Multi-Perspective Influence Mechanism Analysis and Multi-Scenario Prediction of Carbon Emissions—A Case of the Yangtze River Delta, China

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Abstract. Under the mandatory push of meeting carbon emission reduction commitments proposed in the Paris Agreement, the analysis on the peaking time of China's carbon emissions deserves enough attention. This paper focuses on the peaking times of total carbon emissions (TCE) and carbon emission intensity (CEI) in the Yangtze River Delta (YRD). According to the development of carbon emissions in YRD and related targets in the 13th Five-Year Plan, the peaking times of TCE and CEI in different scenarios are predicted based on the influence mechanism analysis of carbon emissions in YRD from the perspective of energy, economy and society. Considering the development characteristics of China at this stage, this paper introduces several new indicators such as full-time equivalent of research and development (R&D) personnel and investment in environmental pollution control. Based on the study results, several policy recommendations are put forward to fulfil China's carbon emission reduction commitments.

1 Introduction

The energy crisis has become the focus of global sustainable development, and global warming caused by the massive consumption and utilization of energy resources is prominent. China's resource-dependent development has made environmental problems increasingly intensified. China's sustainable development faces a serious situation. To bear the responsibility of reducing carbon emission, China has committed to reach its carbon emissions peak in 2030 and reduce its carbon emission intensity by 40-45% in 2020 than that in 2005 in the Paris Agreement^[1].

Fig. 1. China's primary energy consumption system from 2006 to 2017.

As illustrated in Figure 1, fossil energy still accounts for most of the primary energy consumption in China. It is necessary for China to realize commitments in the Paris Agreement and promote sustainable development. The Yangtze River Delta (YRD), as one of the most densely populated regions in China, is an important engine for stimulating China's economic development. The period of the 13th Five-Year Plan is a crucial period for China to fulfil its carbon emission reduction commitments proposed in the Paris Agreement. Some constrained targets about carbon emission reduction have been clarified in the 13th Five-Year Plan. Therefore, this paper conducts a comprehensive and in-depth study on the influence mechanism and development of carbon emissions in YRD to predict the peaking times of TCE and CEI in different development scenarios. Furthermore, this study can provide a valuable reference for the optimization of carbon emission reduction policy.

As to carbon emissions reduction commitments, although some scholars have predicted carbon emissions in China by 2020^[2-6], few studies have predicted the peaking time of carbon emissions in different scenarios. In addition, most scenario design only considered the targets to achieve without considering past development^[7-10]. In this paper, key drivers of carbon emissions in YRD are identified based on the influence mechanism analysis. And the multi-scenario prediction under the constraints of related targets in the 13th Five-Year Plan

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is carried out to determine the peaking times of TCE and CEI in YRD. The research results are conducive to the Chinese government to formulate realistic and scientific policies to abate carbon emissions.

2 Methodology and data

2.1. Data sources

Based on the carbon emission reduction targets, this paper analyses carbon emissions in YRD by using two indicators of TCE and CEI. The data in this paper is collected from the China City Statistical Yearbook and China Energy Statistical Yearbook. Data related to the economy and society is derived from the China City Statistical Yearbook while Data related to energy derived from the China Energy Statistical Yearbook. The datasets can allow us to observe the key drivers of TCE and CEI in YRD and predicts their peaking times in four scenarios.

2.2. Measurement of carbon emissions

Given no official carbon emissions data, the carbon emissions studied in this paper is calculated on the basis of primary energy consumption. In the conversion of primary energy consumption into TCE, the calculation formula is shown in Formula (1):

$$C = \sum E_i \times F_i \times K_i \quad (1)$$

where, C represents the TCE produced by primary energy consumption and its unit is million tons; E_i represents the consumption of the i-th energy; F_i and K_i represent standard coal coefficient and carbon emissions coefficient of the i-th energy, respectively [11]. The standard coal coefficient and carbon emissions coefficient of different kinds of energy are shown in Table 1.

Table 1. Standard coal coefficient and carbon emissions coefficient of different kinds of energy.

