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Research on China's Sustainable Economic Development and Peak Carbon Achievement Issues—Expanded Solow-based Modeling Analysis

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Abstract: ***China's early achievement of carbon peaking is systematic and pioneering, driving energy and economic transformation and upgrading as well as high-quality development under goal-oriented frameworks. Therefore, based on an extended Solow model, energy consumption and carbon dioxide emissions are incorporated into the model for empirical analysis to explore the relationship between carbon peaking and China's sustainable economic development. The study reveals that the elasticity of energy consumption to economic growth is relatively significant, while carbon dioxide acts as a "negative input" to economic growth, with a significantly negative elasticity. The carbon peaking target will accelerate the green and low-carbon transformation of the economic development model, continuously enhancing China's capacity for sustainable economic development. Based on the empirical analysis results, recommendations are proposed, including accelerating the optimization of the energy consumption structure and leveraging the supportive role of technological innovation; vigorously promoting energy conservation and emission reduction strategies and improving the institutional framework for low-carbon development; fostering low-consumption and environmentally friendly production methods and restructuring the economic framework towards low-carbon practices; and gradually refining the carbon trading market mechanism to advance the construction and operation of the carbon market.***

Keywords: Peak carbon, Economic sustainability, Solow modeling.

1. Introduction

As the world's largest energy consumer and greenhouse gas emitter, China has consistently demonstrated its role as a major global power, playing a pivotal role in international efforts to combat global warming. In the fall of 2020, during the 75th session of the United Nations General Assembly, the Chinese government made a solemn commitment to the international community to strengthen its emission reduction measures. It pledged to achieve peak carbon dioxide (CO_2) emissions by 2030 and strive for carbon neutrality by 2060 through the implementation of more effective policy instruments. The Central Economic Work Conference held in the same year formally established the "dual-carbon" goals as a critical direction for economic and social development, laying the policy foundation for comprehensive emission reduction efforts. By 2021, various industrial sectors across the country had begun actively responding to the "dual-carbon" strategy, while academia has been conducting in-depth research on pathways to achieving carbon peaking and carbon neutrality.

China's early achievement of carbon peaking is systematic and pioneering, driving energy and economic transformation and upgrading as well as high-quality development under goal-oriented frameworks. This approach is conducive to implementing the new development philosophy and constructing a new development paradigm that synergizes economic growth, environmental protection, and climate governance. Currently, China is in the middle and late stages of industrialization, and its total energy demand and carbon emissions are expected to continue growing for a certain period. Therefore, achieving the carbon peaking target will impose higher requirements for China to reduce carbon emissions and transition to a low-carbon economy. The implementation of "carbon peaking" and "carbon neutrality" will lead to fundamental changes in the ecological, economic, and energy dimensions of China's economic system, promoting energy conservation, emission reduction, and the development of a low-carbon economy. This will not only contribute to the sustainable development of China's socio-economic system but also help advance global ecological balance.

To ensure the successful realization of the carbon peaking goal, it is crucial to accelerate the green and low-carbon transformation of the economic development model while continuously enhancing China's capacity for sustainable economic development. This effort also involves exploring a paradigm of harmonious coexistence between humans and nature under the framework of Chinese-style modernization. Based on the extended Solow model, this paper investigates the impact of carbon peaking on China's sustainable economic and social development.

2. Literature Review

Domestic academic research on the topic of carbon peaking mainly unfolds along three dimensions. First, methods such as scenario simulation, the Environmental Kuznets Curve theory, and decoupling theory are employed to explore the time node and scale level of China's carbon emission peak. Second, tools like the Logarithmic Mean Divisia Index (LMDI) decomposition method and data envelopment analysis are utilized to deeply analyze the key drivers of carbon emissions and their intensity impact mechanisms. The third type of research focuses on assessing the profound impact of carbon peaking on macro-economic operations.

In terms of empirical research, scholars have adopted diverse research methods. Wang Yong et al. (2017) simulated the economic effects of different peak-attainment time points by constructing a Computable General Equilibrium (CGE) model of the climate protection function and found that the peak-attainment time was positively correlated with economic growth pressure. Mo Jianlei et al. (2018) quantitatively evaluated the synergistic effect of the peaking target and indicators such as the proportion of non-fossil energy based on the energy-economy-environment system model. The relationship between carbon peaking and the quality of economic development has also been thoroughly explored by academics. Fu Hua et al. (2021) pointed out that low-carbon production methods would promote industrial technological innovation and achieve a win-win situation of economic and ecological benefits. Zhang Fang (2021) found through empirical research that the carbon emissions trading policy had a significant economic incentive effect, but there were differences in regional emission reduction effects. Recent studies have further deepened this area. Li Xinan et al. (2022) used a dynamic CGE model to simulate different peaking scenarios and confirmed that the peaking time was closely related to the quality of economic development. Yu Dengke et al. (2022) incorporated carbon emission indicators into the green development assessment system and confirmed that industrial structure optimization had a positive impact on the improvement of total factor productivity.

