Research Article

Prediction on the Peak of the CO₂ Emissions in China Using the STIRPAT Model

Li Li,^{1,2} Yalin Lei,^{1,2} Chunyan He,³ Sanmang Wu,^{1,2} and Jiabin Chen⁴

¹School of Humanities and Economic Management, China University of Geosciences, Beijing 100083, China

²Key Laboratory of Carrying Capacity Assessment for Resource and Environment, Ministry of Land and Resources, Beijing 100083, China

³Foreign Language Department, China University of Geosciences, Beijing 100083, China

⁴Chinese Academy of Land & Resource Economics, Beijing 101149, China

Correspondence should be addressed to Yalin Lei; leiyalin@cugb.edu.cn

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Climate change has threatened our economic, environmental, and social sustainability seriously. The world has taken active measures in dealing with climate change to mitigate carbon emissions. Predicting the carbon emissions peak has become a global focus, as well as a leading target for China's low carbon development. China has promised its carbon emissions will have peaked by around 2030, with the intention of peaking earlier. Scholars generally have studied the influencing factors of carbon emissions. However, research on carbon emissions peaks is not extensive. Therefore, by setting a low scenario, a middle scenario, and a high scenario, this paper predicts China's carbon emissions peak from 2015 to 2035 based on the data from 1998 to 2014 using the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) model. The results show that in the low, middle, and high scenarios China will reach its carbon emissions peak in 2024, 2027, and 2030, respectively. Thus, this paper puts forward the large-scale application of technology innovation to improve energy efficiency and optimize energy structure and supply and demand. China should use industrial policy and human capital investment to stimulate the rapid development of low carbon industries and modern agriculture and service industries to help China to reach its carbon emissions peak by around 2030 or earlier.

1. Introduction

Carbon emissions peak is the maximum of carbon emissions produced by burning fossil fuels. China was the world's first largest emitter of carbon emissions in 2014 [1]. The time when China will reach its carbon emissions peak has become the focus of broad attention. The State Council put forward the target to reduce the emissions intensity of economic growth by 40%–45% below 2005 levels by 2020 [2]. China also announced its goal to reach its carbon emissions peak in around 2030, with the intention of peaking earlier, and to raise the non-fossil fuel share of primary energy supply to approximately 20% by 2030 [3]. In November 2015, President Xi announced that China would reach its carbon emissions peak by around 2030 or earlier [4].

It is still unclear whether China will reach its carbon emissions peak in 2030 and at what level the carbon emissions peak will occur. Also, there is not much research on China's

carbon emissions peak. Therefore, by setting a low scenario, a middle scenario, and a high scenario, this paper predicts China's carbon emissions peak from 2015 to 2035 based on the data of 1998–2014 using the STIRPAT model. Study on China's carbon emissions peak can provide reference for the formulation of carbon emissions reduction policies and sustainable development in the future. Within the parameters of the STIRPAT model and China's official climate targets to date, the remainder of the paper is dedicated to examining these possibilities.

2. Literature Review

In recent years, many institutions and scholars in the world have used different models to forecast China's carbon emissions peak. There are some methods employed for this prediction.

BP Corporation stated that energy growth in the world would be mainly concentrated in emerging economies such as China, India, Russia, and Brazil in the next 20 years from 2011. The global carbon emissions peak would arrive soon after 2020, when carbon emissions would be 20% higher than in 2005 [5]. The International Energy Agency (IEA) also noted that carbon emissions would peak in 2020 [6]. King [7] indicated that China would reach its carbon emissions peak in 2025 without affecting economic growth. By setting the continuous improvement scenario (CIS) and accelerated improvement scenario (AIS), Zhou et al. [8] estimated that China would reach peak carbon emissions under the CIS and AIS in 2033 and 2027, respectively. Liu et al. [9] put forward that China would have a challenge in achieving this goal in 2030 if there were no major policy changes.

