Comprehensive Evaluation of Carbon Emission Reduction Process in Power Industry of China

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Abstract. The power sector accounts for about 41% of China's total carbon emissions from the energy sector, with thermal power being the main source of carbon emissions. The two-carbon target requires energy and power companies to follow a methodical approach to accelerate the diversification of energy supplies and clean, low-carbon, efficient reduction of energy use and electrification. Therefore, it is extremely important to develop a model to monitor and evaluate the carbon reduction process in the power sector. This paper constructs the monitoring index system of carbon emission reduction process in China's power industry from five dimensions: market, technology, social economy, power production and consumption. It then used a fuzzy comprehensive evaluation method to thoroughly assess the overall carbon reduction process across all five systems and the power sector. The results show that the carbon emission reduction process of China's power industry has improved steadily. After 2010, driven by the adjustment of the economic and energy consumption structure and the improvement of energy utilization efficiency, the overall performance of carbon emission reduction in the power industry has gradually improved from a poor level. After 2014, with the establishment of carbon trading market, technological progress and low-carbon transformation of social and economic structure, the process of emission reduction in the power industry has been accelerated, reaching a good level in 2020 and 2021.

Keywords: Electric power industry; Emission reduction process; Fuzzy comprehensive evaluation.

1 Introduction

During the 75th session of the UN General Assembly's general discussion on September 22, 2020, the Chinese president said that China will enact more stringent laws and regulations, aim to peak carbon dioxide emissions by 2030, and work toward becoming carbon neutral by 2060. According to the 14th Five-Year Plan, "energy consumption per unit of GDP and carbon dioxide emissions will be reduced by 13.5% and 18%, respectively," throughout the plan's duration. The developed economies, including the European Union, have reached their peak in terms of carbon dioxide emissions. The transition from "carbon peak" to "carbon neutrality" takes 50–70 years. China's emissions make up approximately 30% of global emissions, more

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than the combined emissions of the US, the EU, and Japan. Only 30 years have passed from "carbon peak" to "carbon neutrality", and hard work must be done.

About 85% of all carbon dioxide emissions and roughly 70% of all greenhouse gas emissions are produced by China's energy consumption; of these, the power industry is responsible for 41% of all carbon emissions, with thermal power being the primary source. The grid links energy production and consumption and is a key player in the clean, low-carbon transformation of energy. Energy and power companies are required under the dual-carbon goal to follow the systematic concept, collaborate in all areas of the source network and the storage and storage system, and quicken the pace of low-carbonization, efficient reduction of energy consumption, and electrification. To measure the power industry's recent progress in reducing carbon emissions, it is crucial to develop a monitoring and assessment model for the industry's carbon emission reduction process.

2 Literature review

There is a lot of literature on carbon emission influencing factors and monitoring. Most of the studies concluded that economic development, power generation structure, power consumption demand, market and science and technology have an impact on carbon emissions in the power sector. Malla examines the influence of the major variables that led to the shift in carbon emissions from 1990 to 2005 using the LMDI model. According to the research findings, the most significant element driving the increase of carbon emissions is power production activity, and the power structure has also had a beneficial role in boosting the rise of carbon emissions[1]. The research results of Zhang et al show that economic activity is the most important factor leading to the growth of carbon emissions in the power generation industry, and thermal power energy efficiency plays a key role in the emission reduction process of the power generation industry[2].

Based on Shrestha's research, the increase in CO2 emissions in Australia, China, India, Japan, Malaysia, Pakistan, South Korea, Singapore, Thailand, and Vietnam was primarily driven by economic growth. Conversely, Bangladesh, Indonesia, and the Philippines experienced a rise in CO2 emissions due to increased electricity intensity in their economies. In the cases of Sri Lanka and New Zealand, changes in the power generation structure were identified as the main factor contributing to the changes in CO2 emissions[3]. Tangyang Jiang used an extended version of the input-output technique, the structural decomposition approach, and the energy consumption method to investigate the structural emission reduction of China's power and heating industry from 2007 to 2015. The findings show that, first and foremost, energy composition, input, and energy intensity have a substantial influence on decreasing CO2 in China's power and heating sectors, and that this effect is growing in terms of CO2 structure impacting power and heating energy[4]. The increased emissions of carbon dioxide are primarily driven by economic activity, but this is counterbalanced by the contribution of the generation structure. Karmellos et al. conducted an analysis to determine the relationship between economic growth and carbon dioxide emissions in each country during the period of 2013-2018. The findings reveal that most countries in the EU-27 are experiencing a strong decoupling between economic growth and carbon dioxide emissions.[5].