By combing through the relevant literature, it is found that many scholars have studied carbon peaking from different dimensions such as carbon emission influencing factors and peak prediction. Through the simulation of different scenarios, they have analyzed the relationship between carbon peaking and China's economic growth rate as well as the quality of economic development. However, the studies on carbon peaking and China's economic sustainable development are relatively scarce and have certain limitations. Therefore, based on the extended Solow model, this paper incorporates energy consumption and carbon dioxide emissions into the model for empirical analysis, explores the relationship between carbon peaking and China's economic sustainable development, and puts forward relevant policy recommendations.

3. Analysis of the Current Situation of Energy Consumption and Carbon Emissions in the Context of Carbon Peaking

Carbon dioxide emissions resulting from human activities mainly stem from fossil fuel consumption. Developing new energy sources, transforming the energy consumption structure, reducing fossil energy consumption, and constructing a green and low-carbon energy system are among the most crucial measures for reducing carbon dioxide emissions, achieving carbon neutrality and carbon peaking, and promoting the sustainable development of China's economy and society.

3.1 Analysis of the Current Energy Consumption Status

3.1.1 Current Situation and Structure of Energy Consumption

China is relatively abundant in fossil energy resources, while the proportions of oil, natural gas, and new energy are relatively small. During the past two decades of rapid economic development in China, the high - speed consumption of disposable fossil energy, mainly coal, has provided a huge impetus for the rapid growth of the social economy.

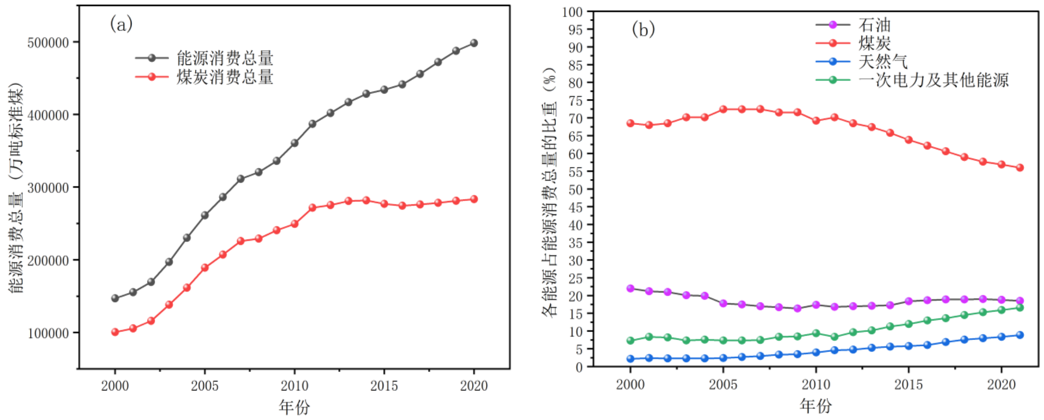

Figure 1: Energy consumption in China. (a) Coal and energy consumption; (b) share of each energy source in energy consumption.

The development of China's energy consumption is presented in Figure 1. Figure 1(a) reveals that since the beginning of the 21st century, the total energy consumption in China has been growing rapidly. The total consumption in 2021 has increased by nearly 3.6 times compared with that in 2000. Since 2015, the coal consumption in China has leveled off, with the consumption remaining at around 2.7 billion tons of standard coal. The proportion of coal consumption has been basically on a downward trend, continuously dropping from a peak of 72.5% in 2007 to 56.0% in 2021.

Compared with the consumption proportions in 2000, the proportions of coal and oil in the national primary energy consumption in 2021 have decreased by 9.0 percentage points and 3.5 percentage points respectively. In contrast, the proportions of natural gas and primary electricity and other energy consumption have increased significantly, reaching 8.9% and 16.6% respectively (Figure 1(b)). Nevertheless, China's energy consumption structure still exhibits the characteristic of “one large and three small”, with coal consumption being dominant.

