



# Forecasting the carbon emissions in Hubei Province under the background of carbon neutrality: a novel STIRPAT extended model with ridge regression and scenario analysis

Congjun Rao<sup>1</sup> · Qifan Huang<sup>1</sup> · Lin Chen<sup>2</sup> · Mark Goh<sup>3</sup> · Zhuo Hu<sup>4</sup>

Received: 24 October 2022 / Accepted: 17 March 2023 / Published online: 25 March 2023  
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2023

## Abstract

The impact of global greenhouse gas emissions is increasingly serious, and the development of green low-carbon circular economy has become an inevitable trend for the development of all countries in the world. To achieve emission peak and carbon neutrality is the primary goal of energy conservation and emission reduction. As the core province in central China, Hubei Province is under prominent pressure of carbon emission reduction. In this paper, the future development trend of carbon emissions is analyzed, and the emission peak value and carbon peak time in Hubei Province is predicted. Firstly, the generalized Divisia index method (GDIM) model is proposed to determine the main influencing factors of carbon emissions in Hubei Province. Secondly, based on the main influencing factors identified, a novel STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) extended model with ridge regression is established to predict carbon emissions. Thirdly, the scenario analysis method is used to set the variables of the STIRPAT extended model and to predict the emission peak value and carbon peak time in Hubei Province. The results show that Hubei Province's carbon emissions peaked first in 2025, with a peak value of 361.81 million tons. Finally, according to the prediction results, the corresponding suggestions on carbon emission reduction are provided in three aspects of industrial structure, energy structure, and urbanization, so as to help government establish a green, low-carbon, and circular development economic system and achieve the industry's cleaner production and sustainable development of society.

**Keywords** Emission peak · Energy conservation and emission reduction · GDIM · STIRPAT extended model · Ridge regression · Scenario analysis method

## Introduction

Climate change has become one of the greatest concerns confronting humanity in the twenty-first century as the problem of global warming grows. The massive emission

of greenhouse gases, led by carbon dioxide, has caused serious damage on the environment, and posed a grave threat to the sustainable development of global community (Ren and Long 2021; Gao et al. 2022). Energy and environmental problems have become the key factors restricting economic and social development. The global community has reached an agreement on the need to take decisive action in response to climate change and make significant strides toward the development of low-carbon economy (Liu et al. 2022a; Ding et al. 2023). China, the world's top carbon emitter, has committed to aggressively reducing its carbon output, promoting a high-quality, environmentally friendly, economic and social growth, reaching its carbon dioxide emission peak before 2030, and achieving carbon neutrality by 2060 (Xi 2021).

At the end of 2017, the Central Economic Work Conference emphasized that the development of the Yangtze River Economic Belt, including Hubei Province, should take ecological priority and green development as the

---

Responsible Editor: V.V.S.S. Sarma

✉ Zhuo Hu  
hzwhut@foxmail.com

<sup>1</sup> School of Science, Wuhan University of Technology, Wuhan 430070, People's Republic of China

<sup>2</sup> School of Management, Wuhan Institute of Technology, Wuhan 430205, People's Republic of China

<sup>3</sup> NUS Business School & The Logistics Institute-Asia Pacific, National University of Singapore, Singapore 119623, Singapore

<sup>4</sup> School of Automation, Wuhan University of Technology, Wuhan 430070, People's Republic of China

program. In July 2021, the National Development and Reform Commission issued the “14th Five-year Plan” for Circular Economy Development (National Development and Reform Commission 2022). Developing circular economy has become a crucial strategy for China’s economic and social development, playing a significant role in both the economy and society.