Cui et al. developed an assessment index system for thermal power plants' potential to save energy and reduce emissions, and the weights were determined using a hierarchical analytic approach. The following findings have been reached: Pollutant emissions are the key factor limiting its potential to save energy and reduce emissions[6]. DSM, smart grid technology, low-carbon power production technology, low-carbon energy usage, and low-carbon power dispatch were recognized as the primary low-carbon components in the power system by Zhou et al. The corresponding evaluation methods are then proposed, the low-carbon benefits from various sources are quantitatively analyzed, and a general comprehensive evaluation model is established, which reasonably integrates various types of low-carbon benefits in the power system while eliminating overlapping effects[7]. Jiang et al. developed a thermal power plant energy consumption index system based on the energy consumption characteristics of thermal power plants. The multi-attribute decision-making approach is used to analyze the thermal power generation index system in China, which gives theoretical direction for energy transformation, energy savings, and emission reduction[8].

A large number of studies have studied the impact of carbon emissions on the power industry, and established a comprehensive evaluation system for power plants and industries. However, most studies are based on the power plant or the power industry itself, and do not take into account the indirect impact of macro-level socioeconomic structure transformation, end-consumption market, carbon market and technological progress on carbon emission reduction in the power industry. The main contribution of this paper is reflected in two aspects: First, the monitoring index system of the emission reduction process of the power industry is constructed from the dimensions of social economy, production system, consumption system, market system and science and technology system; The second is to comprehensively evaluate the emission reduction process of the power industry through fuzzy comprehensive evaluation.

3 Indicator System and Data Sources

On the basis of comprehensively combing the relevant literature on carbon emission reduction in the power industry, combined with the availability of data, 17 indicators are selected from five dimensions: social economic system, production system, consumption system, market system and science and technology system to monitor the process of carbon emission reduction in the power industry. Refer to **Fig. 1** for the framework of indicator system construction. The social and economic system mainly considers the impact of economic structure, energy structure and energy utilization efficiency on emission reduction. Therefore, the three indicators of the proportion of the secondary industry(X1), the proportion of coal consumption(X2), and the power consumption per unit of GDP(X3) were selected. The secondary industry is the main sector of power consumption, so the reduction in the proportion of the secondary industry will help reduce carbon emissions. Coal consumption is the main source of carbon emissions, so the reduction in the proportion of coal consumption is generally conducive to reducing emissions in the power industry.

The production system represents the power sector, with indicators including the proportion of thermal power in total power generation(X4), the proportion of coal as a fuel in thermal power(X5), the proportion of non-fossil energy generation capacity(X6), and the consumption of coal for power generation(X7). These indicators are closely related to carbon reduction in the power sector. The consumption system mainly considers the substitution of electricity for fossil fuels among end-users. The substitution of electricity for fossil energy consumption is represented by the electrification rate. This paper mainly selects the electrification rate of industrial(X8) and household consumption(X9), which has the largest proportion of energy consumption. The higher the electrification rate, the greater the indirect carbon emission reduction. In addition, the proportion of the secondary industry's demand for electricity(X10) is also considered, and the smaller the proportion of demand, the greater the indirect emission reduction.

Market systems include the power market and the carbon market. The electricity market uses the trading volume of green electricity(X11) as an indicator. Green electricity refers to its carbon dioxide emissions as zero or approaching zero during the production of electricity. The carbon market includes carbon market quota volume(X12), CCER transaction size(X13) and average carbon price(X14). Scientific and technological system indicators include research and experimental development expenditures(X15), the number of patents for energy conservation and emission reduction(X16), and the scale of CCUS(X17).