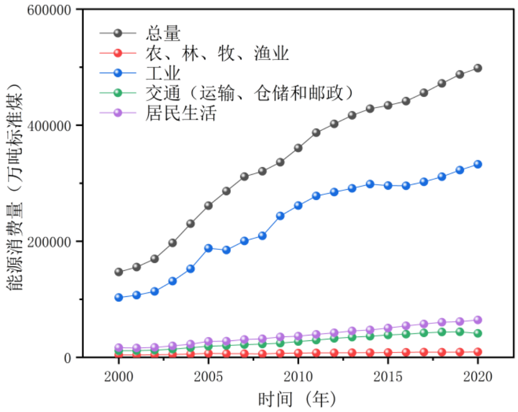

Figure 2: China's energy consumption by sector, 2000-2020

China's aggregate energy consumption primarily consists of industrial consumption, residential consumption, and transportation consumption (encompassing transportation, storage, and postal services). Industrial consumption accounts for a range between 65.0% and 75.0% of the total energy consumption. By the end of 2020, industrial energy consumption in China accounted for 66.8% of the overall energy consumption.

At present, China is in the stage of industrialization deepening. The process of industrialization development confronts issues of imbalance and inadequacy. There remains a considerable distance to traverse before China can truly enter the "post-industrialization era". Consequently, the phenomenon of a relatively high proportion of industrial energy consumption will persist for a certain period.

Furthermore, the overly high proportion of high - energy - consuming industries, as well as their position at the middle and lower segments of the global industrial chain and value chain, are also contributing factors to the high level of industrial energy consumption in China and the coal-dominated structure of the total energy consumption.

3.1.2 Trends in Energy Consumption

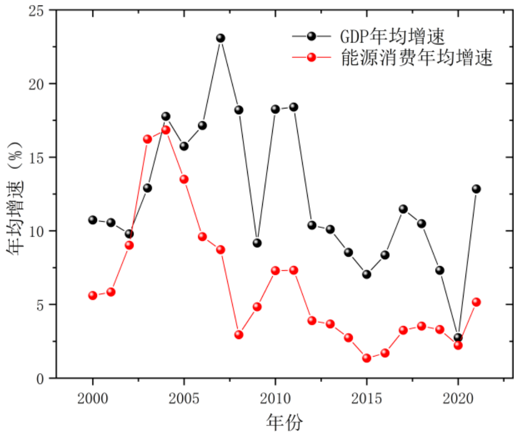

Figure 3: Average annual growth rate of China's GDP and energy consumption, 2000-2021

From 2010 to 2019, China's Gross Domestic Product (GDP) maintained an annual growth rate of over 6%. However, since 2012, economic development and energy consumption have exhibited a distinct decoupling trend (as depicted in Figure 3). This phenomenon fully demonstrates the remarkable achievements China has attained in addressing the challenge of global warming and advancing the sustainable development strategy.

Within the strategic framework of achieving the carbon emission peak target, to effectively promote energy conservation and emission reduction, China has continuously propelled the optimization and upgrading of its industrial structure, accelerated the pace of technological innovation, and facilitated the green transformation through diversified measures. These measures include vigorously developing renewable energy sources, enhancing the carbon sequestration capacity of ecosystems, and improving the carbon emissions trading system. These policy initiatives have achieved phased results: statistical data indicates that in 2021, the proportion of non-fossil energy consumption in China reached 25.5%, an increase of 1.2 percentage points compared to the previous year. The proportion of clean energy sources, such as natural gas, hydropower, nuclear energy, and wind - solar power generation, has continued to expand, signifying that the energy supply structure is steadily progressing towards a low-carbon direction.

3.2 Status of Carbon Dioxide Emissions

In 2006, China became the world's largest carbon dioxide emitter, and in 2021, its carbon emissions accounted for 46% of the global total. With the rapid development of China's economy, its carbon emissions have also shown a tendency to grow rapidly, increasing from 3.5 billion tons in 2000 to 10.08 billion tons in 2020 (Figure 4). China's carbon emissions are confronted with issues such as a large total emission volume and a high proportion of coal consumption. Moreover, there are significant disparities in economic and energy endowments among different regions in China, leading to notable differences in carbon emissions. Chinese enterprises are positioned at the middle and lower ends of the global industrial chain, bearing more "transferred" emissions, and these problems also pose obstacles to the realization of China's emission reduction targets.

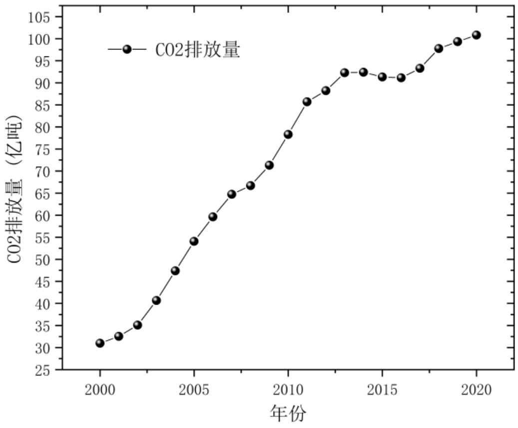

Figure 4: CO_2 emissions in China, 2000-2020

From 2017 to 2021, the carbon dioxide emissions per 10,000 yuan of China's Gross Domestic Product (GDP) declined continuously. By the end of 2019, the reduction had already exceeded the climate action target for 2020 ahead of schedule. In 2021, the carbon dioxide emissions per unit of GDP in China decreased by 3.8% compared to 2020 and had a cumulative decrease of 50.8% compared to 2005. The energy utilization efficiency has been improving year by year. Over the past decade, China's forest area has increased by 7.1% to 227 million hectares, emerging as the main driving force for global "greening". The forest carbon sink has increased by 7.3% to 839 million tons of carbon dioxide equivalent emissions per year.

