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Research on carbon emission peaks in large energy production region in China—Based on the open stirpat model

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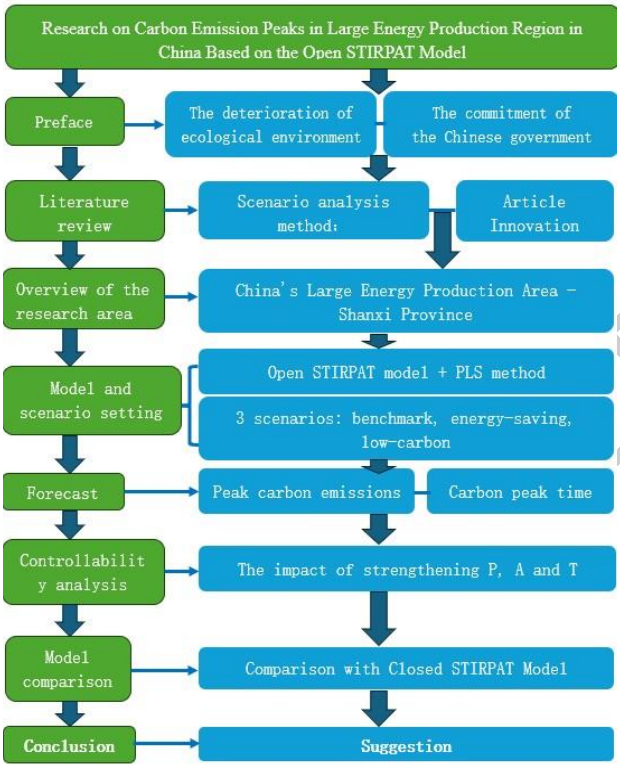
Graphical abstract



Abstract

The interdependence between different regions within a country has an important impact on the prediction of regional carbon emission peaks. In this paper, taking Shanxi Province, a large energy producing region in China, as an example, we select the driving factors to construct an open STIRPAT model from both Shanxi and national levels, and use scenario analysis to predict the carbon emissions of Shanxi Province from 2021 to 2040. The study shows that (1) In the Open STIRPAT model, the year and amount of peak carbon emissions in Shanxi province are mainly determined by the national scenarios. If the baseline scenario is chosen for the whole country, then no matter which scenario is chosen for Shanxi, it will not be able to realize the carbon peak in 2030. Under the scenario combination of low carbon-low carbon, Shanxi will realize the carbon peak in 2027. Under the scenario combination of low carbon-energy saving and energy saving-low carbon, Shanxi will realize the carbon peak in 2028. (2) The peak carbon emissions in Shanxi are mainly affected by the national scenario setting and Shanxi's emission reduction strategy. Controlling per capita GDP and energy consumption of 10,000 yuan GDP is an effective emission reduction strategy. (3) Compared with the open STIRPAT model, the closed STIRPAT model delays the year of peak carbon in Shanxi and overestimates carbon emissions by 20%-44%. Therefore, Shanxi should pay attention to the development of energy saving at the national level in formulating its carbon emission strategy, take it as an important constraint for Shanxi's peak carbon policy, and formulate a flexible carbon emission peaking program.

Keywords: open STIRPAT model, carbon peaking, forecasting, scenario analysis approach

1. Introduction

Under the dual challenges of intensifying global climate change and the actual needs of domestic ecological environment and economic development, in September 2020, Chinese President Jinping Xi announced at the 75th United Nations General Assembly that China was striving to achieve a dual carbon goal, i.e., to peak CO_2 emissions by 2030 and to strive to achieve carbon neutrality by 2060. In 2021, the Central Committee of the Communist Party of China (CPC) and the State Council jointly issued the Opinions on the Complete and Accurate Comprehensive Implementation of the New Development Concept and Doing a Good Job of Peaking Carbon and Carbon Neutrality, a document that clarifies the key tasks China will accomplish in order to achieve its dual-carbon goal.

At present, China has initially formed a roadmap for reaching the peak in the east, followed by the central and western regions. This roadmap takes into account the differences in China's regional economic development-the eastern region is gradually entering the late stage of industrialization, while the central and western regions are generally in the mid-stage of industrialization with high industrial growth, which is superior to the idea of "synchronous low-carbon". The existing roadmap ignores the differences in regional economic development. However, the existing roadmap ignores the division of labor and cooperation among regional economies in the overall economy, fails to recognize the interactions and dependencies among the economies of the eastern, central, and western regions of China, as well as various provincial-level regions, and fails to take into account that regional carbon peaks will be affected by external factors in the region. The regional carbon emission peak policy thus formulated severely inhibits regional economic development.

