Environment Protection Engineering

Vol. 50 2024 No. 1

DOI: 10.37190/epe240104

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A STUDY OF THE PATHWAY TO PEAK CARBON IN CHINA

The achievement of the peak carbon target is a complex and comprehensive project that involves various aspects such as the economy, society, and ecological environment. At the same time as reaching the carbon peak, how to balance economic and social development has become an important issue. This study uses the environmental Kuznets curve (EKC) model to predict China's carbon peaking situation. Three key parameters, namely carbon peaking, economy, and society, are selected, and relevant decision variables are established. A multi-objective planning model is developed to facilitate the coordinated development of carbon peaking, economy, and society, which is solved using a sequential algorithm. The results show that: China's carbon emissions were 6928.905 million t in 2020 and are expected to reach the carbon peak in 2030. At the peak, the per capita gross domestic product (GDP) is estimated to be 16 281.95 $, corresponding to a per capita CO_2 emission of 9.66 t. During China's carbon peak, the GDP is projected to be 23 249.58 billion $, with an arable land area of 121 747 510 ha and sulfur dioxide emissions of 180.64 million t, meeting the expected target values. However, certain indicators such as the ratio of three industries, energy consumption, rural residents' per capita disposable income, and water consumption fall short of expected. Based on these findings, relevant countermeasures have been proposed for the realization path and key breakthroughs for China's carbon peak.

1. INTRODUCTION

The trend of global warming is evolving, primarily driven by the substantial emission of greenhouse gases (GHGs) such as carbon dioxide (CO_2). The international community has been making continuous efforts to control GHG emissions. In September 2020, General Secretary Xi Jinping announced at the 75th United Nations General Assembly that China aims to peak its carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060. China's commitment to transitioning from peak carbon to carbon neutrality is significantly shorter than the timeline followed by developed countries. As the world's largest developing country, China is set to achieve the highest rate of

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reduction in carbon emissions intensity globally. In October 2021, China's State Council issued *Opinions on the Complete and Accurate Implementation of the New Development Philosophy and Doing a Good Job of Peaking Carbon and Carbon Neutrality*. These opinions highlight the importance of integrating peak carbon and carbon neutrality into the goals of economic and social development. By doing so, China aims to align its development objectives with the imperative of addressing climate change. During the ninth meeting of the Central Financial and Economic Commission, it was emphasized that achieving the goal of carbon peaking is a complex and systematic change that requires a multi-dimensional perspective to seek a development path that considers both the economy and society. Therefore, it is crucial to work towards the simultaneous development of the economy and society to achieve this goal. China is currently the world's most populous country and consumes the most energy, with a population of 1.412 billion as of 2020 and a per capita energy consumption of 3.53 t of standard coal. Its annual carbon dioxide emissions exceed 6 billion t, the highest among all countries globally. Moreover, China is in a stage of rapid industrialization and urbanization, making emission reduction a more challenging task than for developed countries. As such, greater efforts are needed to achieve carbon peaking and carbon neutrality. As a major global economy and emitter of greenhouse gases, China's efforts in this regard will have a significant impact on the global fight against climate change.

2. PATHS TO ACHIEVE PEAK CARBON

Peak carbon means that carbon dioxide emissions have reached a historical maximum, and then experienced a plateau and entered a continuous decline, which is the inflection point of carbon emissions from increasing to decreasing. The realization of the carbon peak is a systematic project with multiple perspectives, including economic, social, and industrial, and scholars have explored its realization path from four aspects.

From a research perspective, scholars proposed various paths to achieve peak carbon, primarily focusing on technological innovation [1, 2], upgrading industrial structure [3], transforming energy consumption structure [4], and developing policies and systems [5]. In terms of research fields, scholars explored the realization of peak carbon in areas such as manufacturing [6], agriculture [7], industry [8], transportation [9], and power generation [10]. The research scale covers various levels, including national [11, 12], provincial [13], city [14, 15], and county [16], and the research methods mainly involve the use of Kaya's equation [17], structural decomposition analysis (SDA) [18], logarithmic mean divisia index (LMDI) [19] to study the influencing factors of peak carbon realization. Additionally, models such as STIRPAT [20], Monte Carlo simulation (MCS) [21], and computable general equilibrium (CGE) [22] have been used to predict peak carbon and propose implementation paths. Existing literature mainly proposes paths to achieve peak carbon from specific perspectives or sectors such as industry and transportation. Although some scholars have theoretically elaborated on the relationship between peak carbon and economic and social development [23], few empirical studies systematically investigate how to achieve peak carbon while considering economic and social development. There is a lack of comprehensive data-based implementation paths for China's peak carbon. Therefore, this article explores how China can achieve the goal of peak carbon while promoting economic and social development.