3.3 Analysis of the Impact of Carbon Peak on China's Energy Consumption and CO_2 Emissions

Achieving carbon peak by 2030 is a crucial strategic goal for China. Given that China is still in a period of economic growth and its emissions have not yet peaked, it is of utmost importance to take into account both the low - carbon transformation of energy and the transformation of the economic structure, and to comprehensively consider the contradictions between carbon emission control and socio - economic development.

China will gradually improve the dual control of total energy consumption and intensity. It will optimize the energy structure, enhance energy utilization efficiency, and promote the energy revolution by developing new energy, green energy, and renewable energy. Additionally, efforts will be made to optimize and upgrade the industrial structure, develop green, environmentally friendly, and cleaner-production industries, and promote the green and low-carbon transformation of production and lifestyle. Moreover, China will develop new and clean energy sources to drive the green and low-carbon cycle, promote the trading markets of energy use rights and carbon emission rights, and develop green finance. It will also enhance the carbon-sequestration capacity of ecosystems and promote research on the carbon-sink economy. These measures will strengthen the sustainable development capacity of China's economy and society, inject new impetus into the realization of coordinated multi-objective development, and enhance the overall sustainable development capacity.

Under the constraints of the carbon - peaking strategic goal, it is estimated that by the time China achieves the "dual-carbon" goal in 2060, the proportion of coal will drop to less than 7%, the proportion of non-fossil energy will reach over 73%, and renewable energy will replace the coal-dominated fossil-energy structure, leading to a dramatic change in the overall national energy-consumption structure. While the total energy consumption grows in tandem with economic development, the energy consumption per 10,000 yuan of China's GDP will gradually decline. Meanwhile, when the total carbon-dioxide emissions reach their peak, the peak level is estimated to be controlled between 10 billion tons and 10.8 billion tons. The carbon-dioxide emissions per 10,000 yuan of GDP will also continue to show a downward trend, gradually realizing the decoupling of economic development from carbon-dioxide emissions and continuously optimizing the overall strategic layout for China's sustainable development.

4. Research Methods and Data Explanation

4.1 Theoretical Model

Drawing on the advantages of the Harrod-Domar economic growth model, Robert Solow, within the framework of neoclassical economics, mainly considering output (Y) and production factors such as capital (K), labor (L), and the effectiveness of knowledge (A), proposed the Solow growth model. Considering the one-sector Solow model, the model assumes that the savings rate is exogenous, the production function is progressive or Harrod - neutral, and exhibits constant returns to scale with respect to capital and effective labor, and satisfies the Inada conditions: $\lim_{k\to 0} f'(k) = \infty$, $\lim_{k\to\infty} f'(k) = 0$, the initial level of labor, capital and knowledge is assumed to be established, and the labor and knowledge grows at a constant rate. The specific production function is shown below.

$$Y_t = F(K_t, A_t L_t) \tag{1}$$

In equation (1), t represents the time dimension. The production function exhibits constant returns to scale with respect to the capital factor (K) and the labor factor (L), and satisfies the Inada conditions. The technological progress is labor-augmenting or Harrod - neutral, which is characterized by the total factor productivity A.

In this paper, the capital factor (K), the labor force factor (L), and the energy factor (E) are taken as input factors, the gross domestic product (Y) is taken as the desired output, and the CO_2 emissions (C) are taken as the undesired output to construct the production function.

$$Y(t) = F[A(t), K(t), L(t), E(t), C(t), t] \tag{2}$$

The basic assumptions about the model are as follows:

$$f_K^{'}(\cdot) > 0, f_L^{'}(\cdot) > 0, f_E^{'}(\cdot) > 0, f_C^{'}(\cdot) < 0 \tag{2.1}$$

$$f_K^{''}(\cdot) < 0, f_L^{''}(\cdot) < 0, f_E^{''}(\cdot) < 0, f_C^{''}(\cdot) > 0 \tag{2.2}$$

