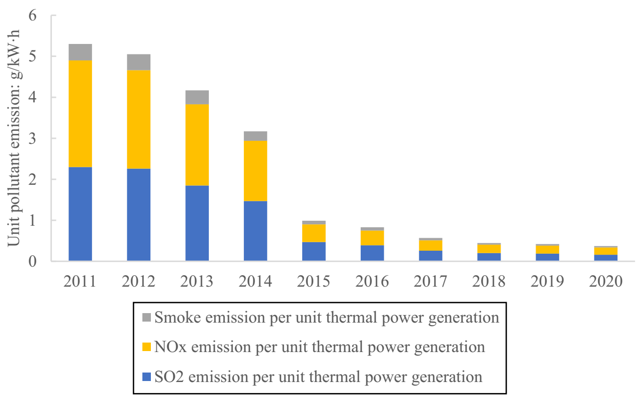

Figure 3.
Pollutant emission per unit of thermal power generation in China from 2011 to 2020

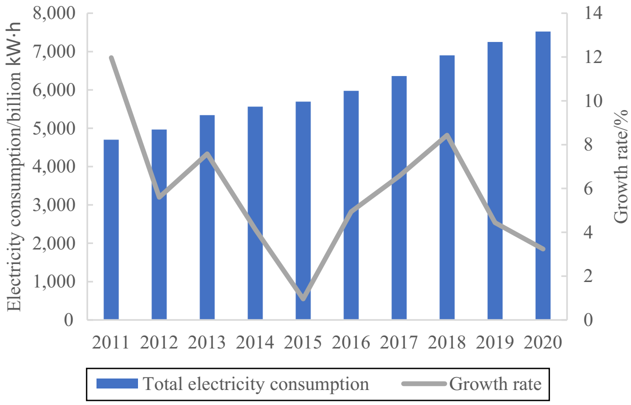

Figure 4.
Changes in electricity consumption and its growth rate in China from 2011 to 2020

consumption is an important trend in the development of the current energy system. As renewable energy undergoes rapid growth, the key position of electricity in energy supply and consumption and its core role in the process of the green and low-carbon transformation of the energy economy have been further highlighted. In 2020, the reform of power demand side management eased the contradiction between power supply and demand, advanced the use frequency of clean energy and significantly improved the efficiency of power consumption. For example, the power consumption of CNY 10,000 of GDP fell to about 632 kW·h, nearly 90 kW·h less than the equivalent value in 2015. The replacement power of electric energy exceeded 200 billion kW·h, and the terminal electrification level reached 27%. In 2020, the ratio of electric energy consumption in primary energy and electric energy in terminal energy consumption were 45.7% and 26.5%, 2.3 and 3.8 percentage points higher than that in 2010, respectively. The proportion of electric energy consumption in China from 2010 to 2020 is shown in Figure 5.

3.2.3 Power technology innovation. When implementing a low-carbon economic model, the power industry has to innovate the existing production processes and technologies based on relevant policies, so as to accelerate the low-carbon technological innovation and expansion of the whole industry. First, with the acceleration of urbanization and the substantial increase in residential power consumption, there are a large number of power