Based on the Intergovernmental Panel on Climate Change (IPCC) carbon emission coefficient method, this study calculated China's carbon emissions from 2005 to 2020 and used the EKC model to predict peak carbon. The study also reviewed the goals of peak carbon, economic and social development, and established a multi-objective planning model based on China's actual situation and future development requirements. By solving the model, a multi-objective balanced development planning path that is in line with China's characteristics was obtained. The aim is to provide support for China's peak carbon realization.

3. DATA AND METHODS

Study area. China has a total land area of 9.6 million square kilometers. The terrain in China is high in the west and low in the east, with mountains, plateaus, and hills accounting for about 67% of the land area, and basins and plains accounting for about 33% of the land area. In 2020, China's total population was 1.41175 billion. China is the world's largest producer and consumer of energy. In 2020, China's comprehensive energy production capacity reached 4.1 billion t of standard coal, crude oil production was 195 million t, natural gas production reached 192.5 billion m^3, and the total energy consumption for the year was 4.98 billion t of standard coal. Coal consumption accounted for 56.8% of the total energy consumption, while clean energy such as natural gas accounted for 24.3%.

China's energy consumption and industrial structure pose certain constraints on its sustainable development. Firstly, China's high dependence on energy consumption for economic development resulted in a large amount of CO_2 emissions. In 2020, China's energy consumption intensity was 1.5 times the world average. Secondly, China's heavy reliance on heavy industry for economic development has created immense pressure to optimize its industrial structure. In 2020, the output value of China's secondary industry accounted for 37.8% of the total output value, with heavy industry, mainly based on the energy industry, accounting for over 40% of the industrial output value.

Data source and processing. Seven energy sources, namely coal, natural gas, electricity, crude oil, gasoline, kerosene, and diesel, are selected to calculate China's carbon emissions. The average low-level calorific value is calculated using the national standard GB/T2589-2008. The carbon content per unit of calorific value and the carbon oxidation rate of the carbon emission factor are derived from the *Guidelines for the Preparation of Provincial Greenhouse Gas Inventories*, and the missing parts are filled in by the data in the *IPCC Guidelines for National Greenhouse Gas Emission Inventories (2006)*. Data on GDP, value added of the three industries, energy consumption, disposable income per capita of urban and rural residents, total population, cultivated land area, employment, total water consumption, and sulfur dioxide emissions were obtained from *China Statistical Yearbook 2006–2021* and *China Tertiary Industry Statistical Yearbook.*

Carbon emissions calculation. The Intergovernmental Panel on Climate Change (IPCC) is a specialized committee established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). It provides authoritative methods and rules for countries worldwide to establish national greenhouse gas inventories and achieve emission reductions. According to the inventory guidelines recommended by the IPCC (2006), the calculation formulas for carbon emission factors of various energy sources EF_i are as follows

$$EF_i = \frac{44}{12} H_i I_i O_i \tag{1}$$

where H_i is the low-level heat generation of the ith energy source, kJ/kg, I_i is the carbon content per unit calorific value of that energy source, tC/TJ, O_i is the carbon oxidation factor of the ith energy source, % < 44/12 is the conversion factor of carbon to CO_2.

The carbon emission accounting formula is as follows

$$C_p = \sum_i C_i EF_i \tag{2}$$

where C_P is CO_2 emissions, million t, C_i is the consumption of the ith energy source, t, EF_i is the CO_2 emission factor of the ith energy source, t CO_2/t. The carbon emission coefficients of each type of energy are shown in Table 1.

Table 1

Carbon emission coefficients of various energy sources

No.	Type of energy consumption	Heat generation [kJ/kg]	Carbon oxidation factor	Carbon emission factor [t CO_2/t]
1	coal	20.908	0.94	1.9003
2	natural gas	38.931 (kJ/m^3)	0.99	2.1622 (kg CO_2/m^3)
3	electric power	–	–	0.8696 (t CO_2/MWh)
4	crude oil	41.816	0.98	3.0202
5	gasoline	43.07	0.98	2.9251
6	kerosene	43.07	0.98	3.0179
7	diesel	42.625	0.98	3.0939

Data source: IPCC 2006 National Greenhouse Gas Emission Guidelines.

EKC model construction. In 1991, Grossman and Krueger from Princeton University in the United States found that the trend of most pollutants showed an inverted U-shaped relationship with the per capita national income, and then proposed the environmental Kuznets curve (EKC) hypothesis [24]. The EKC hypothesis refers to the phenomenon where environmental pollution or damage increases with economic growth in the early stages of economic development. When the economy reaches a certain level, the degree of environmental pollution reaches its maximum. Afterward, as the economy continues to develop, the degree of environmental pollution decreases, and the environmental quality gradually improves. In other words, the trend of changes in pollutant emissions and per capita GDP shows an inverted U-shaped curve relationship.