Energy	Standard coal coefficient	Carbon emissions coefficient (t/tce)
Coal	0.7143 kgce/kg	0.7559
Coke	0.9714 kgce/kg	0.8552
Crude oil	1.4286 kgce/kg	0.5857
Gasoline	1.4717 kgce/kg	0.5538
Kerosene	1.4717 kgce/kg	0.5714
Diesel oil	1.4571 kgce/kg	0.5921
Fuel oil	1.4286 kgce/kg	0.6185
Natural gas	1.2721 kgce/m ³	0.4483

CEI (W) represents the carbon emissions from the growth of per unit of gross national product (GDP). It equals the ratio of TCE (C) to GDP, as shown in Formula (2):

$$W = C / GDP \quad (2)$$

2.3. Establishment of influence mechanism analysis method

2.3.1 System dynamics model

Prof. Forrester of the Massachusetts Institute of Technology first proposed System dynamics in 1956. System dynamics is a model for studying and analysing systems containing complex information feedback based on cybernetics, control engineering, systems engineering, information processing and computer simulation techniques [12]. There are some main loops in the feedback loops inside the system. It is these main loops and their interactions that mainly determine the dynamic behaviour of the system. It provides theoretical support for studying the influence mechanism of carbon emissions in YRD. Since carbon emissions are closely related to the entire process of energy consumption, it's necessary to build a carbon emission system from multiple perspectives. Therefore, system dynamics is applicable for the influence mechanism analysis of carbon emissions in YRD.

2.3.2 STIRPAT model

Ehrlich and Commoner, two American ecologists, first proposed the prototype of STIRPAT model in the 1970s [13]. It is a random special form based on the I-PAT model (Yu and Ma, 2016), expressed as:

$$I = aP^b A^c T^d e \quad (3)$$

where, I, P, A, and T represent different influence from the environment, population, wealth and technology, respectively; b, c, and d are the coefficients of P, A, and T; a is the constant term of the model and e is the random error term.

To simplify the calculation, the STIRPAT model becomes a linear model by taking the logarithm of the two sides of the equation. The linear form is as follows:

$$\ln I = \ln a + b \ln P + c \ln A + d \ln T + \ln e \quad (4)$$

The processed STIRPAT model eliminates the effects of proportional changes. Therefore, the application of STIRPAT model to the quantitative analysis of the key drivers of carbon emissions in YRD is suitable. The model coefficient is an important parameter for calculating the influence degree of each key driver on carbon emissions in YRD.

2.4. Establishment of prediction method

2.4.1 BP Neural Network model

Inspired by the central nervous system of the animal (especially the brain), the neural network model is applied to estimate the unknown approximation function. The neural network is usually presented as interconnected "neurons" that can begin machine learning and pattern recognition from input values due to its adaptive nature of the system. The basic unit of a neural network is a neuron whose basic function is to implement network input and output [14]. The Back Propagation (BP) network is a widely used neural network model, proposed by Rinehart and McClelland in 1986[15].

The error function falls in the negative gradient direction due to the correction of the network weight and threshold through the training of sample data, and the expected output is approximated. It is mostly used for model time series prediction. In this paper, Log-sigmoid function is the transfer function. Its formula is as follows:

$$f(x) = \frac{1}{1 + e^{-x}}, -\infty < x < \infty \quad (5)$$

The back-propagation error function is as follows:

$$E = \frac{\sum_i (t_i + O_i)^2}{2} \quad (6)$$

where, t_i is the expected output while O_i is the calculated output. The error function can be minimized by constantly adjusting the network weights and thresholds.

Since carbon emissions in YRD are affected by various drivers, the application of the BP neural network model is scientific and reasonable to predict the peaking times of TCE and CEI in YRD under the constraints of related targets in the 13th Five-Year Plan.

2.4.1 BP Neural Network model

Scenario prediction is a comprehensive method for predicting various possible development trends of the research object under the premise of simulating various scenarios [16]. We combine the scenario prediction and the BP neural network model to predict the peaking times of China's TCE and CEI.

2.4. Research framework

Figure 2 depicts the study framework of this paper.

Fig. 2. Research framework

3 Results and discussion

3.1 Multi-perspective influence mechanism analysis of carbon emissions in YRD

3.1.1 Multi-perspective analysis of carbon emissions system

Carbon emissions have a lot to do with the development of the economy, society and the supply and demand of energy. This paper uses system dynamics to reveal the relationship between various drivers of carbon emissions and divide carbon emissions system into the three subsystems of economic module, energy module and social module. Based on the multi-perspective analysis of carbon emissions system, the internal relationship diagram of carbon emissions system is shown in Figure 3.

Fig. 3. Internal relationship diagram of carbon emissions system.