The function $f(\cdot)$ satisfies the Inada conditions. The models that meet the above-mentioned assumptions simultaneously include the Cobb-Douglas (C-D) production function and the translogarithmic production function. To regress the output coefficients of various variables as they change with the time trend, the Cobb-Douglas production function is constructed:

$$Y(t) = AK^{\alpha}L^{\beta}E^{\gamma}C^{\tau}, \alpha, \beta, \gamma > 0, \tau < 0 \tag{3}$$

Let α, β, γ, and τ represent the output elasticities of the four factors, and A represent the Hicks-neutral technological progress coefficient. According to the basic assumptions of the economic growth model, taking the natural logarithm on both sides of Equation (3) gives the following results:

$$\ln Y_t = \alpha \ln K_t + \beta \ln L_t + \gamma \ln E_t + \tau \ln C_t + gt, \alpha, \beta, \gamma, g > 0, \tau < 0 \tag{4}$$

According to the classical method of Solow (1957), total factor productivity (TFP) can be obtained by simultaneously differentiating both ends of equation (3) and dividing by Y. The total factor productivity (TFP) can be obtained by dividing by Y and dividing by Y:

$$\frac{1}{Y}\cdot\frac{dY}{dt} = \frac{1}{A}\cdot\frac{dA}{dt} + \alpha\frac{1}{K}\cdot\frac{dK}{dt} + \beta\frac{1}{L}\cdot\frac{dL}{dt} + \gamma\frac{1}{E}\cdot\frac{dE}{dt} + \tau\frac{1}{C}\cdot\frac{dC}{dt} \tag{5}$$

$$T\dot{F}P = \dot{Y} - \alpha\dot{K} - \beta\dot{L} - \gamma\dot{E} - \tau \tag{6}$$

where the variables are labeled with upper endpoints indicating their growth rates. Under neoclassical assumptions, the output elasticities of α, β, γ, τ are then equal to their respective output shares, and the growth rate of total factor productivity is approximately equal to the rate of technical progress. Equation (6) can also be used to perform the green growth accounting analysis required by the text.

After taking derivatives with respect to t on both sides of Eq. (4), the basic assumption of Solow (1957) yields

$$g^{*}=[\gamma(g+n)-\beta(b-c)-\tau m]/(1-\alpha) \qquad (7)$$

g^{*} represents the equilibrium growth rate of the economy in the presence of energy consumption and carbon dioxide emissions. Here, n and g represent the growth rates of the labor force and technological progress respectively. Energy is regarded as a single mixture of primary energy and renewable energy, with its consumption rate being b and its regeneration rate being c. Therefore, for economic growth, non-renewable energy poses an obstacle. Under given circumstances, the higher the consumption rate of non-renewable energy, the greater its constraint on economic growth, which further indicates a higher degree of dependence of economic growth on non-renewable energy. In other words, the structure of energy consumption determines economic growth, i.e., the higher the share of renewable energy sources, the greater the contribution of energy consumption to the economy. Technological progress acts as a driver of economic growth with the force of. Carbon dioxide emissions have a dampening effect on economic growth of the magnitude.

4.2 Data and Variable Explanation

Since some of the relevant data published in the statistical yearbooks are only up-to-date until 2019, the sample period of this paper is set from 1990 to 2019. The data sources are the annual "China Statistical Yearbook" and the International Energy Agency (IEA).

The GDP data is the real GDP of China at constant prices in 1990, which is calculated by converting the gross domestic product index published in the statistical yearbook. The data on carbon dioxide emissions are sourced from the releases of the International Energy Agency (IEA).

The capital stock is calculated through the perpetual inventory method, and the formula is:

$$K_t=(1-\delta_t)K_{t-1}+I_t/P_t \qquad (8)$$

Where K_t and K_{t-1} denote China's real capital stock in year t and year t-1 respectively, I_t is the fixed capital formation in year t, P_t is the fixed asset investment price index in year t, and δ_t is the depreciation rate of fixed assets in year t. In this paper, the real gross capital formation in 1990 estimated by Zhang Jun (2004) is divided by 10% as the capital stock in the base period, and the depreciation rate is fixed at 9.6%.

Since the traditional total labor force is unable to measure the changes in the quality of labor force, this paper measures the stock of human capital in China through the average number of years of education of the national labor force in the past years. The formula is as follows:

$$L_t=H_t*\sum(P_{i,t}*E_i) \qquad (9)$$

Where L_t is the human capital in year t, H_t is the total number of employed people in the country in year t, $P_{i,t}$ is the percentage of each educational level in year t, and E_i is the number of years of education required for each educational level. In this paper, the educational levels are subdivided as follows: illiteracy, elementary school education, lower secondary school education, upper secondary school and secondary school education, and junior college and bachelor's degree or above, and the number of years of education for each educational level is taken to be 1, 6, 9, 12, and 16 years, respectively.