Referring to the empirical research models of domestic and foreign scholars on the EKC curve, the carbon dioxide EKC describes the relationship between per capita carbon dioxide emissions and per capita income. This study selects the quadratic equation form of per capita income used by Shafik and Bandyopadhyay [25] as the explanatory variable and uses the logarithmic form to establish the EKC for carbon dioxide emissions.

$$LP\,\mathrm{CO}_2 = \beta_0 + \beta_1 LPY + \beta_2 \left(LPY\right)^2 + \varepsilon \tag{3}$$

where $LP\ \mathrm{CO}_2$ denotes per capita CO_2 emission in logarithmic form, LPY denotes per capita GDP in logarithmic form, ε is the random error term, β_0 is the intercept term, β_1 and β_2 are the parameters to be estimated.

Based on the inverted U-shape of the EKC, the inflection points of the CO_2 Kuznets curve (ξ) can be accounted for

$$\xi = \exp\left(-\frac{\beta_1}{2\beta_2}\right) \tag{4}$$

By using the properties of a parabola and inflection point theory, it is possible to calculate the per capita GDP level when carbon dioxide emissions reach the inflection point, and from this determine the time needed to achieve win-win development of GDP growth and carbon emission reduction. Based on relevant policies and case studies such as China's 14th Five-Year Plan and the 14th Five-Year Plan for Energy Conservation and Emission Reduction, the GDP and population growth rates for the past 10 years can be predicted.

Multi-objective planning model. Multi-objective modeling is commonly used in resource allocation problems. Multi-objective planning models have solution methods such as the primary objective method, evaluation function method, and objective planning method [26]. The objective planning method first needs to decide the importance of the objective variables, determine the priority of each objective, then set an expected value for all the objective variables, and finally get the final result by solving for the very small value that satisfies the deviation variable. Compared with other solution methods, the advantage of the objective planning method is that the value of the objective variables can be set in advance according to the actual situation, and different values of the objective variables will have different positive and negative deviation variables, so it will not affect the optimal solution of the decision variables, and this method does not require the same unit of the objective variables, which simplifies the calculation process. Therefore, this paper finally chooses to use this method for modeling and solving.

The general form of the multi-objective planning model is

$$\min Z = \sum_{k=1}^{K} P_k \sum_{l=1}^{L} \left(w_{kl}^{-} d_l^{-} + w_{kl}^{+} d_l^{+} \right) \tag{5}$$

$$\sum_{j=1}^{n} c_j x_j + d_l^{-} - d_l^{+} = g_l, \; l = 1, 2, ..., L \tag{6}$$

$$\sum_{j=1}^{n} a_{ij} x_j \le b_i, \; i = 1, 2, ..., n \tag{7}$$

$$x_j \ge 0, \; j = 1, 2, ..., n \tag{8}$$

$$d_j^{-}, d_j^{+} \ge 0, \; l = 1, 2, ..., L \tag{9}$$

Equation (5) is called the objective function, eq. (6) and eq. (7) are constraints, and eq. (8) and eq. (9) denote the non-negative constraints on the decision and deviation variables. Z represents the overall objective. P_k is the kth priority factor, $k = 1, 2, ..., K$, which is used to distinguish the importance of each objective, and the importance of P_1 to P_K decreases in order, i.e., $P_1 > P_2 > \ldots > P_k$. d_j^{-}, d_j^{+} are the amount of positive and negative deviations of the Lth target constraint, w_{kl}^{-} and w_{kl}^{+} are the weighting coefficients of the positive and negative deviation variables of the Lth target constraint assigned to the P_k priority factor, respectively, indicating the importance of the positive and negative deviation variables of different targets. x_j represents the decision variable. a_{ij} the proportion coefficient of decision variables. g_l is the prior expected objective value, $l = 1, 2, ..., L$.

This article establishes a multi-objective planning model for achieving a carbon peak and coordinated economic and social development, taking into account China's actual situation and the availability of indicator data. Carbon emissions at the time of carbon peak are selected as the target parameter for carbon peak, and GDP, the proportion of the three major industries, and total energy consumption are selected as the target parameters for the economic level. Disposable income of urban and rural residents, total population, arable land area, total water consumption, and sulfur dioxide emissions are selected as the target parameters for social development. The total output value of the three industries, labor input and total energy consumption, per capita energy consumption of residents, scientific and technological input, and total population are selected as decision variables (Tables 2 and 3).