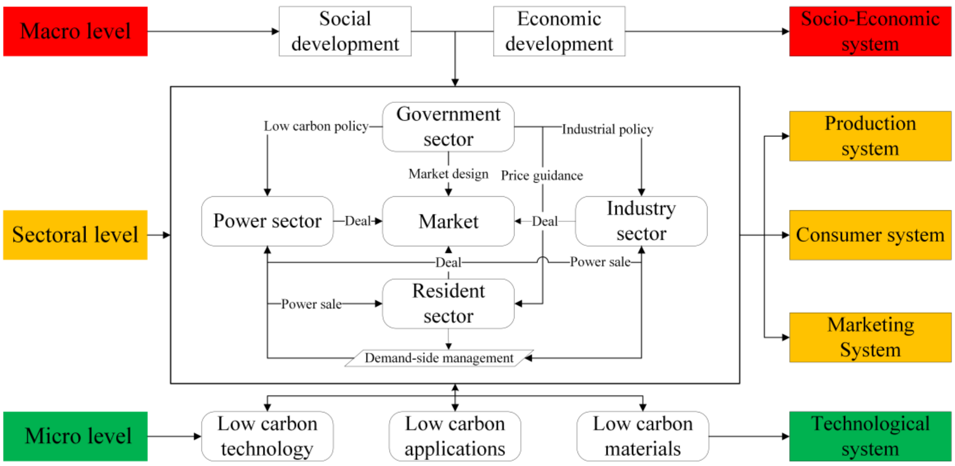

Fig. 1. Framework for monitoring index system of carbon emission reduction process in power industry

According to data availability, annual data from 2000 to 2022 are selected[1]. Data sources include National Bureau of Statistics, National Energy Administration, China Energy Statistics Yearbook, and China Electric Power Yearbook, China Electricity Council, CNESA, Wind, EPS, and CSMAR database. To eliminate the influence of different units on different variables, all variable data is standardized before analysis.

$$x_p = \frac{x_i - x_{min}}{x_{max} - x_{min}} \tag{1}$$

$$x_n = \frac{x_{max} - x_i}{x_{max} - x_{min}} \tag{2}$$

Where, x_p represents a positive indicator and x_n represents a negative indicator.

[1] Carbon market data from 2013-2022, green electricity trading data from 2017-2022.

4 Method

The process of carbon emission reduction in the power industry is affected by many factors, and there is great uncertainty in the influence of various factors and the formulation of standards, so the fuzzy comprehensive evaluation (FCE) method is selected in this paper. The FCE technique is a commonly used decision-making approach that was established on the basis of relevant fuzzy mathematics ideas. The FCE approach, according to fuzzy mathematics' membership theory, converts qualitative assessment into quantitative evaluation.

The evaluation factor set is set as U={U_1, U_2,...U_l}, and l is the number of evaluation indicators. The evaluation set is V={V_1, V_2, V_m}, and m is the number of evaluation grades of evaluation criteria. The weight coefficient set of each evaluation index is W={W_1, W_2,...W_l}; R is a fuzzy matrix for the comprehensive evaluation of carbon emission reduction in the power industry composed of the results of each evaluation index. The evaluation results are as follows:

$$Y = W \cdot R = \{Y_1, Y_2, \dots Y_m\} \tag{3}$$

Establish the fuzzy relationship matrix R = (r_{ij}), and use the half-order trapezoidal affiliation function to establish the affiliation function of each evaluation factor to each level of criteria r_{ij}. Let x_i denote the index value of the ith evaluation factor, and S_{ij} denote the representative value of the grade j of the ith evaluation factor. For the negative indicator, the formula for calculating the membership degree of the ith evaluation factor belonging to the grade is:

$$r_{i1}(x_i) = \begin{cases} 1 & x_i \le S_{i1} \\ \frac{(S_{i2}-x_i)}{S_{i2}-S_{i1}} & S_{i1} < x_i \le S_{i2} \\ 0 & x_i > S_{i2} \end{cases} \tag{4}$$

$$r_{ij}(x_i) = \begin{cases} \frac{(x_i-S_{ij-1})}{(S_{ij}-S_{ij-1})} & S_{ij-1} \le x_i \le S_{ij} \\ \frac{(S_{ij+1}-x_i)}{(S_{ij+1}-S_{ij})} & S_{ij} < x_i \le S_{ij+1} \\ 0 & x_i < S_{ij-1}, x_i > S_{ij+1} \end{cases} \tag{5}$$

$$r_{im}(x_i) = \begin{cases} 1 & x_i \ge S_{im} \\ \frac{(x_i-S_{im-1})}{(S_{im}-S_{im-1})} & S_{im-1} \le x_i < S_{im} \\ 0 & x_i < S_{im-1} \end{cases} \tag{6}$$