2. Literature review

At present, as far as the prediction of peak carbon emissions is concerned, the scenario forecasting method is the most widely used analytical method. Zong (1994) firstly introduced the scenario analysis method in China's strategic forecasting. Chermach (2005) gave a clear definition of scenario analysis and reviewed the theoretical development and current research status of the scenario analysis method. According to Bouhalleb and Smida (2018), scenario planning is a multidimensional structure consisting of three dimensions, namely information acquisition, scenario development, and strategy selection. Scenario analysis is widely used in the fields of energy demand and climate change because it bases its analysis on key assumptions about the economy, industry, and technology, and is able to accommodate a wide range of possible future scenarios, and is characterized by rigor, detail, and comprehensiveness of the analysis. Fang and Wang et.al used scenario analysis to analyze the economic and political impacts on developing countries of the carbon emission reduction target proposed by developed countries in 2009. This carbon emission reduction target will hinder the industrialization process of developing countries, widen the carbon emission gap between developed and developing countries, and bring about further conflicts over the allocation of carbon emission rights. Wen *et al* (2016) used scenario analysis to study the impacts of changes in carbon emission factors and carbon sinks under 27 different scenarios, and finally found 8 effective pathways for China to achieve carbon neutrality by 2060. Carbon Neutrality in China by 2060. Li *et al* (2020) built six scenarios by constructing a backward neural propagation network model to analyze the impacts of different levels of economic development and energy consumption on the trend of carbon price.

Scenario prediction of regional carbon emission peaks requires clarification of the quantitative relationship between carbon emissions and drivers. As for the research on the relationship between the two, the main methods adopted by academics include IPAT model, LEAP model and STIRPAT model, etc. Among them, STIRPAT model is the most widely used, and STIRPAT model is developed from IPAT model. In 1971, Ehrlich *et al* put forward the famous I=PAT equation, which measures the constant relationship between population, affluence and technology. Commoner (1992), based on which, decomposed per capita environmental impacts into per capita wealth and the level of technology that has an impact on the environment, and put forward IPAT equation. Proposed IPAT constant equation. Then, Dietz *et al* (1997) proposed STIRPAT model on the basis of IPAT constant equation. STIRPAT model breaks away from the scope of IPAT constant equation and decomposes regional environmental influences into three categories of population, economic development level and technological factors. The STIRPAT model provides a highly practical model for analyzing the relationship between regional carbon emissions and the driving factors. The STIRPAT model provides a practical model for analyzing the relationship between regional carbon emissions and driving factors, and scholars have since developed the model mainly in the selection and decomposition of driving factors. For example, Cramer (1998) decomposed the population into the number of households and population size. Chen *et al* (2014) decomposed the level of economic development into per capita output and the human development index, etc. More development lies in the aspect of the decomposition of technological factors such as decomposition into the value of the contribution of the secondary industry or the value of secondary production The level of economic development is decomposed into per capita output and human development index more development lies in the decomposition of technical factors, such as the contribution value of the secondary industry or the proportion of the secondary industry in GDP , the energy consumption of 10,000 yuan of GDP, the investment in the whole society's fixed assets, and the location of the economy, etc. However, the existing literature tends to pay more attention to intra-regional factors when analyzing the drivers of regional carbon emissions, which is a closed perspective. In reality, for a large country with a vast territory, there is often a clear regional division of labor between different regions within the country. The development of a region is inevitably influenced by the regions with which it cooperates. Therefore, an open perspective should be established. In such a perspective, regional carbon emissions depend not only on the influence of factors within the region, but also on the influence of factors outside the region.

This paper takes Shanxi Province, a large energy production region in China, as an example, and analyzes the division of labor and interdependence of the regional economy, selects the driving factors from Shanxi and the national level to construct the open STIRPAT model, and uses scenario analysis to predict the peak of carbon emissions in Shanxi Province in the period of 2021-2040. Based on this, the controllability of the peak carbon emissions in Shanxi Province and the adverse effects of the closed perspective on the formulation and implementation of the regional peak carbon emissions policy are analyzed, so as to provide theoretical support for the formulation of the regional peak carbon emissions policy in a more scientific way.

This paper provides a literature review in the second part; The third part introduces the overview of the study area, the research methods used, and the data sources. The fourth part studied the years and carbon emissions of carbon peak in Shanxi Province under different scenario settings based on the open STIRPAT model and scenario analysis method. At the same time, we also analyzed the controllability of Shanxi Province's own carbon emissions and the impact of the closed STIRPAT model on the predicted carbon emissions and peak years in Shanxi Province. The fifth part includes conclusions and policy recommendations.

3. Overview of the study area, research methodology and data sources

3.1. Overview of the study area

Figure 1 illustrates the out-of-province share of all energy, coal, coke and electricity in Shanxi from 1995 to 2022. For all energy, the average value of the out-of-province share for 27 years is 72.3%, which shows that the vast majority of energy produced in Shanxi province is provided to the provinces for use, and it is an important energy production base in China, which provides an important support for the sustained and stable operation of China's macro-economy. At the same time, Shanxi's carbon peaks have an important impact on China's carbon peaks. It is also for this reason that this paper takes Shanxi as an important study area. In terms of coal, the share of coal exported to the province has remained stable at about 69.1%, and from 1998 to 2009, the share of coal exported to the province has fluctuated in an M-shape. In 2001, the share of coal going out of the province was the highest, at 91.3 %. after 2009, there was a small downward trend in the share of coal going out of the province.

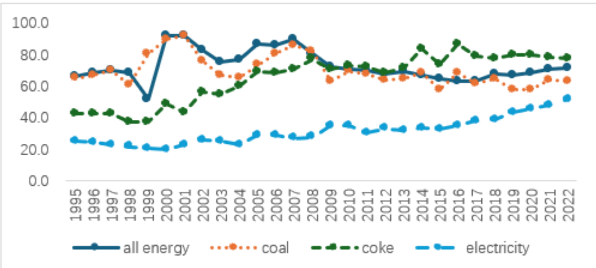


Figure 1. Energy Exports from Shanxi Province, 1995-2022

For coke, the overall upward trend in the share of outgoing provinces from 1995-2022 is from 41.8% in 1995 to 77.2% in 2022. The highest share of outgoing exports was recorded in 2016, at 86.2%. For electricity, the share of exports out of the province has continued to rise since 1995. It reaches its maximum in 2022, at about 51.4%.