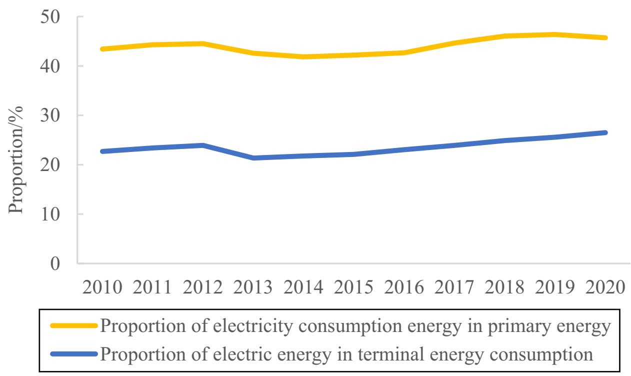

Figure 5.
Proportion of electric energy consumption in China from 2010 to 2020

supply load densities and complex power supply forms in cities, which produce higher requirements for the construction of the national power grid and power technology. To satisfy the power supply demands of modern society, a series of techniques, such as the protection and integration technology of distribution networks, new GIS facilities, direct-current distribution technology under high voltage and self-converting power technologies, have been widely used in the urban electricity supply. Second, the communication technology of China's power industry has achieved excellent development in recent years, especially in terms of power transmission and distribution. For example, the transmission technology of AC 1000 kV and DC 800 kV has reached the world's leading level. To carry out high-power AC transmission, power equipment is also combined with other power technology facilities in the FACTS facility composition, which is used to optimize power dispatching, reduce power costs and power losses and lay a solid foundation for the stability of the power system. Third, due to the renewable and recyclable characteristics of solar energy, it has been widely explored and used in the power industry in recent years. In addition, the direct conversion of solar energy into electric energy also has the advantages of being pollution-free and clean, which meets the policy requirements of energy conservation and emissions reduction in the context of green development. Solar power generation technology consists of two main aspects, photovoltaic power generation and thermal power generation, and has considerable development potential in the future planning of the power industry. Fourth, in recent years, specific practices have found that high-temperature fuel cells can produce up to 88% power generation efficiency through the application of combined cycles, so fuel cells have begun to be applied extensively. At the same time, fuel cell power generation, which possesses the features of low load, low pollution and the substitution of water resources, is conducive to achieving the important goal of zero emissions and alleviating the serious problem of water resource shortages. These features are highly consistent with the concepts of environmental protection and energy conservation. Due to the recent progress and innovation in power technology, the power consumption rate and line loss rate of power stations in China have decreased year by year, as shown in Figure 6.

3.2.4 Power system reform. As the industry that forms the basis of the national economy, the power industry plays an irreplaceable supporting role in the development of the economy and industrial sectors. The development of decarbonization in the power industry

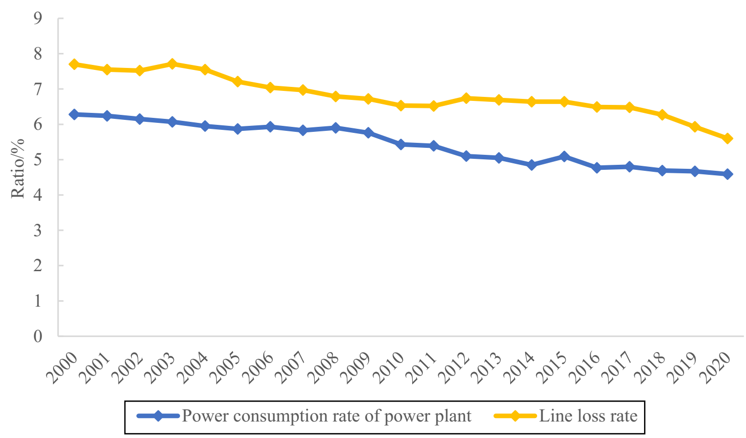

Figure 6. Power consumption rate and line loss rate of power stations in China from 2000 to 2020

is the key to reducing GHG emissions, while strong and effective policies and measures can accelerate the realization of carbon emission reduction targets (Nelson *et al.*, 2012). Therefore, the reform of the power system has a significant impact on the low-carbon transformation of the power industry. Before 1985, the power industry operated under the administrative monopoly of the government, maintaining a high degree of vertical integration of departments. This state of administrative monopoly, combined with vertical integration, seriously inhibited the enthusiasm of other economic entities to run power, reduced the efficiency of the power industry and caused a decades-long nationwide power shortage in China. To solve the problem of power shortages, the power industry has undergone three stages of economic system reform. The first stage (1985–1996) was the incremental reform stage. In this period, the power industry allowed local governments, domestic enterprises and foreign-funded enterprises to enter into the system, forming a diversified investment pattern of "multi-party electricity", so as to improve power supply efficiency and bring about a basic balance in power. However, the government still implemented the management plan of an administrative monopoly on the power industry. The second stage (1997–2001) was the government regulation stage. At this time, the power industry carried out the management mode of the "separation of government and enterprises", aiming to prevent departments from using administrative means to protect their monopoly position and change the pattern of administrative monopoly in the power industry. During this period, the administrative functions of the power sector were transferred to the State Economic and Trade Commission to form an independent management organization, while the power company just retained the right of business functions. These regulations basically changed the management system of the integration of government and enterprises. The third stage (2002–present) is the stage of split reform. According to the guiding ideology of power system reform of "breaking monopoly and introducing competition", the country has officially implemented the horizontal and vertical split reform of the power industry. In the process of vertical separation, the country separated the assets of the original power company according to the power generation and power supply business, and reorganized the power generation and grid enterprises. To form a competitive power generation market, the assets of former state-owned power companies were directly divided into five national independent power generation enterprises. These enterprises would need to participate in price competition if they wanted to enter the power grid industry.