As a crucial region in central China, Hubei Province has set carbon emissions reduction and industrial structure optimization as its top growth priorities in order to advance both the sustainability of society and the industry’s clean output. Within the background of the overall trend of energy-saving and emission reduction, how to actively develop circular economy and materialize carbon peak and carbon neutrality as quickly as feasible in accordance with the requirements of environmental protection and low-carbon circular economy development system has evolved into a focal point for advancing Hubei Province’s high-quality development. Under the new normal, the adjustment of social and economic structure in Hubei province is accelerating, and the growth rate of energy consumption is gradually slowing down. However, with the expansion of industrialization, rising level of urbanization and constant changes in the energy consumption structure, energy demand continues to grow, and the strain on resources and the environment intensifies, the challenge of lowering emissions and cutting down on energy use is still a huge one. Under this background, the study on peak and neutralization of carbon emission in Hubei Province not only serves as a demonstration for the goal of carbon neutrality in developed provinces, but also provides decision support for exploring sustainable development paths and formulating reduction measures of carbon emissions.

Taking the data of statistical yearbook of Hubei Province in 2000–2020 as sample data, this paper focuses on the system research of carbon emissions forecasting in Hubei Province. Our aim is to forecast the peak value and peak time of carbon emissions in Hubei Province. Based on our findings and in conjunction with the growth trend of carbon emissions, this paper provides appropriate countermeasures and recommendations on how to better realize the objective of carbon neutrality, in order to give theoretical support for further boosting eco-friendly, low-carbon, and high-quality sustainable development in Hubei Province.

The main contributions of this study are summed up below.

- (1) A decomposition model of carbon emission factors in Hubei Province based on GDIM decomposition method was proposed. The model decomposed the driving factors into three aspects: economic development scale, population scale, energy consumption and each relative quantity factor, and calculated the contribution degree of each influencing factor from 2000 to 2020. The results show that low-carbon energy-saving technology development as well as the modernization and upgrading of industrial structure are essential for the purpose of curbing carbon emissions.
- (2) Based on the actual economic and social development of Hubei Province, the traditional STIRPAT model was expanded, and its variables were expanded into six types, namely, total population, per capita gross domestic product (GDP), energy intensity, urbanization rate, industrial structure, and energy structure. For this extended model, in order to avoid the interference of multicollinearity and preserve the information of carbon emissions and influencing factors to a greater extent, this paper used ridge regression to re-regression the STIRPAT extended model, and proposed a new STIRPAT extended model with ridge regression to overcome the multicollinearity problem.
- (3) The scenario analysis method was used to set the variables of the STIRPAT extended model with ridge regression, and the future carbon emissions of Hubei Province were predicted by constructing different scenarios and development paths. The carbon peak times and peak values under various scenario models were analyzed, so as to provide the emission reduction path and suggestions suitable for Hubei Province’s development. Results indicate that under the condition that the economic scale, population and urbanization keep developing at a high speed, accelerating industrial transformation and upgrading, as well as continually optimizing the energy structure, can effectively mitigate the effects of population expansion and urbanization on carbon emissions, allowing us to meet the target of reaching a carbon peak before 2030 and achieving a win-win scenario in terms of economic development and environmental conservation.

The remaining sections of this work are structured as follows. “Literature review” provides the literature review. “Analysis of carbon emission status in Hubei Province” analyzes the current situation of carbon emissions in Hubei Province. The main influencing factors of carbon emissions in Hubei Province are determined using a GDIM decomposition model in “Main influencing factors analysis of carbon emission in Hubei Province.” In “Carbon emission forecasting via STIRPAT extended model with ridge regression,” a carbon emission prediction model via a STIRPAT extended model with ridge regression is established based on the identified influencing factors. In “Forecast of emission peak value and carbon peak time in Hubei Province,” the scenario analysis method is applied to set the variables of the STIRPAT extended model with ridge regression, so as to predict the emission peak value and carbon peak time in Hubei Province. “Conclusions and policy implications” summarizes this paper and presents some policy interpretation.