3.2. The open STIRPAT model

The closed STIRPAT model was developed from the IPAT model and the equation is expressed as follows.

$$I = a \times P^{b} \times A^{b} \times T^{d} \times e \tag{1}$$

Where I, P, A, and T denote the carbon emissions, demographic factors, economic development level, and technology level of the region, respectively, a is the model coefficient, b, c, and d are the indices of variables P, A, and T, respectively, and e is the model error term.

As shown in Figure 1, the carbon emissions of Shanxi Province, as an important energy production region, are inevitably affected by the energy demand brought about by the economic development of the whole country. In view of this, based on the closed STIRPAT model, the open STIRPAI model is constructed by selecting the carbon emissions of Shanxi as an indicator of environmental pressure and choosing the driving factors from both the Shanxi and national levels. The formula is expressed as follows.

$$I = a \times P_i^{b} \times A_i^{c} \times T_i^{d} \times e \tag{2}$$

Where I is the Shanxi carbon emissions; P, A and T are the driving factors, b, c and d are the indices of the driving factors; and the subscript i takes the value of 1 or 2 to indicate the driving factors affecting carbon emissions at the Shanxi level and the national level, respectively.

For the selection of drivers in the open STIRPAT model, drawing on the existing literature, the population is decomposed into population size and urbanization rate, the level of economic development is decomposed into GDP per capita and the share of the secondary industry, and the technological factors are decomposed into energy consumption of 10,000 yuan of GDP and the share of renewable energy.

(1) The demographic factor is decomposed into two items: population size and urbanization rate. Population size (P) is measured by the number of resident population; urbanization rate (U), by the proportion of urban population to resident population. Urban lifestyle is an energy-intensive one, and per capita energy consumption in cities is about 3.5-4 times higher than per capita energy consumption in rural areas, which has a significant impact on regional carbon emissions.

(2) The level of economic development is decomposed into two items: GDP per capita and the share of the secondary industry. Among them, the proportion of secondary industry (IN) indicates the proportion of value added of secondary industry in GDP. According to the "Matching-Clark theorem" of the evolution of industrial structure, with the development of economy and the increase of national income per capita, the labor force firstly transfers from the primary industry to the secondary industry, and then transfers to the tertiary industry when the economy further develops and the national income per capita further increases. In other words, according to the "matching first Clark's theorem", the evolution of the industrial structure can be used to measure economic development.

(3) The technical factor is broken down into two items: energy consumption per 10,000 yuan of GDP and the share of renewable energy. The energy consumption of 10,000 yuan of GDP is denoted by T, which is the most commonly used indicator for measuring the technical factors of regional environmental pressure. The share of renewable energy, RE, is measured by the share of renewable energy consumption in total energy consumption. An increase in the share of renewable energy reduces dependence on fossil energy and contributes to a decrease in carbon emissions.

Taken together, the logarithmically processed open STIRPAT model is shown in equation (3).

$$LnI = lna + b_i lnP_i + c_i lnA_i + d_i lnT_i + f_i lnU_i + g_i lnIN_i + h_i lnRE_i + lne \quad (3)$$

In the formula, P, A, T, U, IN and RE, respectively, are the driving factors of Shanxi's carbon emissions I. b, c, d, g and h, respectively, are the regression coefficients of the variables InP, lnA, lnT, lnU, lnIN and InRE, which reflect the elasticity relationship between the driving factors and Shanxi's carbon emissions, i.e., the elasticity coefficient.

3.3. Scenario Analysis Setting

In order to predict the peak of regional carbon emissions using scenario analysis, it is necessary to set up several scenarios for the future development of the region on the basis of comprehensive consideration of the various influencing factors or indicators of carbon emissions. Fu *et al* (2010) explored the low-carbon development of China from 2005 to 2050 in a baseline scenario, a low-carbon economic transition scenario and a low-carbon economic harmonious development scenario. Wang *et al* (2014) predicted the peak carbon emissions of Jilin Province from 2010 to 2050 in a baseline scenario, an energy-saving scenario, an energy-saving and a low-carbon scenario and a low-carbon scenario. With reference to the analysis of existing literature, this paper sets up three scenarios, namely, the baseline scenario, the energy saving scenario and the low carbon scenario, to predict the peak carbon emissions of Shanxi Province in the time span of 2021-2040.

3.3.1. Baseline scenario

The growth rates of population, economy and technology in Shanxi in the coming period are set based on the average annual growth rates of Shanxi's population size, Shanxi's GDP per capita and Shanxi's energy consumption of 10, 000 yuan GDP during the 13th Five-Year Plan period. The baseline scenario basically reflects the state of economic development and carbon emission under the guidance of emission reduction policies in the past five years. Unlike Wu *et al* (2018) who used the growth rate of the past ten years as a reference, this paper uses the growth rate of the past year as a reference. This is due to the fact that Shanxi and China's economy have undergone major changes in the past five years, such as the continuous slowdown of economic growth, the existence of a certain downward trend in the population size, and the increasing degree of aging. The growth rate of the past ten years is not a reasonable estimate of the future trend.