3.3 Achievements in the low-carbon development of the power industry

Electricity is the basic driving force of economic and social development. Hence, the low-carbon development of the power industry is a vital area for carbon emission reduction in the energy system. The CO_2 emissions of the power industry are the main source of CO_2 emissions from energy activities. In fact, the main method of power generation in China is thermal power generation and the carbon emissions of this method come from the burning of fossil fuels. Therefore, this paper selects eight major fossil fuels in the power production process, namely, raw coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil and natural gas, as the final consumption of thermal power generation to calculate the carbon emissions of China's power industry. According to the IPCC emission calculation Guide (Liang *et al.*, 2021), formula (1) is used to calculate the carbon emissions of China's power industry. The results are shown in Figure 7:

$$C = \sum_{i=1}^{8} E_i \times \gamma_i \tag{1}$$

In formula (1), C represents the total carbon emissions of the power industry, E_i refers to the consumption of fossil energy i and γ_i refers to the carbon emission factor of the energy i.

The carbon emission factors of the eight fossil fuels under consideration here are in accordance with “2016 IPCC Guidelines for National Greenhouse Gas Inventories”. Specific values can be seen in Table 1.

This nearly keeps pace with the development of national GDP in the electricity demands of residents and enterprises. With the rapid development of the social economy, the demand of residents and enterprises for electric energy is growing with each passing day, to meet the demands of daily life and market operation. Therefore, the substantial increase in electricity consumption has led to a sharp rise in carbon emissions from the power industry. In 2020, carbon emissions reached 1.6 billion tons and increased by 41.2% compared with 2010. Detailed data regarding China’s carbon emissions from 2010 to 2020 are shown in Figure 7.

Although the electricity consumption of the whole society and the carbon emissions of the power industry have increased, the coal consumption per unit of power generation and power supply shows a downward trend year by year. The standard coal consumption rate of electric power is the most important economic index of thermal power stations, and it is also a comprehensive energy consumption index used to describe the function of main generator engines and the power consumption of auxiliary machines. With the progress of the power generation technology of thermal power units and the enhancement of the awareness of energy conservation and emissions reduction, thermal power plants have the potential to transform power generation equipment, leading to high efficiency and environmental protection, according to the actual power generation situation. At the same time, they will enable the operation analysis and management of generating units, deeply reduce the standard coal consumption index of the power supply and make a positive contribution to the implementation of the “double

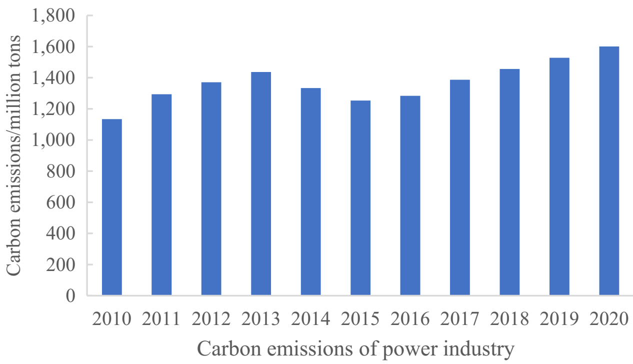

Figure 7.
Carbon emissions of China’s power industry from 2010 to 2020

Table 1.
Table of carbon emission factors of various energy sources

Type of energy	CEF (10^4t/10^4tce)
Raw coal	0.756
Coke	0.855
Crude oil	0.586
Gasoline	0.554
Kerosene	0.517
Diesel oil	0.591
Fuel oil	0.619
Natural gas	0.448

carbon" goal. By the end of 2020, the standard coal consumption for power generation and power supply in China were 287.2 and 304.9 g/kW·h, respectively, which are 16.3% and 17.6% lower than in 2005. The data intensity of the carbon dioxide emissions of electricity has been effectively alleviated. The coal consumption of electricity production and electricity supply in China's power industry from 2000 to 2020 is shown in Figure 8.

4. Low-carbon development goals of the power industry

The 19th National Congress of the Communist Party of China established a two-step strategic plan, that is, to realize socialist modernization by 2035 and to build a prosperous, strong, democratic, civilized, harmonious and beautiful modern socialist country by 2050. The "14th five-year plan" is the key period for China to embark on a new journey and advance towards the second Centennial goal, as well as to accelerate the construction of a clean, low-carbon, safe and efficient energy system. Therefore, China has put forward the goal of the carbon peak and carbon neutrality. On the one hand, this establishes the direction for China's comprehensive green transformation of economic and social development; on the other hand, it contributes a key force to global joint action to deal with climate change. In short, the carbon peak and carbon neutralization goals are inherent requirements of China's high-quality development. Nevertheless, the high-quality development of the economy and society, and the adjustment and optimization of the energy structure, have put forward new standards and requirements for the power system.