3.1.2 Quantitative analysis of key drivers of carbon emissions in YRD

As the trading system in China’s energy market still needs to be improved, the acquisition of data such as energy price and carbon tax is difficult. China has set clear development targets for residents' living standards, energy consumption structure and industrial structure stage by stage. Therefore, ten key drivers of carbon emissions in YRD are identified from the three perspectives of economy, energy and society, as shown in Table 2.

Table 2. Key drivers of carbon emissions in YRD.

Perspective	Key driver		Unit
Economy	GDP	A1	Billion yuan
	Household consumption level	A2	Yuan
	Proportion of secondary industrial output-value	A3	%
Energy	Energy production	T1	10 ⁴ tce
	Energy consumption	T2	10 ⁴ tce
	Energy intensity	T3	tce /10 ⁴ yuan
	Efficiency of energy conversion	T4	%
	Renewable energy consumption ratio	T5	%
Society	Full-time equivalent of R&D personnel	P1	Million people one year
	Investment in environmental pollution control	P2	Billion yuan

After substituting the normalized data into Equation (4) of TCE and CEI separately, the multiple regression analysis is carried out by SPSS. This paper selects the backward regression method to reduce the multi-collinearity degree of linear STIRPAT equations. Therefore, the fitting results of the equations are more consistent with the actual development trend of TCE and CEI. The adjusted regression equations are as follows:

$$\ln C = 0.21 \ln A_1 + 0.14 \ln A_2 + 0.22 \ln A_3 - 0.03 \ln P_1 - 0.05 \ln P_2 + 0.17 \ln T_1 + 0.26 \ln T_2 + 0.19 \ln T_3 - 0.14 \ln T_4 - 0.16 \ln T_5 + \ln e$$
 (7)

$$\ln W = 0.23 \ln A_1 + 0.15 \ln A_2 + 0.06 \ln A_3 - 0.13 \ln P_1 - 0.04 \ln P_2 + 0.12 \ln T_1 + 0.29 \ln T_2 + 0.26 \ln T_3 - 0.22 \ln T_4 - 0.27 \ln T_5 + \ln e$$
 (8)

Therefore, the influence degree of each key driver of carbon emissions in YRD can be calculated according to Equation (7) and Equation (8) as shown in Figure 4.

Fig. 4. Influence degree of each key driver of carbon emissions in YRD.

As to the TCE growth, the positive influence of energy consumption growth is the largest while the negative influence of renewable energy consumption ratio growth is the largest. Compared with the regression results of TCE, the growth of CEI is not only influenced by energy intensity positively, but also by full-time equivalent of R&D personnel negatively. As can be seen, the control of energy consumption, optimization of energy consumption structure and application of technological achievement are the bases for carbon emission reduction. Therefore, the increase of scientific research investment is an important guarantee for the realization of CEI control targets, and there is still much room for exploration of carbon emission reduction potential relying on technological progress.

3.2 Multi-scenario prediction of carbon emissions in YRD

The key drivers of carbon emissions in YRD are taken as the main parameters of the scenario design. Not only YRD's development during the period of 11th and 12th Five-Year Plan (2006-2015) but also the related targets

in the 13th Five-Year Plan are important references for determining scenario parameters. The scenario parameters and the interval of each parameter's average annual growth rate are shown in Figure 8.

Based on these planning targets, the following four scenarios are designed:

- (1) The benchmark scenario is a scenario in which the parameters maintain the current development trend.
- (2) The economic development first scenario is a scenario that considers carbon emission reduction on the premise of ensuring rapid economic development.
- (3) The energy-saving scenario is a scenario that maintains the status quo of economic development on the premise of improving energy utilization efficiency.
- (4) The low-carbon scenario is a scenario that maintains the status quo of economic development on the premise of reducing carbon emissions.

The specific settings of scenarios are shown in Table 3.

Fig. 5. Interval of each parameter's average annual growth rate.

Table 3. Design of scenarios

Scenario Parameter	Benchmark scenario	Economic development first scenario	Energy-saving scenario	Low-carbon scenario
A1	Low	High	Low	Low
A2	Low	High	Low	Low
A3	High	High	Low	Low
P2	Low	Low	High	High
P3	Low	High	Low	High
T1	Low	High	Low	Low
T2	Low	High	Low	Low
T3	Low	Low	Low	Low
T4	Low	High	High	High
T5	High	High	Low	High

Taking the value of designed parameters and the data of TCE and CEI during the period of 2006–2015 as the input value, this paper uses the MATLAB programming language to divide these data into training, verification and test samples randomly. Figure 6 and Figure 7 clearly shows the predicted development trend of YRD's TCE and CEI from 2016 to 2030 in different scenarios.