3.3.2. Energy saving scenarios

On the basis of the achievement of the energy saving and emission reduction targets of the 13th Five-Year Plan and the carbon emission reduction targets of the 14th Five-Year Plan, the constraints of the policy measures have been further increased, and the targets for population growth, industrial structure, energy utilization and energy-saving technologies have been set more stringently. At this time, although economic growth is still the main goal of social development, the overall energy-saving and low-carbon awareness of the society has been greatly improved, and various low-carbon technologies and strategies have been adopted to seek coordinated and sustainable development of the economy and the resources and environment. The energy-saving scenario basically reflects the economic development and carbon emission status that the economy and society can achieve through stricter energy-saving and carbon emission constraint policies on the basis of the emission reduction in the past five years.

3.3.3. Low-carbon scenarios

The low-carbon scenario calls for comprehensive low-carbon development and construction of the regional economy, emphasizing the sustainable development of resources and the environment and the comprehensive development of the economy and society. At this time, the economy and society, while ensuring basic economic growth objectives, begin to change the mode of social development and economic growth, accelerate the development and application of energy-saving and low-carbon technologies, and change the energy structure and consumption patterns. The low-carbon scenario basically reflects the state of carbon emissions that the economy and society can achieve through their own efforts and active restraints on their own behavior.

Since the Open STIRPAT model selects the influencing factors of carbon emissions in Shanxi from both the Shanxi and national levels, and the regional development scenarios are set to be baseline, energy-saving and low-carbon, so that there are nine scenario combinations in the Open STIRPAT model, as shown in Table 1.

Table 1. 9 scenario settings

Shanxi	Nationwide		
	Baseline scenario	**Energy saving scenarios**	**Low carbon scenarios**
Baseline scenario	baseline - baseline	baseline - energy saving	baseline - low carbon
Energy saving scenarios	energy saving - baseline	energy saving - energy saving	energy saving - low carbon
Low carbon scenarios	low carbon - baseline	low carbon - energy saving	low carbon - low carbon

3.4. Data sources

Relevant data from 1995-2020 were used for model fitting. The regional population, GDP, urbanization rate, proportion of secondary production, and proportion of renewable energy were obtained from the *Shanxi Statistical Yearbook (1996-2021)* and the *China Statistical Yearbook (1996-2021)*. The carbon emission data of Shanxi Province are calculated based on the consumption data and carbon emission coefficients of each energy type, and the main energy types are raw coal and washed coal, coke, gasoline, diesel, kerosene, fuel oil, blast furnace gas, coke oven gas and natural gas, and the raw data of the consumption of different energy types are from *China Energy Statistical Yearbook (1996-2021)*, and the coefficients of standard coal and carbon emission are based on *China Energy Statistical Yearbook (1996-2021)*. The data were determined from *China Energy Statistical Yearbook and IPCC (2006)*, respectively.

Table 2. Fitting results based on the open STIRPAT model (1)

	Model 1	**Model 2**	**Model 3**	**Model 4**
lna	-11.097	30.425	-4.263	-153.569
lnP1	1.423		0.609	
lnA1	0.756***		0.586***	
lnT1	0.568**		0.471*	
lnU1			0.589*	
lnIN1			-0.188	
lnRE1			-0.034	
lnP2		-2.595		13.9
lnA2		0.849***		1.036***
lnT2		0.311		0.436
lnU2				-3.554*
lnIN2				0.305
lnRE2				0.024
F-statistic	288.78	369.99	196.2	187.01
Adjusted R^2	0.9771	0.9708	0.9791	0.9772

*Note：***, ** and * indicate significance at the 1%, 5% and 10% levels respectively.*

Table 3. Fitting results based on the open STIRPAT model (2)

	Model 5	**Model 6**	**Model 7**	**Model 8**	**Model 9**
lna	-35.143	-16.407*	-63.865	-7.405	-213.746
lnP1	1.731*	1.548	1.371	-0.055	0.727
lnA1	0.289	0.633***	0.124	0.607***	0.06
lnT1	0.806***	1.088***	1.015**	0.966**	1.055**
lnU1			-0.715	-0.482	-0.318
lnIN1			0.215	-0.292	0.187
lnRE1			-0.005	-0.025	-0.016
lnP2	1.697		4.295		17.959
lnA2	0.578		1.010*		1.076
lnT2	0.228		0.331		0.112
lnU2		1.284*		1.975	-2.814
lnIN2		0.027		1.175	0.919
lnRE2		-0.044		0.138	-0.077
F-statistic	266.82	230.79	157.23	128.4	115.47
Adjusted R^2	0.9840	0.9815	0.9825	0.9787	0.9821

*Note：***, ** and * indicate significance at the 1%, 5% and 10% levels respectively.*

4. Results and analysis

4.1. Fitting of Shanxi carbon emissions based on the open STIRPAT model

In order to overcome the multicollinearity between independent variables (multiple variables with VIF values much larger than 10), partial least squares (PLS) was chosen for regression. Combining multiple regression, principal component analysis and typical correlation analysis, the partial least squares method is able to deal with regression analysis under the condition of serious covariance among multiple independent variables, and has the unique advantage of retaining all independent variables in the final model. Based on the partial least squares method, the open STIRPAT model of carbon emissions in Shanxi Province was constructed according to equation (3). (Tables 2 and 3).