4.1 "Carbon peak" aims

The carbon peak period represented by 2021–2030 is the stage where the traditional power system is transformed. The key task during this phase is to make the carbon emission of the power system reach their peak before the energy system, weakening the position of coal power within the power supply system. Additionally, the development focal point should be shifted away from providing electric power towards flexible service and coupling new energy power generation, for the purpose of realizing the leapfrog development of wind power and photoelectricity (Energy, Transitions, C, 2019), and laying a solid foundation for the replacement of traditional energy with new energy and the construction of a new power system. During this period, it is necessary to adjust the single power supply structure of thermal power generation and to establish wind power and photovoltaic power as the main force to reduce coal and low carbon (Grubb *et al.*, 2006). It is expected that, by 2030, China

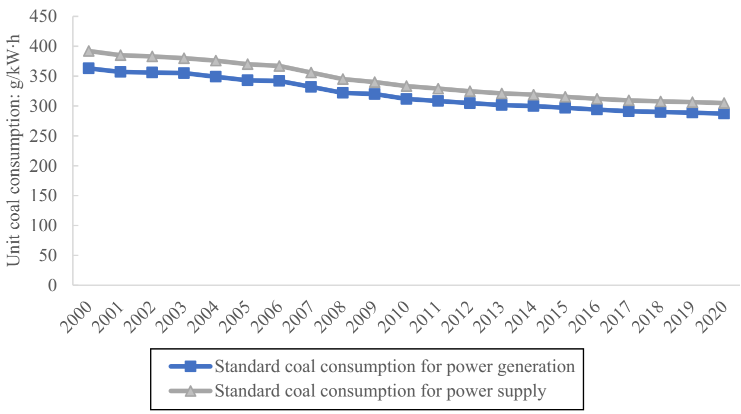

Figure 8. The coal consumption of electricity production and electricity supply in China's power industry from 2000 to 2020

will basically realize the additional generation of nonfossil energy and wind and light energy, which can meet the demand for all additional electricity, resulting in the proportion of installed wind and solar power increasing to about 50%. In the meantime, China's carbon dioxide emissions per unit of GDP will drop by more than 65% compared with 2005. To achieve the carbon peak goal, the power industry first needs to establish a peak awareness of coal and electricity and make technological improvements to tap the potential of low emissions and high energy conservation. At the same time, the power industry needs to enhance innovation investment in the renewable energy industry and make up for the technical shortcomings of industrial development. These developments will not only promote the integration of local manufacturing and the global supply chain but also realize the coordination of key links and provide important resource guarantees for the carbon emissions of the power industry to reach the peak in advance. Additionally, the government needs to reform the power system, build a unified national power market system, break down market barriers and form unified trading rules and technical standards. In this way, the construction of power market mechanisms can quickly adapt to the transformation of the energy structure, which will provide a reliable institutional guarantee for the power market to become a key industry covering carbon emissions.

4.2 "Carbon neutralization" aims

The carbon neutrality period represented by 2031–2060 is the mature stage of the development of new power systems. The key task of this stage is to ensure that, within a certain timescale, the total GHG emissions directly or indirectly generated by biological subjects can be offset through afforestation, energy conservation and emission reduction, allowing us to achieve "zero emissions" of carbon dioxide. The realization of carbon neutrality involves the linking up of various economic and social sectors, which is a complex, long-term and systematic problem. As the largest carbon emission department in the energy system, the conditions of power generation technology, power grid facilities and the supporting industries of the power system the basic guarantee of power sources that will promote the achievement of the carbon neutrality goal (Sepulveda *et al.*, 2018). To accomplish the task of carbon neutrality, we need to build a diversified clean energy supply system and improve the emergency standby and peak shaving capacity of the power system by optimizing the positioning of coal power functions. The power industry not only needs to take on the energy consumption and emissions from transportation, construction, industry and other fields but also to use clean energy to replace the existing fossil energy power supply. At the same time, because the power grid constitutes the core hub of carbon emissions reduction in the power system, it should not only meet the power demands of the economy and of society but also adopt a wide range of technologies in combination to provide protection for the large-scale development and utilization of new energy (Clack *et al.*, 2017). On the energy consumption side, we should comprehensively promote the electrification of power consumption and energy conservation and efficiency improvement, as well as controlling energy consumption (especially the usage of fossil energy) within a reasonable range, foregrounding the concepts of energy conservation and green development. Furthermore, power consumers should strengthen energy efficiency management, improve the substitution effect of electric energy and fully realize the response potential of the demand side through proactively participating in energy conservation and emission reduction activities. Finally, the government should perfect relevant policies and pricing mechanisms to regulate the electricity carbon market. This is because the carbon pricing tool that covers the whole economic system in the policy will help to turn the new power system into a green, low-carbon, safe, controllable, smart and flexible clean energy allocation platform (Kaplow, 2010; Borenstein *et al.*, 2019).