Based on the modified EKC curve, Zhu et al. [10] estimated that China's energy consumption and carbon emissions would peak in 2043 and 2040 under the current level of technology. Based on the Kuznets model, Lin and Jiang [11] predicted that China's carbon emissions would peak in approximately 2020. Using the IPAC model and the baseline scenario, low carbon scenario, and enhanced low carbon scenario, Jiang et al. [12] designed the path of low carbon development. The results showed that China's carbon emissions would peak around 2030 in the enhanced low carbon scenario and peak around 2040 in the baseline scenario. Pan et al. [13] deemed that China's carbon emissions would peak sometime between 2035 and 2045. Based on global dynamic energy and the environment GTAP-Dyn-E model, Liu et al. [14] predicted the carbon emissions in the world's eight major economies (The United States, the European Union, Japan, Australia, China, India, Brazil, and South Africa) from 2010 to 2050. The results showed that China could not reach the peak before 2050. Yuan et al. [15] recognized that China's carbon emissions would peak during the period from 2030 to 2035 using Kaya identity. Based on the government-dominant scenario, market-dominant scenario, and a hybrid government market-dominant scenario, Wu et al. [16] adopted a revised version of the Kaya to make analysis on carbon emissions in developing countries. Similarly, Mavromatidis et al. [17] employed Kaya identity in analyzing the main drivers of emissions reduction of the Swiss building stock. He [18] analyzed the target and the path of China's carbon emissions to 2030 and noted that China needed to improve its energy technology innovation and energy management system and reformed the pricing mechanism to promote the realization of the carbon emissions goal. Chai and Xu [19] calculated China's carbon emissions from 2025 to 2030 by setting different scenarios. Yi et al. [20] quantitatively assessed CO₂ emissions reduction from 2005 to 2020 using LMDI (Log Mean Divisia Index) and scenario analysis. The results showed that the 40–45% reduction target might be achieved. Wang et al. [21], Wang et al. [22], Fu et al. [23], Li et al. [24], and Wang et al. [25] utilized the STIRPAT model to find out the factors which affected CO₂ emissions in different areas.

From the results of China's carbon emissions peak above, it can be observed that the great difference lies in the year of the carbon emissions peak predicted. Scholars have

also adopted different models and methods, such as the scenario analysis method, the index decomposition method, the structure analysis method, and the STIRPAT model.

The scenario analysis method is easy to be used and can be analyzed and compared with a variety of scenarios. However, the biggest flaw of this method is that the parameter setting of scenario prediction is quite arbitrary. The influence factors of carbon emissions are not comprehensive in the scenario analysis method, which may miss some more important variables as a result. For example, urbanization has a great effect on the increasing of carbon emissions, but it is difficult for the model to reflect this situation.

Historical data can be used in the index decomposition method and the structural analysis method to accurately measure the influence factors of carbon emissions. The influence of the energy structure and the industrial structure on carbon emissions is relatively weak. This does not mean that the index decomposition method is not important for the impact of energy structure and industrial structure on carbon emissions. However, due to the short period of the study, the changes in these variables are not large.

The STIRPAT model has two advantages. Firstly, it has better expansibility and can introduce multiple independent variables to test the influence of each independent variable's pressure on the environment when analyzing environmental stress. Secondly, the STIRPAT model is nonlinear, so the introduction of the index can be used to analyze the environmental impact of the nonequal proportion of individual factors.

3. Model and Data

3.1. Model. The STIRPAT model is derived from the IPAT model. Ehrlich and Holdren [26] first put forward the IPAT model in 1971. The IPAT model was adopted to quantitatively calculate the impact of people on the environment. I expresses environmental impact, P denotes population, A indicates affluence, and T denotes technology level. However, although the IPAT model has been widely recognized and applied to the analysis of influence factors of environmental change, there are also some obvious shortcomings. One shortcoming is that the influence of each factor is equal. To make up for this defect, Dietz and Rosa [27] put forward the stochastic format, which was called the STIRPAT model in

$$I = \alpha P^a A^b T^c e. \quad (1)$$

The variables a , b , and c are the exponential terms of every factor, and e is the stochastic error. The STIRPAT model can be turned into the IPAT model if $\alpha = a = b = c = 1$. The STIRPAT model is widely used to study carbon emissions and their influence factors [28].

Taking the natural logarithm of (1), (2) can be obtained in the following:

$$\ln(I) = \alpha + a(\ln P) + b(\ln A) + c(\ln T) + e. \quad (2)$$

As urbanization level (UL), energy consumption structure (ECS), and economic structure (ES) are important influence factors of CO₂ emissions, this paper introduces UL,

TABLE 1: Description of the variables used in the paper.

Variable	Symbol	Definition	Unit
CO ₂ emissions	I	CO ₂ emissions in China	Ten thousand tons
Total population	P	Total population	Ten thousand
GDP per capita	A	GDP per capita (ten thousand yuan)	Ten thousand
Carbon intensity	T	CO ₂ emissions per GDP	Tons/ten thousand yuan
Urbanization level	UL	The proportion of city population in the total population	%
Energy consumption structure	ECS	The proportion of coal consumption in energy consumption	%
Economic structure	ES	The percentage of the output value of the second industry in GDP	%

ECS, and ES into the model. The description of the variables used in this paper (Table 1) and the modified model are shown in the following:

$$\ln(I) = \alpha + a \ln(P) + b \ln(A) + c \ln(T) + d \ln(UL) + m \ln(ECS) + n \ln(ES) + e. \quad (3)$$

Regression analysis is performed for (2). Regression coefficients reflect the elastic relationships between explanatory variables and the variables being explained.