Model 1 and Model 3 are the regression results when only the Shanxi influence factors are selected as the explanatory variables, and Model 2 and Model 4 are the regression results when only the national level factors are selected as the explanatory variables. It can be seen that the fit of these four models are all higher, between 0.9708-0.9791, with larger F-statistics (sig values are all less than 0.000), and the fit of Model 1 and Model 3 are better than the Model 2 and Model 4, indicating that the open STIRPAT model of carbon emissions in Shanxi should be constructed on the basis of the influential factors in Shanxi. Models 5-9 are constructed by adding the national level factors on the basis of the Shanxi influence factors. Compared with Models 1-4, the fits of Models 5-9 are somewhat improved, ranging from 0.9787 to 0.9840, with larger F-statistics (sig values are all less than 0.000), which indicate that the idea of the open STIRPAT model proposed in this paper is applicable. All these models explain the variation of carbon emissions in Shanxi well. Among them, model 5 has the highest fit of 0.9840 and F value of 266.82 (sig value of 0.000), and model 5 has fewer explanatory variables, which is convenient for scenario analysis, and can be used to make predictions about the peak of carbon emissions in Shanxi. Therefore, model 5 is chosen to predict the carbon emissions of Shanxi from 2021 to 2040.

Table 4. Parameter setting criteria for different scenarios

Scenario combination		code	P1	A1	T1	P2	A2	T2
baseline	baseline	1	lower	higher	lower	lower	higher	lower
baselin	energy saving	2	lower	higher	lower	mod	mod	mod
baseline	low carbon	3	lower	higher	lower	higher	lower	higher
energy saving	baseline	4	mod	mod	mod	lower	higher	lower
energy saving	energy saving	5	mod	mod	mod	mod	mod	mod
energy saving	low carbon	6	mod	mod	mod	higher (honorific)	lower (one's head)	higher (honorific)
low carbon	baseline	7	higher	lower	higher	lower	higher	lower (one's head)
low carbon	energy saving	8	higher	lower	higher	mod	mod	mod
low carbon	low carbon	9	higher	lower	higher	higher	lower	higher

4.2. Scenario parameterization

For the explanatory variables of model 5, i.e., population size, per capita output, and energy consumption of 10,000 yuan of GDP in Shanxi province and the whole country, three types of rates are set for the forecast time period (2021-2040), i.e., low rate, medium rate, and high rate, respectively.

4.2.1. Setting of Drivers in Mountain West

With regard to population size, the low rate of population growth in Shanxi Province in 2021-2040 is based on the actual annual growth rate of the population of Shanxi Province during the 13th Five-Year Plan period (-1.29‰). The high rate is based on the actual population growth rate of Shanxi Province in 2020-2022 (-1.37‰). The medium rate is based on the average of the low and high rates (-1.33‰).

In terms of GDP per capita, the low rate of GDP per capita in Shanxi Province for 2021-2040 is based on the real annual growth rate of GDP per capita in Shanxi Province during the 13th Five-Year Plan period (5.5%), while the high rate is based on the target set in the 14th Five-Year Plan (7.03%). The high speed rate is determined according to the target set in the "14th Five-Year Plan" of Shanxi Province (7.03%). The medium rate is based on the average of the low and high rates (6.27%).

In terms of energy consumption of 10,000 yuan GDP in Shanxi Province, the high rate of energy consumption of 10,000 yuan GDP in Shanxi Province in 2021-2040 is based on the actual annual growth rate of energy consumption of 10,000 yuan GDP in Shanxi Province during the 13th Five-Year Plan (-3.95%), and the low rate is based on the target set in the 14th Five-Year Plan (-3.08%) for 2020-2022 in Shanxi Province. The low rate is determined according to the target set in the "Fourteenth Five-Year Plan" of Shanxi Province for 2020-2022 (-3.08%). The medium rate is determined on the basis of the average of the low and high rates (-3.52%).

4.2.2. Setting of national drivers

As for the national population size. Drawing on the results of Zeping Macro's projections, the low rate of China's population growth is set at (-2.24‰) and the high rate at (-6.19‰) for the period 2020-2040. The medium rate is based on the average of the low and high rates (-4.22‰).

National GDP per capita. According to Cai's (2021) conclusions, the low rate of China's GDP per capita is set at (4.7%) and the high rate is set at (4.9%) for 2020-2040. The medium rate is determined based on the average of the low rate and the high rate (4.8%).

The national energy consumption of 10,000 yuan GDP. Drawing on the findings of Wu *et al*., (2018) the low rate of China's 10,000 yuan GDP energy consumption is set at (-2.1%) for the period 2020-2040. The high rate is set at (-2.86%) according to the target in China's 14th Five-Year Plan. The medium rate is based on the average of the low and high rates (-2.48%).

Based on the scenario combination settings in section 2.3, the rate of change of each scenario driver was determined against the parameter settings for each factor as shown in Table 4.

4.3. Analysis of peak carbon emissions in Shanxi with open STIRPAT modeling

Based on the parameterization, the carbon emissions of Shanxi Province in 2021-2040 were projected under different scenarios (Figure 2). Under different combinations of scenarios, the year and size of the peak carbon emissions in Shanxi Province are different.