5. Empirical Analysis

5.1 Unit Root Test

The data of the four variables in the model of this paper, gross domestic product (GDP), capital stock (K), human capital (L), energy consumption (E), and CO_2 emissions (C) are typical time series with significant trends and non-stationary characteristics. In order to avoid pseudo-regression between the sample data, the series were first subjected to the ADF unit root test to determine their smoothness. The logarithms of the above variables were taken as $\ln Y$, $\ln K$, $\ln L$, $\ln E$, $\ln C$, respectively, and the unit root test was performed. The results showed that the p-values of $\Delta^2\ln Y$, $\Delta^2\ln K$, $\Delta^2\ln L$, $\Delta^2\ln E$, $\Delta^2\ln C$ were less than 0.05 (Table 1) and the original hypothesis was rejected and it was concluded that at 5% level of significance, $\Delta^2\ln Y$, $\Delta^2\ln K$, $\Delta^2\ln L$, $\Delta^2\ln E$, and $\Delta^2\ln C$ were all smooth. Therefore, all the variables pass the unit root test and are in an $I(2)$ stationary process. Furthermore, a cointegration test is conducted on the variables to examine whether there is a long - run equilibrium relationship among them.

Table 1: ADF unit root test for each variable

variable	ADF	P-value
$\Delta^2 lnY$	-5.109891	0.0003
$\Delta^2 lnK$	-3.248670	0.0279
$\Delta^2 lnL$	-4.856836	0.0007
$\Delta^2 lnE$	-5.911436	0.0000
$\Delta^2 lnC$	-4.333965	0.0022

5.2 Cointegration Analysis

Since all variables are integrated of order two ($I(2)$), which meets the prerequisite for the cointegration test, a Vector Autoregression (VAR) model composed of the variables lnY, lnK, lnL, lnE, and lnC is first constructed. The lag order of the VAR model is determined based on various criteria. By comprehensively considering five indicators, namely the Likelihood Ratio (LR), Final Prediction Error (FPE), Akaike Information Criterion (AIC), Schwarz Criterion (SC), and Hannan-Quinn Criterion (HQ), it is found that the symbol "*" marks the minimum lag order for each indicator, and the number of indicators pointing to lag order 2 is the largest. Therefore, 2 is selected as the optimal lag order (Table 2).

Table 2: Table of Optimal Lag Orders

Lag	LogL	LR	FPE	AIC	SC	HQ
1	-1281.579	NA	2.38e+34	93.32706	94.51653	93.69069
2	-1235.746	58.92842*	6.23e+33*	91.83897*	94.21791*	92.56624

In the cointegration estimation, it is assumed that the trends of all sequences in the VAR (2) model are stochastic trends, and the Johansen cointegration test is carried out. The results are shown in Table 3 below:

Table 3: Johansen cointegration test

Unrestricted Cointegration Rank Test (Maximum Eigenvalue)

Hypothesized No. of CE(s)	Eigenvalue	Max-Eigen Statistic	0.05 Critical Value	Prob.**
None*	0.885364	58.48175	33.87687	0.0000
At most 1*	0.793961	42.65165	27.58434	0.0003
At most 2*	0.638819	27.49615	21.13162	0.0055
At most 3	0.351549	11.69556	14.26460	0.1226
At most 4	0.000536	0.014468	3.841465	0.9041

Under the assumptions of “None”, “At most 1”, and “At most 2”, the p-values are all less than 0.05. Thus, the null hypothesis is rejected. Collectively, this indicates that there exists a long - term stable equilibrium relationship among the variables lnY, lnK, lnL, lnE, and lnC, that is, there is a long - term equilibrium relationship between GDP and capital stock (K), human capital (L), energy consumption (E), and CO_2 emissions (C).

A Vector Error Correction Model (VECM (2)) is established, and the long - term cointegration relationships of various variables are obtained:

$$\ln Y = 0.25\ln K + 0.30\ln L + 0.51\ln E - 0.67\ln C$$

$$(0.0097) \quad (0.0201) \quad (0.5149) \quad (0.105)$$

The t-statistics are presented in parentheses in the above equation. The coefficients preceding each variable in the cointegration vector mirror the long-run relationships among the variables. The elasticity coefficient of capital with respect to economic growth is relatively low, standing at 0.25. The elasticity coefficient of human capital with respect to economic growth is somewhat more significant, reaching 0.30. The elasticity coefficient of energy consumption with respect to economic growth is more pronounced, being 0.51. Carbon dioxide has emerged as a “negative input” for economic growth, with its elasticity being significantly negative.