## Literature review

Many academic research on carbon emissions have been done in recent years, in line with the broader movement toward low-carbon economy and sustainable development (Cansino et al. 2016; Zhu et al. 2022a), and developed many quantitative analysis methods for carbon emissions (Zhu et al. 2022b; Zhou et al. 2022; Rao et al. 2022a). At present, studies on carbon emission research focus on two aspects, i.e., driving factors decomposition of carbon emission and carbon emission forecasting.

In terms of driving factors decomposition of carbon emission, the existing decomposition methods include impact (I) affected by population (P), affluence level (A), and technology (T) (IPAT) (Yue et al. 2013); index decomposition analysis (IDA) (Wang et al. 2022; Yin and Mao 2023); logarithmic mean Divisia index (LMDI) (Gao and Zhu 2020; Rao et al. 2022b); GDIM (Liu et al. 2022b; Wen et al. 2023); and STIRPAT (Huang et al. 2021). Based on these methods, an extended LMDI model with scale effect of scientific research was established, and the results showed that improving scientific research efficiency and optimizing industrial structure can effectively reduce carbon emissions (Gao et al. 2020). Similarly, the LMDI method via an extended IPAT model was proposed by Ge et al. (2020) to made an analysis for carbon decomposition and forecast the carbon emissions by setting three different scenarios, and the results showed that economic progress is the main cause of increased carbon emissions, with population growth and energy consumption pattern following closely behind, and industrial structure and technological progress significantly contribute to the benefits reduction. The IDA method was first used to investigate what causes carbon emissions from household energy use in Guangdong Province (Xie et al. 2020). Subsequently, a hybrid method combining IDA with production-theoretical decomposition analysis (PDA) is presented to investigate the elements that contribute to China's carbon emissions from three levels of industrial, regional, and national and forecast; the development trend of carbon emissions by setting medium scenario and high scenario; and the conclusion was drawn that as time goes on, technical development and the optimization of industrial structures would play a larger role in lowering carbon emission intensities (Chen et al. 2022). Similarly, a generalized GDIM method was proposed for decomposing the driving factors of carbon emissions of industrial sectors in Shaanxi Province and computed the contribution rate of carbon emissions, and it found that rising carbon emissions are substantially connected to rising GDP and energy consumption (Qian et al. 2020). Although these methods provide some good quantitative tools to determine the influencing factors of carbon emissions, the factors identified are not very comprehensive, and most of them do

not consider regional differences and regional characteristics when determining the main influencing factors of carbon dioxide emissions. In this sense, this paper takes Hubei Province as the object under the background of achieving the “double carbon” goal, and decompositions the influencing factors of carbon emissions in Hubei Province via the GDIM method, so as to investigate the contribution of multiple influencing factors to carbon emissions.

In terms of carbon emission forecasting, the STIRPAT model and scenario analysis are the popular methods which are the most widely used for forecasting carbon emissions. At the beginning, population size, affluence level, and technological factors are regarded as the key factors causing environmental bearing pressure, and then a IPAT model (Ehrlich and Holdren 1971; Ehrlich and Holden 1972) is proposed, which was later improved into the STIRPAT model (Dietz and Rosa 1994). Subsequently, the STIRPAT model was expanded by introducing climate variables, urbanization rate, and trade openness to forecast the carbon emissions in regional sectors of China (Yang et al. 2018). Similarly, the STIRPAT model is extended by introducing urbanization rate and conducted a special study on the impact of urbanization level on carbon dioxide emissions, and the results showed that urbanization rate is significantly positively correlated with carbon emissions (Hu 2018). Subsequently, the total substitute energy, total fossil energy, urban total population, per capita GDP, and merchandise trade GDP were introduced to extend the STIRPAT model, and the results showed that per capita GDP, total fossil energy, total urban population, and total energy have the greatest impact on carbon emissions (Zhang et al. 2019). Also, the influence of economic urbanization and technology on carbon emissions were considered to expanded STIRPAT model, and the empirical analysis of this model showed that GDP per capita and population size have positive impact on carbon emissions, and population urbanization, economic urbanization, and energy intensity have inhibitory effects on carbon emission (Liu et al. 2021). On this basis, the STIRPAT model is applied to determine the drivers of carbon emissions in Xinjiang, and the application results showed that urbanization and per capita GDP have considerable beneficial impacts on carbon emissions (Chai et al. 2022). Moreover, the drivers of building carbon emissions were explored according to the demand and supply and introduced six identified factors to establish different STIRPAT models, and the empirical analysis showed that the indirect emission intensity and building construction among six identified factors have the greatest impact on carbon emissions (Zhu et al. 2022c). In recent years, scenario analysis combined with STIRPAT model is the most common. For example, the industrial structure factors were introduced to extend the STIRPAT model, and the scenario analysis method was integrated to predict the peak value of energy carbon emissions in Shanxi Province. The