Analysed by peak time, the low-carbon-low carbon scenario peaks earliest in 2027, the low-carbon-energy-efficient scenario, energy-efficient-low carbon scenario peaks in 2028, the baseline-low carbon scenario, energy-efficient-energy-efficient scenario peaks in 2029, the low-carbon-baseline scenario peaks in 2030, the baseline- energy-efficient scenario, energy-efficient-quasi scenario and the baseline-baseline scenario peak in 2031, 2032 and 2034, respectively. 2031, 2032 and 2034 respectively.

Analyzed by peak size, the low-carbon-low carbon scenario has the smallest peak at 107.27 million tons, followed by low-carbon-energy-saving (111.01 million tons), energy - saving-low carbon (111.94 million tons), energy-saving - energy-saving (116.52 million tons), baseline - low carbon (117.84 million tons), low-carbon - baseline (119.51 million tons), baseline - energy-saving (123.59 million tons), energy-saving - baseline (127.15 million tons), energy-saving - baseline (136.73 million tons), and energy-saving - baseline (136.73 million tons).

127.15 million tons), baseline-baseline (136.73 million tons).

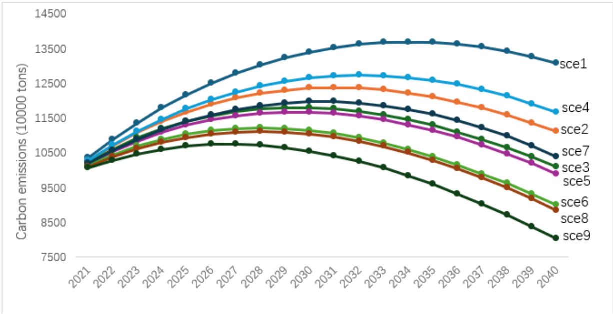


Figure 2. Trend of carbon emissions in Shanxi under different scenario settings, 2021-2040

From the above analysis, it can be seen that Shanxi will not be able to achieve carbon peaking before 2030 when the three scenarios of baseline-benchmark, baseline-energy-saving and energy-saving-benchmark occur. At present, China has reached a consensus on further energy conservation, emission reduction and low-carbon development, and the "13th Five-Year Plan" for controlling greenhouse gas emissions released at the end of 2016 proposes that "by 2020, carbon dioxide emissions per unit of gross domestic product (GDP) will be 18% lower than that in 2015 ". This is a more stringent carbon emission reduction target compared with that of the 12th Five-Year Plan, and it also proposes to promote the "low-carbon revolution in energy utilization" by "optimizing the use of fossil energy" and "accelerating the development of non-fossil energy". It also proposes to build a low-carbon industrial system by optimizing the use of fossil energy and "accelerating the development of non-fossil energy, and to build a low-carbon industrial system by accelerating industrial restructuring and controlling emissions from the industrial sector, and to strengthen low-carbon scientific and technological innovation by means of accelerating the research and development and demonstration of low-carbon technologies and "increasing the popularization and application of low-carbon technologies. In other words, at the national level, it will strengthen low-carbon scientific and technological innovation. That is to say, the national level (including Shanxi) in the energy use, industrial structure and energy-saving technology and other aspects of carbon emission control will continue to tend to be strict, basically coincides with the paper on the regional social development of energy saving scenarios set, in view of this, this paper believes that Shanxi 2030 before the peak of carbon emissions can be realized.

Meanwhile, the size of the peak carbon emissions in Shanxi is mainly affected by the scenarios at the national level, and less by the selection of scenarios in Shanxi province. Taking 2030 as an example. When the baseline, energy-saving and low-carbon scenarios are selected at the national level, and Shanxi selects the baseline scenario, the carbon emissions will be 133.83, 123.41 and 117.83 million tons, and the carbon emissions will decrease by 7.8% and 12% respectively. When Shanxi selects the energy-saving scenario, the carbon emissions will be 126.32, 116.49 and 111.22 million tons, and the carbon emissions will decrease by 7.8% and 12% respectively. When Shanxi selects the low-carbon scenario, the carbon emissions will be 1195.49 and 1112.02 million tons, and the carbon emissions will decrease by 7.8% and 12%. When Shanxi chooses the low-carbon scenario, the carbon emissions will be 11951, 11028 and 105.29 million tons, and the carbon emissions will decrease by 7.7% and 11.9% respectively.

And when Shanxi chooses the baseline, energy-saving and low-carbon scenarios, when the baseline scenario is chosen at the national level, the carbon emissions are 13,383, 12,632 and 11,951 tons, and the carbon emissions will decrease by 5.6% and 10.7%, respectively. When the energy-saving scenario is chosen at the national level, the carbon emissions are 12,341, 116,490 and 110,280 tons, and the carbon emissions will decrease by 5.6% and 10.6%. When the low-carbon scenario is selected at the national level, the carbon emissions are 117.83, 111.22 and 105.29 million tons, and the carbon emissions will decrease by 5.6% and 10.6% respectively. The comparison shows that the influence of the change of the national scenario on the size of the peak of carbon emission in Shanxi is much more than that of the scenario setting in Shanxi province.