For those models that contain many independent variables, there may be a certain correlation or high correlation between them. This situation may distort the model and make it difficult to estimate accurately. Thus, multicollinearity test should be done to detect it. Ridge regression is a good method to avoid multicollinearity, which was first proposed by Hoerl in 1962. He and Kennard developed it systematically in 1970 [29]. The use of ridge regression is a good way to detect multicollinearity problems.

3.2. Data. The data of P , A , T , UL , ECS , and ES between 1998 and 2014 were all from the Wind Data [30], China Statistical Yearbooks [31], and National Bureau of Statistics of China [32].

4. Results and Discussion

4.1. Influence Factors and the Regression Equation Fitting

(1) *Population from 1998 to 2014.* China's population was 1248 million in 1998 and it increased to 1368 million in 2014 [31]. Although China's population increased during this period, the population growth rate decreased over the same period, with the exception in 2005 (as shown in Figure 1).

(2) *GDP per Capita from 1998 to 2014.* China's GDP per capita was 6.8 thousand yuan in 1998, and it rose to 46.5 thousand yuan in 2014 [31]. Over this period, China's GDP per capita

FIGURE 1: Total population in China from 1998 to 2014 (million) and the growth rate (%).

increased, while the growth rate rose slightly with the lowest point of 5.37% in 1998 and the highest point of 22.5% in 2007 (as shown in Figure 2).

(3) *Carbon Emissions Intensity from 1998 to 2014.* China's carbon emissions intensity decreased from 3.88 tons/ten thousand yuan in 1998 to 1.34 tons/ten thousand yuan in 2014, while when it increased slightly in 2002, 2003, and 2009 (as shown in Figure 3).

(4) *Urbanization Level from 1998 to 2014.* China's urbanization level had been consistently increasing from 33.85% in 1998 to 54.77% in 2014. Although the urbanization level increased during this period, the urbanization growth rate decreased except in 2007 and 2010. The lowest growth rate of 1.94% occurred in 2014, and the highest rate of 4.5% was achieved in 1998 (as shown in Figure 4).

(5) *Energy Consumption Structure from 1998 to 2014.* China's energy consumption structure increased slightly from 1998 to

FIGURE 2: GDP per capita in China from 1998 to 2014 (ten thousand yuan) and the growth rate (%).

2014. The highest growth rate of 3.13% occurred in 2005, and the lowest growth rate of -2.97% occurred in 2000 (as shown in Figure 5).

(6) *Economic Structure from 1998 to 2014.* There was a little change in China's economic structure from 1998 to 2014. The highest economic structure was 59.7% in 1998, and the lowest was 46.2% in 2001. The highest growth rate was 17.68% in 2003, and the lowest growth rate was -22.35% in 2001 (as shown in Figure 6).

(7) *The Regression Equation Fitting.* Taking $\ln(I)$ as the dependent variable and $\ln(P)$, $\ln(A)$, $\ln(T)$, $\ln(UL)$, $\ln(ECS)$, and $\ln(ES)$ as the independent variables, ridge k and the coefficients for estimated values of ridge k were shown in Table 2.

From Table 2, it could also be seen that the ridge k tended to be stable when the ridge parameter was bigger than 0.45. Thus the paper chose the ridge parameter k as 0.45, and the regression equation was as follows:

$$\ln(I) = 3.06 \ln(P) + 0.13 \ln(A) - 0.19 \ln(T) + 0.54 \ln(UL) + 1.1 \ln(ECS) - 0.12 \ln(ES) - 2.57. \quad (4)$$

From (4), it can be observed that positive changes in the population, GDP per capita, urbanization level, and energy consumption structure will increase the total amount of carbon emissions. However, it can be observed that positive changes in the carbon emissions intensity and economic structure will reduce the total amount of carbon emissions. Comparing the fitted values with the actual values of carbon emissions from 1998 to 2014, the random errors of all years were less than 5% except 2001 and 2002. There was a better fitting between the fitted values and the actual values (as shown in Figure 7).

4.2. *The Scenarios Setting.* We assume there are three development scenarios in China's future: the low, middle, and

FIGURE 3: Carbon emissions intensity in China from 1998 to 2014 (ton/ten thousand yuan) and the growth rate (%).