Table 2

Decision variables

Decision variable	Symbol	Statistical indicator	Unit
x_1	GDP_1	primary industry GDP added value	billion $
x_2	GDP_2	secondary industry GDP added value	billion $
x_3	GDP_3	tertiary sector gdp added value	billion $
x_4	E_1	primary industry energy consumption	million t of standard coal
x_5	E_2	secondary industry energy consumption	million t of standard coal
x_6	E_3	tertiary sector energy consumption	million t of standard coal
x_7	E_4	domestic energy consumption	million t of standard coal
x_8	L_1	employment in primary industry	million people
x_9	L_2	employment in secondary industry	million people
x_{10}	L_3	employment in the tertiary sector	million people
x_{11}	T	expenditure on scientific and technological activities	billion $
x_{12}	P	total population	million people

Table 3

Object variable

system	Target variable	Statistical index	Unit
Carbon peaking	y_1	carbon emission	ten thousand t of CO_2
Economic development	y_2	gross domestic product	hundred million $
	y_3	proportion of primary industry	%
	y_4	proportion of secondary industry	%
	y_5	proportion of tertiary industry	%
	y_6	total energy consumption	million t of standard coal
Social development	y_7	per capita disposable income of urban residents	$
	y_8	per capita disposable income of rural residents	$
	y_9	total population	million people
	y_{10}	arable land area	ha
	y_{11}	total water consumption	million m^3
	y_{12}	sulfur dioxide emission	ten thousand t of SO_2

4. RESULTS AND ANALYSIS

4.1. CARBON EMISSION CALCULATION RESULTS

In 2005, China's carbon emissions were 6928, 902 500 t, and by 2020, carbon emissions will be 12 721, 537 230 t. During the period of 2005–2020, China's CO_2 emissions showed an overall upward trend, mainly due to the continuous development of China's industry and the expansion of industrial production scale, which led to a large consumption of fossil energy. The dominant position of coal in energy consumption ultimately led to an increase in carbon emissions. From 2010 to 2020, the growth rate of CO_2 emissions slowed down, as China focused on improving energy resource utilization efficiency, controlling total energy consumption, continuously optimizing industrial and energy structures, vigorously building a green industrial system, strengthening energy-saving management in key areas, and achieving significant results in energy consumption "dual control" work (Fig. 1).

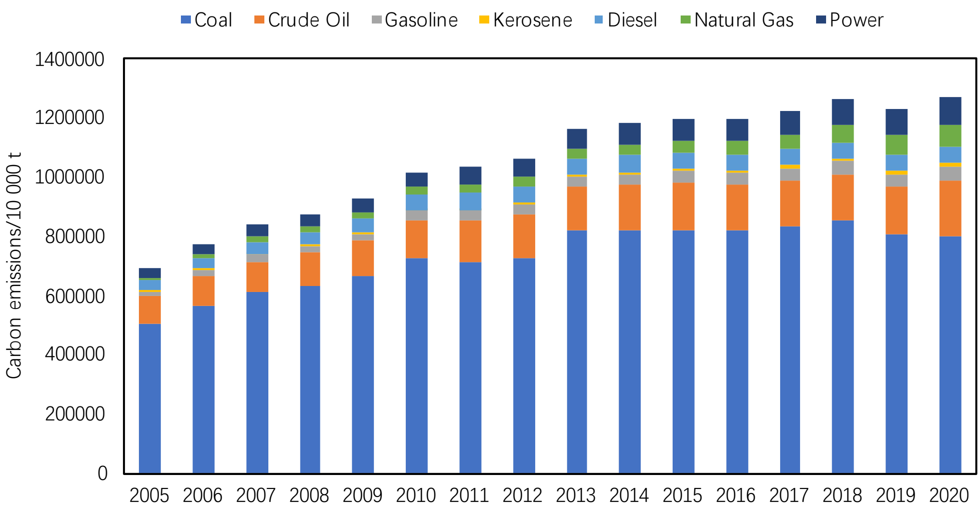

Fig. 1. Carbon emissions in China from 2005 to 2020

From the perspective of carbon emissions structure, coal is the main source of carbon emissions, followed by crude oil. During the research period, carbon emissions generated by coal consumption accounted for more than 50% of the total carbon emissions. Due to the promotion and use of natural gas, as well as China's optimization of energy consumption structure, the consumption of natural gas has increased, leading to an increase in its carbon emissions. With the development of energy-saving and emission-reduction technologies and the popularization of clean energy, the use of diesel and crude oil has shown a downward trend, and their carbon emissions have correspondingly decreased.

4.2. PEAK CARBON EMISSIONS PROJECTIONS

The EKC model was applied to calculate China's carbon peaking, and the parameters of the model are estimated using the ordinary least squares (OLS) method, and the regression results are shown in Table 4.

Table 4

Results of least square estimation

Variable	Coefficient	Standard error	t-Statistic	Probability
c	–16.165	3.476	–4.651	<0.001
LPY	3.155	0.671	4.703	<0.001
L^2PY	–0.135	0.32	–4.176	0.001
R-squared	0.997	Adjusted *R*-squared		0.983
F-statistic	371.778	Prob (F-statistic)		0.000

c represents a constant, LPY represents the logarithmic form of per capita GDP, and L^2PY represents the logarithmic form of the square of per capita GDP.