5.3 VECM Analysis

Based on the test of the cointegration relationship, this paper further constructs a vector error correction model (VECM) to integrate short-term fluctuations with long-run equilibrium.

$$\Delta \mathrm{lnY} = 0.398\mathrm{CEM} - 0.270\Delta \mathrm{lnY}(-1) - 0.596\Delta \mathrm{lnY}(-2) + 0.198\Delta \mathrm{lnK}(-1) - 0.163\Delta \mathrm{lnk}(-2) + 0.004\Delta \mathrm{lnL}(-1) - 0.002\Delta \mathrm{lnL}(-2) - 0.366\Delta \mathrm{lnE}(-1) - 0.514\Delta \mathrm{lnE}(-2) + 0.115\Delta \mathrm{lnC}(-1) + 0.203\Delta \mathrm{lnC}(-2) + 8427.461$$

Adj. R-squared=0.93, F-statistic=36.89, Log likelihood= -221.33, AIC=17.28

In the dynamic equation of real output, the coefficient of determination is 0.93. This indicates that 93% of the fluctuations in the short-term real GDP growth rate can be accounted for by the short-term changes of the five variables and the long-run relationships among them. The VECM results suggest that in the short term, regulating energy consumption and CO_2 emissions will significantly trigger fluctuations in economic growth.

5.4 Green Growth Accounting

In this paper, based on the empirically analyzed cointegration relationship, the contribution of factor inputs is calculated as the product of the factor growth rate and the estimated output elasticity of each factor. The growth rate of GDP is the sum of the growth rates of these four factors (capital, human capital, energy consumption, and CO_2 emissions) and total factor productivity. Therefore, the contributions of K, L, E, and C - representing capital, human capital, energy consumption, and CO_2 emissions respectively - to GDP are measured as their contribution shares (Table 4). This is to examine the true sources of China’s economic growth under the constraints of energy consumption and CO_2 emissions.

Table 4: China’s green total factor productivity and the contribution of each factor (%), 2000 to 2019

year	GDP	TFP	K	L	E	C
2000	7.83	6.72	2.29	0.01	2.86	-4.05
2001	7.66	3.42	2.37	2.27	2.98	-3.38
2002	8.34	5.74	2.63	0.64	4.60	-5.26
2003	9.09	7.54	3.05	0.85	8.27	-10.63
2004	9.17	7.94	3.17	0.58	8.59	-11.11
2005	10.23	10.05	3.26	-0.53	6.89	-9.44
2006	11.27	9.05	3.28	0.91	4.90	-6.87
2007	12.43	9.65	3.42	0.67	4.45	-5.75
2008	8.84	5.64	3.33	0.40	1.50	-2.03
2009	8.59	6.33	3.94	0.50	2.47	-4.64
2010	9.58	9.08	3.87	-0.51	3.72	-6.57
2011	8.76	5.54	3.62	2.19	3.73	-6.32
2012	7.32	3.57	3.39	0.35	1.99	-1.98
2013	7.24	4.84	3.23	0.37	1.87	-3.08
2014	6.89	2.68	2.91	-0.02	1.40	-0.08
2015	6.54	2.32	2.65	0.12	0.69	0.76
2016	6.37	2.94	2.44	-0.03	0.87	0.14
2017	6.45	3.88	2.13	0.36	1.66	-1.57
2018	6.28	5.72	2.11	-0.12	1.80	-3.22
2019	5.66	3.01	1.94	0.09	1.68	-1.06

It can be observed that the contribution of energy consumption to GDP is relatively large, while the negative impact of CO_2 emissions on economic growth is quite significant. Moreover, the larger the share of energy consumption in GDP, the more pronounced the inhibitory effect of CO_2 on GDP. From 2000 to 2019, the average growth rate of China’s green total factor productivity was 5.78%, which was substantially lower than the economic growth rate of 8.22%, and its average contribution rate was relatively low. This indicates that the low contribution of total factor productivity to economic growth is attributed to the low rate of technological progress. China’s economic growth mainly relies on capital input and energy consumption, at the expense of high CO_2 emissions. As an environmental cost, CO_2 has a notable negative impact on China’s economic growth. However, since 2003, when China proposed the binding targets for energy conservation and emission reduction in the Outline of the 11th Five-Year Plan, the negative offsetting effect of CO_2 emissions on economic growth has been decreasing year by year. This shows that external shocks such as energy conservation and emission reduction policies or technological progress have effectively reduced the impact of CO_2 emissions on economic growth to a certain extent.

In the context of the Carbon Peaking Strategy, China’s energy consumption structure will be continuously optimized. The proportion of renewable energy is on the rise and is replacing coal as the main energy source. Additionally, with technological progress, the energy utilization rate will be continuously improved. Therefore, it can be anticipated that, for the sustainable development of China’s economy and society, the 2030 carbon-peaking target will not only promote China’s energy revolution, optimize the energy consumption structure, and release the constraints on China’s economic growth, but also enhance the carbon-sequestration capacity of ecosystems, promote green, low-carbon, and energy-saving technologies, and gradually weaken the negative impact of CO_2 emissions on economic growth.