Fig. 6. Prediction results of YRD's TCE.

Fig. 7. Prediction results of YRD's CEI.

In the low-carbon scenario, the peaking times of TCE and CEI in YRD are the earliest, 2019 and 2023 respectively. The second is the energy-saving scenario in which the TCE and CEI in YRD will peak in 2021 and 2024, respectively. The latest peaking times are in the economic development first scenario, 2024 and 2027 respectively. Maintaining the current development trend (the benchmark scenario) can also meet China's carbon

emission reduction commitments. YRD's TCE and CEI will peak in 2021 and 2025, respectively. Moreover, the peak of CEI in the economic development first scenario (0.130) is 1.33 times the amount of that in the low-carbon mode (0.098) while the peaks of TCE in these scenarios don't have much difference. Therefore, under the premise of controlling the TCE, China should take effective measures to control CEI to achieve its carbon emission reduction targets. While ensuring sustained development of economy and society, it's necessary for China to advance its peaking times of TCE and CEI, leading to the realization of sustainable development. If China only focuses on the amount of economic growth, it is bound to face increasing pressure on the share of international carbon emission reduction. It's crucial to give full play to the role of government regulation to adhere to the low-carbon development scenario. Considering that the energy consumption of the secondary industry is relatively strong, promoting the low-carbon transformation of the secondary industry is the key to achieving low-carbon development.

4 Conclusions and Policy recommendations

4.1 Conclusions

This paper conducts in-depth research on carbon emissions in YRD and predicts the peaking times of YRD's TCE and CEI scientifically. Given the current situation of carbon emissions in YRD, this paper introduced new drivers such as household consumption level, full-time equivalent of R&D personnel and investment in environmental pollution control from the perspectives of economy, energy and society to scientifically analyse the influence mechanism of carbon emissions in YRD. In this paper, ten key drivers of carbon emissions in YRD are identified, and the influence degree of each key driver is calculated by the STIRPAT model, providing a reference for the multi-scenario prediction. Based on the utilization of BP neural network model and the design of different scenarios, the peaking times of TCE and CEI in YRD are predicted separately under the constraints of related targets in the 13th Five-Year Plan. The following conclusions can be drawn:

(1) Increasing the scientific research investment is an important guarantee for China to achieve its carbon emission reduction targets, which is because the control effects of full-time equivalent of R&D personnel, efficiency of energy conversion and energy intensity directly influence carbon emissions in YRD.

(2) Promoting the low-carbon transformation of the secondary industry can make China reach its carbon emissions peak as early as possible. Because the peaking times of TCE and CEI in the low-carbon scenario are the earliest and the low-carbon transformation of the secondary industry is the key to achieving low-carbon development.

(3) The adjustment of energy consumption structure is one of the most important bases for carbon emission

reduction because the positive influence of energy consumption growth on TCE in YRD is the largest while the negative influence of renewable energy consumption ratio growth is the largest.

4.2 Policy recommendations

According to the conclusion of this study, we propose the following policy recommendations:

(1) Promoting technological progress by increasing investment in scientific research is the key to reducing carbon emissions in YRD. Technological innovation is the core means to improve energy processing conversion efficiency and reduce energy intensity. The shift of China's resource-dependent development to innovation-driven development not only needs to strengthen technological innovation in the advanced low-carbon industry but also needs to popularize advanced energy-saving technology. Only by transforming technological advantages into industrial and economic advantages can YRD achieve a fundamental shift in the development mode. It is in line with the process of global energy technology innovation, providing a strong technical guarantee for China's carbon emission reduction.

(2) Giving play to the role of government macro-control to promote the low-carbon transformation of the secondary industry is a powerful guarantee for achieving China's carbon emission reduction targets. The irrationality of industrial structure is the main reason for carbon emissions in YRD growth. So, improving structural energy savings brought about by industrial transformation and upgrading is the main means of reducing carbon emissions in YRD. The Chinese government should strengthen the institutional guarantee for low-carbon development. For example, drivers of carbon emissions should be incorporated into national and local development plans, clarifying the responsibility of governments at all levels to achieve carbon emission reduction targets.

(3) It is essential to establish and improve a scientific and efficient carbon market to optimize energy consumption structure. At present, China has started to build several regional carbon market pilots. The perfection of carbon market in YRD can guide social investment orientation and accelerate the process of low-carbonization of energy consumption structure, providing continuous momentum for the achievement of carbon emission reduction targets.

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