The regression model based on equation (3) is

$$LP\,CO_2 = -16.165 + 3.155LPY - 0.135L^2PY \tag{10}$$

According to the model estimation results, the coefficient of determination and adjusted coefficient of determination of the model reached 0.997 and 0.983, respectively, indicating that the model fits the sample very well. At the same time, the model passed the *F*-test, indicating that the joint effect of various explanatory variables on the explained variable is significant. From the t-test results, the *P*-values of each variable were less than 0.10, indicating that the coefficients of each variable were significant.

Calculating the inflection point of China's CO_2 EKC yields:

$$\xi = \exp\left(-\frac{\beta_1}{2\beta_2}\right) = 16\,281.95 \tag{11}$$

The results show that when China's per capita GDP is less than 16 281.95 \$, per capita carbon dioxide emissions increase with the increase of per capita income. When the per capita GDP is greater than 16 281.95 \$, the per capita carbon dioxide emission decreases with the increase of per capita income. Therefore, when the per capita GDP is 16 281.95 \$, the maximum value of per capita carbon dioxide emission is reached, which is the theoretical inflection point of China's carbon emission, and the corresponding per capita carbon dioxide emission is 9.66 t.

4.3. MULTI-OBJECTIVE PROGRAMMING MODEL SOLVING

According to the research of Chen et al. [27], based on China's GDP data in the past 20 years, combined with relevant literature such as China's 14th Five-Year Plan, related policies, and case studies, it is concluded that the GDP growth rate in China will be 5.3% from 2020 to 2025 and 5.1% from 2025 to 2030. According to the medium forecast of *China Population Projection 2023* and combined with the actual situation in China, the total population of China will change in the future as shown in the following Table 5.

Table 5

Optimal target value (China's population) in billion

Year	2023	2024	2025	2026	2027	2028	2029	2030	2032	2033	2034	2035
Population	1.404	1.400	1.397	1.388	1.379	1.374	1.369	1.363	1.363	1.357	1.351	1.345

Combined with the EKC model, the population and GDP projections yield China's carbon peak in 2030, with a peak GDP of 22193.3 billion $, CO_2 emissions of 13 515,720 000 t, and a per capita GDP of 16 281.95 $.

Table 6

Optimal target value

Statistical index	Target value at peak carbon
Carbon emissions, ten thousand t	1 351 572
Gross domestic product, billion $	220 946.1
Proportion of primary industry, %	6
Proportion of secondary industry, %	32
Proportion of tertiary industry, %	62
Total energy consumption, million t of standard coal	664 545.87
Per capita disposable income of urban residents, $	9053.99
Per capita disposable income of rural residents, $	4116.31
Total population, ten thousand people	136 300
Arable land holdings, ha	121 727 500
Total water consumption, billion m^3	6578.8
Sulfur dioxide emissions, million t	250.64

According to the prediction of the Economic Forecasting Department of the China, National Information Center and drawing on the experience of optimizing and upgrading industrial structures abroad, the expected target proportions of the three industries at the time of the carbon peak are set as 6, 32, and 62%. According to the *Outline of National Territory Planning of China (2016–2030)* issued by the State Council, the target for the amount of arable land in China in 2030 is 121 727 500 ha. Through SPSS time series forecasting, the target values of various related indicators are predicted, including total population, total energy consumption, disposable income of urban and rural residents, total water consumption, and sulfur dioxide emissions. The target value of disposable income of urban and rural residents is modified under the condition of considering narrowing the gap between rich and poor. The target values of various related indicators are shown in Table 6.

According to the different purposes to be achieved by the model, different priority levels can be set for the above objectives to construct the objective function. This study focuses on how China can balance economic and social development to achieve a carbon peak. Therefore, the carbon peak target and GDP, which is a core indicator of regional economic conditions and development level, are set as the priority (P_1). According to the *Action Plan for Carbon Peak by 2030* issued by the State Council, which mentions the main objectives during the 14th Five-Year Plan and 15th Five-Year Plan periods, adjustments and optimizations of industrial structure and energy structure have made significant progress. Therefore, industrial structure and total energy consumption are set as the next priority (P_2), and an important indicator of measuring people's living standards – disposable income of urban and rural residents – is also placed at the same level. The remaining indicators, including population, arable land, and resource constraints, are considered the following priority (P_3). Based on the priority levels of each objective, an objective function is constructed, and other model equations are determined using the regression fitting method to establish the following multi-objective programming model.