6. Conclusions and Policy Implications

The carbon-peaking strategic layout, by compelling the optimization of the energy structure, energy conservation, and emission reduction, not only enhances China’s attention to “resources and the environment” and improves the sustainable development capacity of China’s resources and environment, but also injects more high-quality energy impetus into China’s economic growth. It helps China’s economic development break free from the negative impact of CO_2 emissions, truly realizes the coordinated development of multiple objectives, and enhances China’s overall sustainable development capacity. However, currently, China still faces challenges in achieving the carbon-peaking goal and requires strong policy and measure guarantees. Based on the analysis of this paper, in order to achieve the carbon-peaking goal and maintain the path of sustainable economic development, the following policy recommendations are put forward:

6.1 Accelerate the Optimization of the Energy Consumption Structure and Give Full Play to the Supporting Role of Technological Innovation

Promote the optimization and upgrading of the energy consumption system and the full exploitation of China’s abundant renewable energy resources, such as hydropower, photovoltaics, and wind power. By expanding the scale of clean energy applications and promoting renewable alternatives like biofuels, we can continuously increase the proportion of non-fossil energy in the energy consumption structure and gradually build a new energy system led by renewable energy. Strengthen the driving role of scientific and technological innovation, increase investment in the research and development of green and low-carbon technologies, and make breakthrough energy technologies a strategic priority. Focus on the development of key technologies for clean production and carbon neutrality, and promote the upgrading of energy technologies in the direction of innovation-driven, low-carbon, environmentally friendly, and efficient utilization.

6.2 Vigorously Promote the Energy Conservation and Emission Reduction Strategy and Improve the Systems Related to Low-Carbon Development

Implementing the energy conservation and efficiency-enhancing strategy is a key initiative to reduce energy consumption and carbon emissions. The concept of low-carbon development needs to be extended to a broader range of industrial sectors. Improve the carbon emission control mechanism and explore the organic integration of total carbon emission control with the current pollution reduction assessment system. Optimize the green and low-carbon policy system, improve the innovation incentive mechanism, give full play to the supporting role of technological innovation in green transformation, and cultivate the low-carbon technology industry as a new engine of economic growth. Continuously adhere to the concept of green development, implement low-carbon policies, advocate low - carbon travel and the use of low-carbon and energy-saving products, promote the formation of a consensus on low-carbon emission reduction in society, create a favorable atmosphere for carbon emission reduction, actively build a “low - carbon society”, and practice a low- carbonlifestyle.

6.3 Promote Low-Consumption and Environmentally Friendly Production Methods and Reconfigure a Decarbonized Economic Structure

Actively guide high-energy-consuming and high-polluting industries towards energy-saving production and promote industrial production methods to be more low-consumption and environmentally friendly. In the industrial sector, where carbon emissions are most concentrated, there is an urgent need to accelerate breakthrough technological innovation, promote the application of environmentally friendly industrial technologies, and advance the substitution of traditional energy sources with clean energy sources such as electricity, hydrogen, and biomass, so as to help the industrial sector take the lead in realizing the inflection point of carbon emissions. At the same time, it is necessary to accelerate the elimination of backward production capacity, optimize the layout of high-energy-consuming industries, promote the upgrading of traditional industries in the direction of green and low - carbon, and push the industrial structure to a higher level. Actively expand high-tech industries and strategic emerging industries, deepen the reform of the factor market, improve the intensive utilization of production factors, build a green industrial system featuring green, low-carbon, and circular development, and promote a more rationalized industrial structure.

6.4 Gradually Improve the Carbon Trading Market Mechanism and Promote the Construction and Operation of the Carbon Market

Gradually expand the scope of participation of market entities, enlarge the scale of the carbon trading market, and encourage the participation of different entities in carbon trading by expanding the scope of trading industries. Cultivate and improve the chain of market participants and stimulate the enthusiasm of carbon trading entities to participate. Accelerate the improvement of the national carbon emissions trading system and introduce the carbon tax mechanism in a timely manner to prompt enterprises to fully consider the cost of carbon emissions in their production and operation. Relevant departments should gradually reduce the proportion of free quotas, expand the scale of paid quotas, and moderately raise the price level of the carbon trading market. Establish a sound carbon emission statistics and monitoring system and improve the construction of the carbon footprint database. Scientifically plan the carbon derivatives market and strengthen the regulatory system of the carbon financial market. Lay a solid foundation for spot-based futures trading. Through measures such as gradually improving the carbon trading market mechanism, the carbon trading emissions market will become an important means of achieving the carbon-peaking goal.

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