FIGURE 4: Urbanization level in China from 1998 to 2014 (%) and the growth rate (%).

high emission scenarios. In the low emission scenario, each variable changes slightly. Each variable changes moderately in the middle emission scenario. The changes of each variable are larger in the high emission scenario.

(1) *Population Setting.* Taking the population of 2015 [31] as the baseline and the scenario setting from the UNPD [33], the low, middle, and high emission scenarios, the annual growth rates would be -2.81%, -1.95%, and -1.91%, respectively (as shown in Figure 8).

(2) *GDP per Capita Setting.* Referring to the data of GDP per capita of 2015 [31] and the scenario settings from the IEA [6], the change of China's GDP per capita from 2015 to 2035 was set (as shown in Figure 9).

(3) *Carbon Emissions Intensity Setting.* The data of carbon emissions intensity in 2015 were taken from NBSC [31]. The scenario setting was based on the target of reducing the emissions intensity of economic growth by 40%–45% below 2005 levels by 2020 [4] and reducing the emissions intensity of economic growth by 60%–65% below 2005 levels by 2030

TABLE 2: The coefficients for estimated values of ridge k .

RIDGE	_RMSE	Intercept	x1	x2	x3	x4	x5	x6
0		0	0.078284	1.853315	0.971664	3.98E-08	-3.6E-09	-1.3E-09
0.05	0.013621	-4.06856	3.91358	0.154094	-0.1459	0.672474	1.647865	0.028697
0.1	0.01573	-3.70058	3.663732	0.147276	-0.17567	0.635763	1.588497	-0.00499
0.15	0.018005	-3.45057	3.515171	0.143406	-0.18573	0.613803	1.508606	-0.03088
0.2	0.020388	-3.25215	3.406391	0.140245	-0.18989	0.597171	1.428594	-0.05225
0.25	0.022793	-3.08336	3.318024	0.137428	-0.19154	0.583269	1.352639	-0.07037
0.3	0.025169	-2.9346	3.242079	0.134839	-0.19191	0.571062	1.281704	-0.08596
0.35	0.027488	-2.80075	3.174591	0.132426	-0.19156	0.560039	1.215826	-0.09948
0.4	0.029739	-2.6787	3.113325	0.130158	-0.19078	0.549911	1.154741	-0.11129
0.45	0.031916	-2.56636	3.056892	0.128016	-0.18972	0.540495	1.098091	-0.12166
0.5	0.034019	-2.46223	3.004369	0.125982	-0.18848	0.531666	1.045499	-0.13078
0.55	0.036049	-2.36517	2.955104	0.124047	-0.18712	0.523336	0.996607	-0.13884
0.6	0.03801	-2.27429	2.908617	0.122199	-0.18569	0.515438	0.951084	-0.14598
0.65	0.039906	-2.18888	2.864542	0.12043	-0.18421	0.507918	0.908627	-0.15232
0.7	0.04174	-2.10834	2.822592	0.118734	-0.1827	0.500737	0.868964	-0.15795
0.75	0.043515	-2.03218	2.782534	0.117105	-0.18117	0.49386	0.831852	-0.16295
0.8	0.045236	-1.95998	2.744178	0.115536	-0.17964	0.487257	0.797071	-0.16741
0.85	0.046905	-1.89138	2.707365	0.114025	-0.17811	0.480907	0.764426	-0.17137
0.9	0.048525	-1.82606	2.671962	0.112566	-0.17658	0.474787	0.733739	-0.17491
0.95	0.0501	-1.76375	2.637852	0.111157	-0.17506	0.46888	0.704854	-0.17805
1	0.051632	-1.70421	2.604937	0.109793	-0.17356	0.463171	0.677627	-0.18084

FIGURE 5: Energy consumption structure in China from 1998 to 2014 (%) and the growth rate (%).

FIGURE 6: Economic structure in China from 1998 to 2014 (%) and the growth rate (%).

[34]. The variation range was based on the reference to Qu and Guo [35] and The Associated Press [36] (as shown in Figure 10).

(4) *Urbanization Level Setting.* China's urbanization level in 2015 was 56.1% [37]. The scenarios were set by the UN [33] (as shown in Figure 11).

(5) *Energy Consumption Structure.* China's energy consumption structure in 2015 was 64.0% [23]. The scenarios were set according to BP [38] (as shown in Figure 12).

(6) *Economic Structure Setting.* China's economic structure in 2015 was 40.5% [31]. The scenarios were set according to Li

and Huang [33]. The trends of economic structure in the low, middle, and high emission scenarios were shown in Figure 13.