- Objective function

$$\min Z = \Big(P_1\left(d_1^+ + d_2^-\right) + P_2\left(d_3^+ + d_4^+ + d_5^- + d_6^+ + d_7^- + d_8^-\right) \\ + P_3\left(d_9^- + d_{10}^- + d_{11}^- + d_{12}^+\right)\Big) \quad (12)$$

- Binding conditions

$$y_1 = 3.768x_2 + 1.085x_3 - 80.697x_4 - 0.365x_5 + 2.725x_6 - 30.342x_7 \\ - 18.331x_{11} - 46.885x_{12} + 6\,961\,678.9 + d_1^- - d_1^+$$

$$y_2 = x_1 + x_2 + x_3 + d_2^- - d_2^+$$

$$y_3 = \frac{x_1}{x_1 + x_2 + x_3} + d_3^- - d_3^+$$

$$y_4 = \frac{x_2}{x_1 + x_2 + x_3} + d_4^- - d_4^+$$

$$y_5 = \frac{x_3}{x_1 + x_2 + x_3} + d_5^- - d_5^+$$

$$
\begin{aligned}
& y_6 = x_4 + x_5 + x_6 + x_7 + d_6^- - d_6^+ \\
& y_7 = 0.238x_1 - 0.024x_2 + 0.039x_3 - 0.703x_8 - 0.907x_9 + 1.612x_{10} \\
& \qquad - 0.331x_{11} + 0.251x_{12} - 65\,488.921 + d_7^- + d_7^+ \\
& y_8 = 0.98x_1 - 0.001x_2 + 0.016x_3 - 0.094x_8 - 0.260x_9 - 0.188x_{10} \\
& \qquad + 0.540x_{12} + d_8^- + d_8^+ \\
& y_9 = x_{12} + d_9^- - d_9^+ \\
& y_{10} = -0.00057x_1 - 0.001x_4 + 107.434 + d_{10}^- - d_{10}^+ \\
& y_{11} = 0.011x_1 - 0.001x_3 + 0.330x_4 - 0.006x_5 - 0.067x_7 + 0.01x_{10} \\
& \qquad - 7543.28 + d_{11}^- - d_{11}^+ \\
& y_{12} = -0.004x_2 - 1.963x_4 - 0.024x_5 + 0.13x_6 + 0.153x_7 - 0.693x_{12} \\
& \qquad + 93\,550.72 + d_{12}^- - d_{12}^+
\end{aligned}
\tag{13}
$$

The sequential algorithm is used to solve the model with lingo17.0. When solving the first level objective, we make $P_1 = 1$, $P_2 = 0$, and $P_3 = 0$ to obtain the deviation variables that satisfy the first level constraint. Then we make $P_1 = 1$, $P_2 = 1$, and $P_3 = 0$ to solve the deviation variables that satisfy the second level constraint. Similarly, we can obtain the third level, each solution is obtained based on the previous one, and finally we can find the deviation variables of all constraints and the optimal solution of the model. The results of the model solution are shown in Tables 7 and 8.

Table 7

Solution results of decision variables when carbon reaches peak

Decision variable	Statistical indicators	Value	Carbon peak final value
x_1	primary industry GDP added value, billion $	1065.35	1487.97
x_2	secondary industry GDP added value, billion $	5268.70	7589.13
x_3	value added of tertiary industry GDP, billion $	7541.00	14 172.47
x_4	primary industry energy consumption, million t of standard coal	91.18	82.46
x_5	secondary industry energy consumption, million t of standard coal	3516.5	4085.91
x_6	tertiary industry energy consumption, million t of standard coal	881.15	1310.25
x_7	domestic energy consumption, million t of standard coal	680.1	801.25
x_8	number of people employed in the primary industry, million people	177.15	154.68
x_9	secondary industry employment, million people	215.43	205.46
x_{10}	tertiary industry employment, million people	358.06	589.46
x_{11}	expenditures for scientific and technological activities, million $	1383.57	2312.12
x_{12}	total population, ten thousand people	141212	134268

GDP share changes in terms of the primary sector GDP at the time of the carbon peak was 1487.97 billion $, accounting for 6.40% of the total GDP, a decrease of 2.26% compared with 2020, the secondary sector GDP was 7589.13 billion of $, accounting for 32.60% of the total GDP compared with 2020, a decrease of 5.30%. The GDP of tertiary industry is 14 172.47 billion $, accounting for 61.00% of the total GDP, an increase of 6.60% from 2020. The proportion of primary and secondary industries decreases and the proportion of tertiary industry increases when carbon reaches the peak, and the change is the largest, optimizing the industrial structure of three, two, one, which means that China is changing from the original industrial-led economy to the service-led economy.