4.4. Controllability analysis of peak carbon emissions in Shanxi

In each combination of scenarios, the rate constraints on one of the influencing factors are strengthened sequentially (from high rate to medium rate to low rate or vice versa), and the impacts of the factors on the peak of Shanxi's carbon emissions are quantitatively analyzed to study the controllability of Shanxi's own peak of carbon emissions. Since only the Shanxi factor can be influenced, the analysis focuses on P1, A1 and T1.

The unit of carbon emissions in Table 5 is 10000 tons. Table 5 shows the projections of the peak carbon emissions in Shanxi when the constraints of P, A and T are strengthened in turn, and the following conclusions can be drawn. (1) No matter what scenarios are chosen by the whole country, the strengthening of the constraints on the size of the population in Shanxi will not affect the year of the peak of carbon emissions in Shanxi. (2) No matter what scenario is chosen for the whole country, Shanxi's choice of strengthening the constraint of GDP per capita or the constraint of 10,000 yuan of energy consumption can advance the time of reaching the peak. Therefore, in order to further advance the peak time, the best strategy for Shanxi is to strengthen the GDP per capita constraint and the 10,000 Yuan energy consumption constraint.The effect of strengthening the rate constraints of P, A and T on the magnitude of peak carbon emissions in Shanxi is also closely related to the choice of scenarios at the national level. Take the Shanxi baseline scenario, the national-level baseline, energy-saving and low-carbon scenarios as an example. Strengthening the rate constraint of P leads to the reduction of carbon emissions in Shanxi by 26.3 million tons, 186.1 million tons and 144.8 million tons in the peak year, respectively.

Strengthening the rate constraint of A leads to the reduction of carbon emissions in Shanxi by 9.6203 million tons, 7.838.1 million tons and 6.929.4 million tons in the peak year, respectively. Strengthening the rate constraint of T leads to the reduction of carbon emissions in Shanxi by 8.7641 million tons, 5.7243 million tons and 4.4873 million tons, respectively.

Table 5. Carbon emissions and time to peak in Shanxi under the reinforced constraint scenario

Variant	Shanxi	Nationwide	Strong constraint	Peak time	Medium constraint	Peak time	Weak constraint	Peak time
P1	baseline	baseline	13646.2	2034	13659.4	2034	13672.5	2034
	baseline	energy saving	12340.5	2031	12349.8	2031	12359.2	2031
	baseline	low carbon	11769.8	2029	11777.0	2029	11784.2	2029
	Energy saving	baseline	12704.3	2032	12714.7	2032		
	Energy saving	energy saving	11645.0	2029	11652.2	2029		
	Energy conservation	low carbon	11188.0	2028	11194.1	2028		
A1	baseline	baseline	12710.5	2033	13178.6	2034	13672.5	2034
	baseline	energy saving	11575.4	2030	11951.2	2031	12359.2	2031
	Standard of reference	low carbon	11091.3	2028	11427.2	2029	11784.2	2029
	Energy saving	baseline	12282.0	2032	12714.7	2032		
	Energy saving	energy saving	11305.4	2029	11652.2	2029		
	Energy saving	low carbon	10883.2	2027	11194.1	2028		
T1	baseline	baseline	12796.1	2031	13175.8	2033	13672.5	2034
	baseline	energy saving	11786.7	2029	12039.1	2030	12359.2	2031
	baseline	low carbon	11335.5	2028	11532.2	2029	11784.2	2029
	Energy saving	baseline	12364.5	2031	12714.7	2032		
	Energy saving	energy saving	11422.6	2029	11652.2	2029		
	Energy saving	low carbon	11013.6	2027	11194.1	2028		

The influence of the rate constraints of strong P, A and T on the time and size of the peak carbon emissions in Shanxi is affected by the scenario setting at the national level and the emission reduction strategy of Shanxi, indicating that the stricter the national scenario setting is, the earlier the time of the carbon peak in Shanxi will be. The relative importance analysis of variables is applied to model (5), and it is found that the relative importance of P2, A2, T2, P1, A1 and T1 are 16.51%, 18.68%, 15.47%, 14.87%, 18.31% and 16.16%, respectively. The total relative importance of the national variables is 50.66% and the total relative importance of the Shanxi variables is 49.34%. This further serves to demonstrate the necessity of using an open model, i.e., the timing of carbon peaking in Shanxi is affected by the national carbon emission reduction plan. When formulating the peak carbon policy, Shanxi province must jump out of the closed perspective of relying only on its own efforts to achieve energy saving and emission reduction goals, and formulate a flexible peak carbon policy from an open perspective, taking the energy saving and low carbon development of the national economy as an important constraint for the regional peak carbon policy. On the other hand, as far as emission reduction strategies are concerned, the strategy that Shanxi should focus on adopting should be to strengthen the per capita GDP constraint and the 10,000 yuan energy consumption constraint, rather than controlling population growth.

4.5. Forecast of peak carbon emissions in Shanxi under the closed STIRPAT model

Since the previous literature mainly analyzes from the closed perspective, in order to better understand the impact of the open perspective on the regional carbon emission peak, this paper gives the prediction of the peak carbon emission of Shanxi in the STIRPAT model from the closed perspective and analyzes it comparatively.