4.3. *Prediction of the Carbon Emissions Peak and Discussion.* The results of low emission scenario, middle emission scenario, and high emission scenario are shown in the Figure 14.

(1) In the low emission scenario, China will keep a lower population growth rate, as well as a slower rate of change in GDP per capita, and urbanization and economic structure. China's carbon emissions will reach their peak of approximately 8.27 billion tons in 2024. The result is consistent with that of Boqiang Lin [37] who said that if

FIGURE 7: The fitting values and the actual values of carbon emissions from 1998 to 2014 (a hundred million tons).

FIGURE 8: The trends of population in the low, middle, and high emission scenarios (a hundred million).

haze were managed strictly, carbon emissions could peak before 2024. The Center for Energy & Environmental Policy Research in the Beijing Institute of Technology [39] also predicted that carbon emissions would peak in 2025 in the low emission scenario.

(2) In the middle emission scenario, China's carbon emissions will peak in 2027, at approximately 8.83 billion tons, which is 0.57 billion tons more than in the low emission scenario.

(3) In the high emission scenario, carbon emissions will have raised by 2030, peaking at 9.37 billion tons. Then, there will be a slight decrease from 2030 to 2035. The result is consistent with Bi [40], who predicted that carbon emissions would increase from 8.01 billion tons in 2015 to 9.35 billion tons in 2030, peaking in that year. The results also approached that of Yue et al. [41].

5. Conclusions and Policy Implications

5.1. Conclusions. As carbon emissions reach the peak, economic development will have fundamental changes in China

FIGURE 9: The trends of GDP per capita in the low, middle, and high emission scenarios (ten thousand/per person).

FIGURE 10: The trends of carbon emissions intensity in the low, middle, and high emission scenarios (ton/ten thousand).

FIGURE 11: The trends of urbanization level in the low, middle, and high emission scenarios (%).

FIGURE 12: The trends of energy consumption structure in the low, middle, and high emission scenarios (%).

FIGURE 13: The trends of economic structure in the low, middle, and high emission scenarios (%).

and fossil energy consumption will also reach its peak. Then, a decoupling of economic growth and fossil energy will occur. According to the results above, the conclusions are as follows:

(1) In different scenarios, carbon emissions will peak at different levels in different years. In the low carbon scenario, carbon emissions will peak earliest at the lowest level. In the middle carbon emission scenario, carbon emissions will peak three years later at a slightly higher level than that in the low carbon scenario. In the high carbon emissions scenario, carbon emissions will peak in the latest but at the highest level among the three scenarios.

(2) China's target to reach its carbon emissions peak in approximately 2030 can be realized. In the high carbon emissions scenario, although the peak year occurs at latest, it falls before 2030. By then, the energy consumption structure and industrial structure will be optimized, and low carbon technologies will also be applied on a large scale. The development of renewable energy will have a certain base and show a trend of rapid development. The energy structure will be greener.

FIGURE 14: The trends of change of China's carbon emissions from 2015 to 2035 (a hundred million tons).

5.2. Policy Implications. According to the results and the conclusions above together with the targets, the paper puts forward some policy implications in the following.

(1) In the choice of targets, combining with China's development and the predicted carbon emissions peak, the Chinese government can consider achieving the carbon emissions peak during "the 15th Five-Year Plan." China's carbon emissions peak can be maintained at approximately 9 billion tons. By then, China's industrialization will have basically been completed, the GDP per capita will be closer to 60 thousand yuan, and the urbanization level will reach approximately 70%. If large-scale innovative technologies are applied, China can be expected to realize its low carbon transformation and carbon emissions peak smoothly.

(2) On the realization of the targets, China should formulate its national strategy and regional strategy as soon as possible to achieve the carbon emissions peak. Every industry also ensures the implementation of the targets. At the same time, energy efficiency should be improved, and the energy structure, demand, and supply should be optimized. Incentivizing low carbon industries, modern agriculture and service industries will be conducive to the earlier realization of the carbon emissions peak.

Competing Interests

The authors declare no competing interests.

Authors' Contributions

Li Li and Yalin Lei designed the research and methodology; Sanmang Wu collected the data and compiled all the data and literature; Li Li and Sanmang Wu finished the experiment and calculation; Yalin Lei, Li Li, and Jiabin Chen analyzed the results and put forward the policies; Yalin Lei and Li Li revised the manuscripts and approved the manuscripts; Yalin Lei will be responsible for the future questions from readers as the corresponding author.

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