The unit GDP energy consumption of the primary industry was 0.856 t/ten thousand $ in 2020, and it decreased to 0.554 t/ten thousand $ at the time of the carbon peak, a decrease of 0.312 t/ten thousand $. During the same period, the unit GDP energy consumption of the secondary industry decreased from 6.67 to 5.38 t/ten thousand $, and that of the tertiary industry decreased from 1.168 to 0.925 t/ten thousand $. The unit GDP energy consumption of all three industries has decreased, indicating that the growth rate of energy consumption in China is slower than the economic growth rate, and energy consumption is gradually decoupling from economic development. To achieve carbon peak and promote the joint development of the economy and society, it is necessary to reduce the dependence of economic development on energy. At the same time, unit GDP energy consumption is influenced by various factors such as technological level, industrial structure, and energy structure. The secondary industry has experienced the largest decrease in unit GDP energy consumption, indirectly reflecting the regulation of high-energy-consuming industries and the improvement of energy utilization efficiency during the process of economic development.

From the perspective of employment, the proportion of employment in the primary industry was 31.52% in 2020 and decreased to 13.22% at the time of carbon peak. During the same period, the proportion of employment in the secondary industry decreased from 17.10 to 7.13%, while that of the tertiary industry increased from 51.37 to 79.64%. Therefore, in the process of promoting carbon peak, reducing employment in high-energy-consuming secondary industries and increasing employment in low-energy-consuming and high-benefit tertiary industries is an important way to improve the overall economic benefits and efficiency and address the problem of employment structure lagging behind the industrial structure in China.

Looking at the expenditure on scientific and technological activities, at the time of carbon peak, the expenditure on scientific and technological activities was 67.62% higher than that in 2020. Scientific and technological funding supports the development of basic research, technological research and development, application demonstrations, and other aspects. Scientific and technological innovation promotes the continuous optimization of energy structure, promotes the reduction of carbon emission intensity, and drives the adjustment of industrial structure. Therefore, it is an important support for achieving both economic and social development goals and carbon peak.

Table 8

Solution results of target value when carbon reaches peak

Target variable	Statistical indicator	Target value at carbon peak	Calculation results at carbon peak
y_1	carbon emissions, ten thousand t	1 351 572	1 342 185
y_2	gross domestic product, billion $	22 094.61	23 249.58
y_3	proportion of primary industry, %	6	6.4
y_4	proportion of secondary industry, %	32	32.6
y_5	proportion of tertiary industry, %	62	61
y_6	total energy consumption, million t of standard coal	6645.46	6279.87
y_7	per capita disposable income of urban residents, $	9053.99	9075.10
y_8	per capita disposable income of rural residents, $	4116.31	3895.93
y_9	total population, ten thousand people	136 300	134 268
y_{10}	arable land holdings, ha	121 727 500	121 747 510
y_{11}	total water consumption, billion m^3	657.88	876.46
y_{12}	sulfur dioxide emissions, million t	250.64	180.64

The carbon emissions at the peak moment increased by 700.313 million t compared to the year 2020 (Table 8). The calculated GDP value is 1154.97 billion of $ higher than the expected value, with an increase of 9374.53 billion of $ compared to 2020, indicating that China has sustained economic growth during the process of achieving carbon peak. The calculated carbon emission intensity is 5.77 t/ten thousand $, which is lower than the expected value of 0.344 t/thousand $. Carbon emission intensity depends on factors such as technological progress, economic growth, and changes in industrial structure. The decrease in carbon emission intensity indicates that China's economic development is gradually decoupling from carbon emissions. It is transitioning from industries dominated by high carbon emissions to a green and low-carbon industrial structure, and making progress in energy green and low-carbon technologies.

In terms of industrial structure, under the premise of ensuring carbon peaks and GDP growth, compared with the proportion of the three industries in China in 2020, which will be 8.7, 43.3 and 47.9%, the proportion of the primary industry will decrease by 2.3%, the proportion of the secondary industry will decrease by 1.5%, which is a relatively small change, and the proportion of the tertiary industry will increase by 3.9%. Although the industry is upgrading towards a three, two, one structure, it has not reached the target ratio of industrial structure. It shows that the industrial structure at the time of carbon peak still has a certain distance from developed cities, and the proportion of high-energy-consuming industries in the low-end of the value chain, such as building materials and chemicals, is still high, and the transformation of the industrial structure will take a longer period of time.

From the point of view of energy consumption, the total consumption exceeds the expected value, and the calculated value of energy consumption per unit of GDP is 3.07 t/ten thousand $, which is lower than the expected value of 0.3 t/ten thousand $. This indicates that China's economic development and energy consumption are gradually decoupling, but the transformation of the energy consumption structure needs to be strengthened in order to simultaneously achieve the goals of carbon peaking and economic and social development.

From the point of view of per capita income, the disposable income of urban residents solved at the time of carbon peak was 9075.1 $, exceeding the target expectation of 21.11 $. The per capita disposable income of rural residents was 3895.93 $, which was higher than that of 2020, but less than the target value of 220.38 $, and the income gap between urban and rural residents increased further, and the gap between the rich and the poor of the society became wider. Combined with the reasoning of the proportion of the three industries and the ratio of the number of employed people, the increase in the value of residents' income is related to the upgrading of the industrial structure. The secondary and tertiary industries have the advantages of high profitability and technological innovation, and are mainly concentrated in towns and cities, while the productivity of the primary industry, which is concentrated in the countryside, is low. The technological differences between industries and regional differentiation form the basis of the income gap between urban and rural residents. At the same time, the development of secondary and tertiary industries is faster than that of primary industries, which creates more jobs for urban residents and makes the income level of urban residents rise faster, increasing the income gap.