For positive indicators:

$$r_{i1}(x_i) = \begin{cases} 1 & x_i \ge S_{i1} \\ \frac{(x_i-S_{i2})}{S_{i1}-S_{i2}} & S_{i2} < x_i \le S_{i1} \\ 0 & x_i < S_{i2} \end{cases} \tag{7}$$

$$r_{ij}(x_i) = \begin{cases} \frac{(x_i-S_{ij+1})}{(S_{ij}-S_{ij+1})} & S_{ij+1} \le x_i \le S_{ij} \\ \frac{(S_{ij-1}-x_i)}{(S_{ij-1}-S_{ij})} & S_{ij} < x_i \le S_{ij-1} \\ 0 & x_i < S_{ij+1}, x_i > S_{ij-1} \end{cases} \tag{8}$$

$$r_{im}(x_i) = \begin{cases} 1 & x_i \le S_{im} \\ \frac{(S_{im-1}-x_i)}{(S_{im-1}-S_{im})} & S_{im} < x_i \le S_{im-1} \\ 0 & x_i > S_{im-1} \end{cases} \tag{9}$$

4.1 Determine Evaluation Grade

V={V1, V2, Vm} represents the evaluation set. In this article, V_1-V_4 represents four grades of very good, relatively good, general and relatively poor, respectively. According to the national carbon emission reduction target and the carbon emission reduction target of the power industry, and with reference to existing literature, the evaluation level of each index is designed as shown in **Table 1**.

4.2 Determine Weight

This paper uses the CRITIC method to determine the weight of each evaluation index. The CRITIC method is based on contrast strength and conflict when constructing weights. Among them, the contrast intensity is reflected in the form of standard deviation. Generally speaking, the larger the standard deviation, the larger the gap between various categories. The conflict is reflected by the correlation coefficient between the indicators. If the negative correlation between the indicators is large, the conflict is greater. The mathematical calculation formula of the introduced information quantity is as follows:

$$H_j = S_j \sum_{i=1}^{p}(1 - r_{ij}) \tag{10}$$

where S_j is the standard deviation and r_{ij} is the correlation coefficient. The larger the H_j, the greater the influence of the j attribute on the decision, and more weight should be assigned to it. Therefore, the objective weight of the jth attribute is expressed as:

$$W_j = \frac{H_j}{\sum_{j=1}^{p} H_j} \tag{11}$$

This article first determines the weights of various indicators in the subsystem and calculates the comprehensive scores of each subsystem. Based on the comprehensive scores, CRITIC is used again to determine the weights of each subsystem. The results are shown in the **Table 1**. From the perspective of primary indicator weights, the impact of socio-economic and market systems is significant. From the perspective of the weight of the secondary indicators, energy efficiency, green power trading volume, CCER scale, secondary industry power demand, economic structure, thermal power share and energy consumption structure have a greater impact, with weights exceeding 6%.

Table 1. Weights and grading representative values of various indicators

Primary indicators	Weight	Secondary indicators	Weight	Unit		Graded Representative Values			
						V1	V2	V3	V4
Socio economic system	24.97	X1	6.79	%	<	20	40	50	60
		X2	6.34	%	<	50	60	70	80
		X3	11.84	KWh/10^4 ¥	<	600	800	1000	1300

Production system	15.28	X4	5.21	%	<	40	60	70	80
		X5	6.52	%	<	50	70	80	90
		X6	2.50	%	>	70	50	40	30
		X7	1.06	g/kWh	<	250	300	350	400
Consumer system	15.43	X8	4.12	%	>	50	30	20	10
		X9	3.88	%	>	40	30	20	10
		X10	7.43	%	<	50	55	60	70
Market system	28.20	X11	9.38	10^8 KWh	>	1000	500	10	1
		X12	4.73	10^8 ton	>	10	1	0.1	0.01
		X13	8.75	10_8 ton	>	10	1	0.1	0.01
		X14	5.34	¥/ton	>	70	50	30	20
Technical system	16.12	X15	4.57	100 million yuan	>	50000	30000	10000	5000
		X16	5.72		>	50000	10000	5000	1000
		X17	5.84	10^4 tons/year	>	10000	1000	500	1

5 Results

According to the calculation results and the principle of maximum affiliation, the evaluation levels V1-V4 are assigned as 4, 3, 2 and 1, respectively, and the results of the comprehensive evaluation of the monitoring and evaluation of carbon emission reduction process in China's electric power industry are shown in **Fig. 2**.

As shown in the evaluation results, before 2010, the comprehensive evaluation score of China's power industry's carbon emission reduction process was 1, which was always in a poor level. However, in 2008, China took advantage of the opportunity to host the Olympic Games to increase support for energy conservation and emission reduction. The economic structure and energy structure began to transition to low carbonization. The score of the carbon emission reduction process in the power industry gradually increased, hovering between poor and average. In 2012, the technology system score started to rise, benefiting from the increase in R&D expenditure and the number of patents, as well as the development of CCUS.