5. Conclusions and discussions

As the carbon emissions of the power industry are relatively high, the low-carbon measures of this industry have important theoretical and practical significance for promoting green development and accelerating low-carbon transformation. Based on the existing literature, this paper further analyzed the low-carbon development status of China's power industry and the achievements in carbon emission reduction by using descriptive statistics. The following conclusions can be drawn. China's power supply energy structure has been optimized, power consumption efficiency has been improved, power technology has been innovated and the power system has been reformed. Meanwhile, according to the IPCC emissions calculation guide (Liang *et al.*, 2021), we calculated the carbon emissions of the power industry and found that the carbon emission intensity of this industry has been effectively controlled. Finally, we proposed relevant policy recommendations by analyzing the carbon peak and carbon neutrality targets of the power industry.

The power industry should clarify its development direction and principles in terms of power system planning. Under the framework of China's economic system reform with high-quality development, the power industry, as an important area for low-carbon reform, should play a leading and exemplary role. Power planning should first be directed against the inconsistency between the development of power technology and carbon emission reduction targets; a feasible and cost-effective low-carbon transformation path with the concept of "energy economy-security-green" should be explored. In addition, we suggest implementing the coordinated promotion of pollution control and low-carbon development in the reform of environmental management systems, as well as fully considering the positioning of coal electricity in this new context. Through the research and development of new technologies to assist in environmental regulation (such as the pollution control of thermal power plants, energy and water conservation, GHG control), we may comprehensively promote the reform of environmental and economic policies in the power industry.

It is important to realize the harmonious development of production activities and the natural environment during the process of power production. At the production stage, staff can further separate the carbon dioxide in the emission source and then store it in a pollution-free manner with the help of relevant technologies, so as to achieve the purpose of lowering carbon emissions. At the same time, technicians can optimize the quality control technology of power coal blending, and improve the efficiency of thermal power generation by controlling coal blending standards, raw coal quality, calorific value and other indicators. Traditional power production has been unable to satisfy the requirements of the current low-carbon economy. To strictly abide by economic principles, the power industry can introduce smart grid and UHV technology to optimize power dispatching. These measures will reduce the costs and losses associated with power transportation, and realize the interconnection of power equipment and power information sharing.

Adhering to the electrification of power consumption will help to improve the quality and level of power substitution. The power sector should devote efforts to the research and planning of power consumption, in combination with the requirements of the major strategy of national economic and social development, the transformation of old and new kinetic energy and the upgrading of industrial structures, so as to effectively ensure that the power demands of all regions and industries can be met. The power sector ought to push forward the transformation and upgrading of power grids, emphasize the coordinated development of power grids at all levels and highlight the role of power grids as hubs and platforms in energy transformation and resource allocation. These actions will enable the intelligent development of integrated energy systems by improving the comprehensive utilization efficiency of multiple energies. Additionally, the power sector can support the technology research and development and project application activities related to power substitution by issuing incentives or subsidies. Mobilizing the enthusiasm of users (power demanders) to participate in power substitution will certainly improve the power substitution rate and terminal power efficiency.

The government should perfect the power market mechanism and reduce the burden of transforming and upgrading the power industry. By broadening the freedom of the power generation rights trading market, the country can reduce the early burden of power enterprises using new energy technologies for industrial upgrading. Meanwhile, the country can stop provincial governments from collecting additional fees, such as power generation rights trading fees, to reduce the intermediate cost of power enterprises in the market for power generation rights trading. Additionally, the government can establish energy-saving and emissions-reduction platforms for the power industry in various regions, which can improve the carbon emission trading market system, and standardize and institutionalize the trading of carbon emissions and pollution rights. These behaviors will help provide more financing opportunities for enterprises using new energy sources for power generation, so as to alleviate the capital shortage caused by excessive investment in the early stage of research and development and stimulate the clean development of power enterprises.

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