In terms of cultivated land and water consumption, Arable land holdings has decreased compared to the area in 2020, but it still exceeds the target value. In the economic structure transformation, the proportion of the primary industry is reduced and the number of employments is reduced, the cultivated land retention is reduced at the same time. It shows that in the process of low-carbon transformation, there is a certain sacrifice for the primary industry. The total amount of water consumption exceeded the target value, indicating that water resources were protected and saved while carbon emissions were controlled. From the point of view of sulfur dioxide emissions, the emissions have reached the target value, indicating that the upgrading of the industrial structure and the transformation of the energy consumption structure, focusing on the governance of the coal chemical industry and other industries can not only reduce the emission of carbon dioxide, but also reduce the emission of sulfur dioxide.

5. CONCLUSION AND DISCUSSION

This paper discusses the issue of whether China can take into account economic and social development when it reaches the carbon peak. Firstly, the IPCC coefficient method is used to calculate China's carbon emissions from 2005 to 2020. Then the EKC model is used to predict the carbon peaking situation. Finally, the economic and social development indicators are selected, and the economic and social development targets when China reaches the carbon peaking are predicted according to the relevant plans and policies, and on this basis, a multi-objective planning model is constructed, and the targets are divided into three levels according to the realistic needs. The objective function as well as the constraints are constructed and solved according to the priority level of the objectives, and the following conclusions are drawn:

- China's carbon emissions show an upward trend from 2005 to 2020. China's carbon emissions in 2005 were 6 928 902 500 t, and by 2020 they will be 12 721 537 230 t. The carbon peak will be achieved in 2030, and the GDP at the peak will be 23 249.58 billion $, the population will be 1363 million people, and the carbon dioxide emission will be 13421.85 million t.
- Energy consumption per unit of GDP in all three industries has decreased, indicating that economic and social development and energy consumption are gradually decoupled. The number of people employed in primary and secondary industries has decreased while the number of people employed in tertiary industries has increased significantly, which means that the problem of lagging employment structure in China has been improved. The increase in science and technology funding is obvious, indicating that science and technology innovation is an important support to achieve economic and social development and carbon peaking at the same time.
- According to the target calculation results: carbon emission is less than the expected value, the calculated value of GDP is greater than the expected value, and carbon emission intensity is less than the expected value, indicating that China's economic development is gradually decoupling from carbon emission. The proportion of industrial structure and total energy consumption do not reach the set target value, indicating that it takes longer to transform China's industrial structure and energy consumption structure. The income gap between urban and rural residents further increases, indicating the need to pay attention to the income gap in the development process.

After China reaches the peak of carbon emission, there is still a certain distance compared with the industrial structure of developed countries, the proportion of secondary industry is still high, and most of the secondary industry is resource-consuming heavy industry, which leads to a large amount of carbon emission in the process of China's economic development. Therefore, China should promote the development of a new type of industrialization with green development and innovation and create a circular industrial chain. China's energy consumption per unit of GDP has been decreasing, total energy consumption is less than the target value, economic development and carbon emissions are gradually decoupled, and the environment and the economy are moving towards coordinated development. The current structure of energy consumption is an important influence on the growth of China's carbon emissions, and consideration must be given to reducing the proportion of coal consumption in total energy consumption and actively developing renewable and new energy sources. China is also focusing on the development of multiple energy integration technologies, expanding the scale of complementary utilization of multiple non-fossil energy sources, and building a new type of energy system.

Calculations show that China needs a large amount of scientific and technological inputs to realize carbon peaking and that scientific and technological innovation is a key move to realize carbon peaking. With rich scientific and educational resources and a good "hard science and technology" industrial base, China has an inherent advantage in green science and technology innovation, which lays a solid technological foundation for realizing peak carbon.

Calculations show that the gap between rich and poor at peak carbon is further widened than the target value, that the level of integrated urban-rural development is lagging, and that narrowing the gap between the living standards of residents is the most basic goal of integrated urban-rural development and the rural revitalization strategy. From the perspective of national policies in recent years, the overall status of agriculture has been upgraded, the income gap between urban and rural residents has tended to narrow, and urban-rural relations have gradually converged, but the problem of urban-rural disparity in China is still obvious. Narrowing the income gap between urban and rural areas requires increasing the openness of urban and rural areas, promoting the unification of factor markets, promoting integrated urban-rural development, and creating a mutually beneficial and win-win situation for both urban and rural areas.

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