For equation (3), take i as 1 for regression analysis, which is the closed STIRPAT model. Table 2 and Model 1 show the regression results of the closed STIRPAT model. Figure 3 reports the carbon emissions of Shanxi Province in different scenarios from 2021 to 2040. It can be seen that (1) under the baseline scenario and the energy saving scenario, Shanxi Province is unable to achieve carbon peaking in 2040. Under the Low Carbon Scenario, Shanxi Province achieves carbon peaking in 2039. Either scenario is later than the peak time in the open model. (2) The maximum carbon emissions in Shanxi Province under the baseline, energy-saving and low carbon scenarios in the closed model are 181.66 million tons, 156.81 million tons and 135.45 million tons, respectively. Under the baseline, energy-saving and low-carbon scenarios in the open model, the highest carbon emissions in Shanxi Province are 126.05 million tons, 118.54 million tons and 112.60 million tons, respectively. It can be seen that the predicted carbon emissions of Shanxi Province under the closed model are higher, 20%-44% higher under different scenarios.

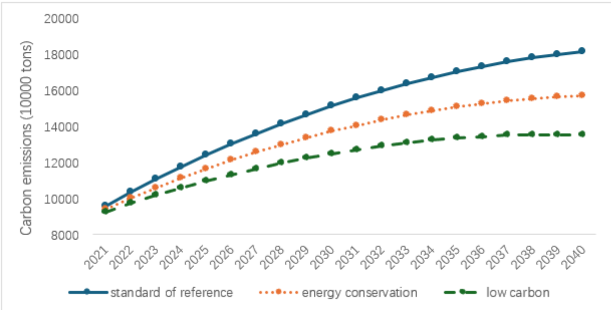


Figure 3. Projections of Shanxi carbon emissions in the closed model, 2021-2040

5. Conclusions and recommendations

5.1. Conclusion

This paper incorporates the economic interdependence between different regions within a country into the model, selects drivers from both the Shanxi Province (a large energy-producing region in China) and the national level, constructs an open STIRPAT model, and predicts the peak carbon emissions of Shanxi Province in 2021-2040 by combining with the scenario analysis method. Based on this, it analyzes the influencing factors of the peak of the carbon emissions in Shanxi Province and the strategies of carbon reduction. The conclusions are as follows.

(1) In the Open STIRPAT model, the year and amount of peak carbon emissions in Shanxi Province are mainly determined by the national scenarios; if the baseline scenario is chosen for the whole country, Shanxi will not be able to realize carbon peak in 2030, no matter which scenario it chooses. Shanxi will peak in 2027 under a combination of low carbon - low carbon scenarios, and in 2028 under a combination of low carbon - energy saving and energy saving - low carbon scenarios. Since China has reached a consensus on further energy saving, emission reduction and low-carbon development. Carbon emission control at all levels across the country will continue to be tightened. This paper concludes that peak carbon is achievable in Shanxi by 2030.

(2) The peak value of carbon emissions in Shanxi is mainly influenced by the national scenario setting and the emission reduction strategy of Shanxi. The analysis of the relative importance of variables shows that the national level variables (including population size, GDP per capita and energy consumption of 10,000 yuan GDP) explain 50.66% of the changes in the carbon emission value of Shanxi, and the Shanxi level variables explain 49.34%. Shanxi can only tighten the constraints on GDP per capita and energy consumption of 10,000 yuan GDP if it wants to advance the time of carbon peak and reduce the emissions at the same time. The emission reduction strategy of controlling population size will not work.

(3) Compared with the open STIRPAT model, the closed STIRPAT model delays the peak year and overestimates the carbon emissions of Shanxi Province, which are 20%-44% higher under different scenarios. When the closed STIRPAT model is used to predict the peak carbon emissions of Shanxi, Shanxi can only reach the peak in the predicted time period in the low carbon scenario.

5.2. Recommendations

In formulating a regional carbon emissions peaking policy and control program, Shanxi Province must step out of the previous closed perspective of relying solely on its own efforts to achieve energy conservation and emission reduction goals. From an open perspective, Shanxi Province must pay special attention to the energy-saving and low-carbon development of the national economy as an important constraint on the regional economic peak carbon policy, and formulate a flexible peak carbon emission program.

(1) We should strengthen our own energy conservation and emission reduction capacity and make efforts to reach the peak of carbon emissions as early as possible. We should recognize that the peak of regional carbon emissions is largely affected by the selection of scenarios at the national level determined by indicators such as the national population size, the national per capita GDP, and the national full GDP energy consumption, and prevent the formulation of harsh and inflexible target requirements for the region's economic indicators in order to fulfill the task of the peak of carbon emissions and avoid the possible adverse impact of carbon emission control programs on the regional economic development. (c) To prevent the setting of harsh and rigid target requirements for the region's economic indicators in order to accomplish the peak carbon emissions mandate and to avoid the possible negative impacts of carbon emission control scenarios on regional economic development.

(2) Shanxi must also recognize that the traditional closed perspective analysis will underestimate the impact of the various influencing factors on the regional carbon emission peaks, and the formulation of carbon emission control programs based on this will also lead to the reinforcement of the constraints imposed by the local government on the influencing factors, which is not conducive to the development of the regional economy.

(3) For the central government, when breaking down and formulating regional carbon emission peak tasks and related targets, it should not only take into account the differences in the development stages of the eastern, central and western regions of China, but also consider the impact of factors such as the interdependence of

regional and urban economies on the peak of regional carbon emissions, so as to formulate a reasonable program for regional carbon emission peaks.

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