With the establishment of the carbon trading market in 2013, the comprehensive carbon emission reduction score of the power sector stabilized above 2, between average and better. Improvements in power generation and consumption systems did not start until after 2018, with thermal power accounting for less than 70 percent for the first time and non-fossil energy capacity accounting for more than 40 percent of installed capacity. From the perspective of the consumer side, the proportion of power demand in the secondary industry is lower than 70% for the first time, and the electrification rate of industrial and residential consumption has increased significantly. Although the comprehensive scores of the production and consumption systems have increased in recent years, they have not yet reached a good level, which has led to the comprehensive evaluation of carbon emission reduction processes in the power industry always being between good and average levels.

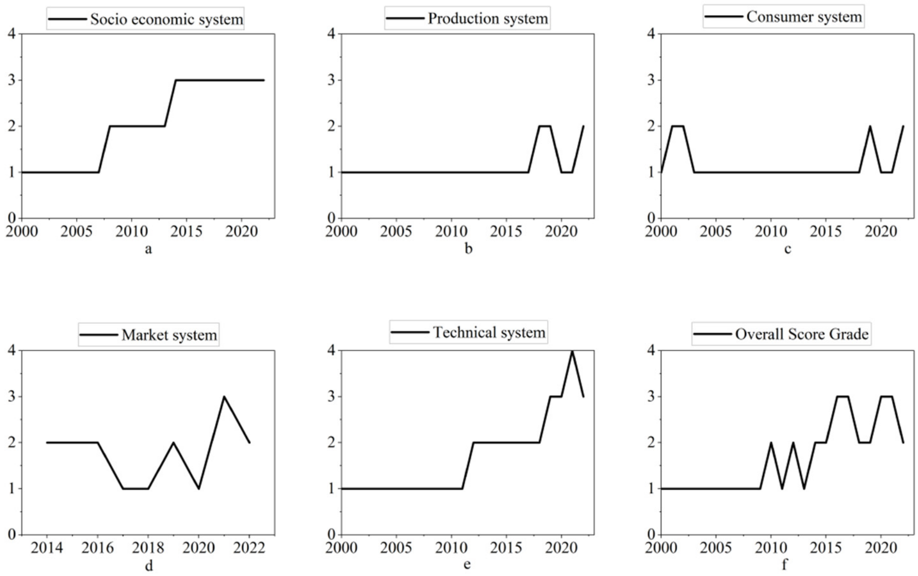

Fig. 2. Comprehensive Evaluation Results of Carbon Emission Reduction Process in Power Industry

Since 2020, the overall carbon emission growth of the power industry has slowed down due to the impact of COVID-19. The significant increase in the number of patents at the technical level, as well as the establishment of a national carbon trading market in 2021, have led to a brief improvement in the carbon emission reduction process in the power industry. However, with the rapid economic recovery in 2022 and a significant increase in electricity demand, the evaluation results have returned to the average level once again. Overall, the carbon emission reduction process in China's power industry is generally improving, but there are multiple influencing factors and repeated processes.

6 Conclusion

This paper constructs the monitoring index system of carbon emission reduction process in China's power industry from 17 indicators in five dimensions: social economy, production, consumption, market and technology. Fuzzy comprehensive evaluation method is adopted for evaluation and CRITIC method is used to calculate the weight of each index to obtain the comprehensive score of the carbon emission reduction process in the power industry. The result shows. The carbon emission reduction process scores of China's power industry are stable and rising. After 2010, driven by the adjustment of the economic and energy consumption structure and the improvement of energy utilization efficiency, the overall performance of carbon emission reduction in the power industry has gradually improved from a poor level. After 2014, with the establishment of a carbon trading market, technological progress and low-carbon transformation of the social and economic structure, the process of reducing emissions in the power market has accelerated, reaching a good level in 2020 and 2021.

Based on the empirical results, this paper puts forward five suggestions: First, continue to promote the low-carbon transformation of the social and economic structure, especially improve energy efficiency. The second is to further reduce the proportion of thermal power, expand the installed scale of clean energy, increase the utilization rate of wind power, solar energy and water energy, and reduce coal consumption for power generation. The third is to reduce the proportion of electricity demand in the secondary industry and increase the electrification rate of industrial and residential consumption. Fourth, vigorously develop the carbon trading market and green power trading, and start the CCER project as soon as possible. Fifth, increase research and development support for low-carbon energy-saving technologies and promote the commercialization of CCUS projects.

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