results showed that population factors had the most significant driving effect on carbon emissions (Guan et al. 2021). In addition, the LMDI and STIRPAT models were mixed to conduct the empirical investigation on the variables impacting China's carbon emissions using, and the results showed that the level of economic development was the main driver of carbon emissions (Shan 2021).

Based on the above existing research on carbon emission forecasting, some problems need to be further studied. For example, the STIRPAT model used in most literature has few independent variables, which only include three influencing aspects: population scale, affluence degree, and technological level. Considering the complexity of carbon emission forecasting, the STIRPAT model must be expanded in accordance with the real circumstances influencing regional development if its accuracy and universality are to be improved. In addition, due to the large number of influencing factors selected in the STIRPAT extended model, there may be correlation between different factors, which easily leads to the problem of multicollinearity, thus affecting the accuracy of the model, and leading to distortion of the model coefficients and errors in the prediction of carbon emissions. However, many existing literatures do not consider the possible multicollinearity problem in the STIRPAT extended model. Against the background of overcoming the multicollinearity problem, this paper proposes a new STIRPAT extended model with ridge regression, i.e., use ridge regression to re-regression the STIRPAT extended model.

## Analysis of carbon emission status in Hubei Province

Until date, there have been two main categories about carbon emission quantification forms: calculation-based and measurement-based. Specifically, from the perspective of the existing accounting methods of greenhouse gas emissions, they can be mainly summarized into emission factor method, mass balance method, and measurement method (Sun and Huang, 2022). Unable to obtain carbon emissions data directly, so this paper adopts the emission factor method to measure the carbon emissions in Hubei Province. The emission factor method is proposed by the "IPCC (Intergovernmental Panel on Climate Change) national greenhouse gas listing guidance" (IPCC 2019), and its calculation formula is as follows.

$$C = \sum_i E_i \delta_i, \quad (1)$$

where  $C$  is the measured carbon dioxide emission, and its unit is ten thousand tons;  $i$  represents the type of energy

**Table 1** The carbon dioxide emission coefficient of each type of energy

Types of energy	Emission coefficient of CO <sub>2</sub>	Types of energy	Emission coefficient of CO <sub>2</sub>
Raw coal	1.9745	Natural gas	2.1622
Cleaned coal	2.4044	Crude oil	3.0202
Washed coal	1.3727	Gasoline	2.9251
Briquette coal	1.9360	Kerosene	3.0334
Coke	2.8604	Diesel oil	3.0959
Coke oven gas	0.8593	Fuel oil	3.1705
Blast furnace gas	0.8427	Liquefied petroleum gas	3.1013
Other gas	0.6921	Refinery dry gas	3.0082

consumption;  $E_i$  is the consumption of energy  $i$ , and its unit is ten thousand tons or hundred million cubic meters;  $\delta_i$  is the carbon dioxide emission factor of energy  $i$ , which can be decomposed into an expression according to the emission factor, namely,

$$C = \sum_i E_i \cdot \text{NCV}_i \cdot \text{CEF}_i \cdot \text{COF}_i \cdot 44/12. \quad (2)$$

In Eq. (2), NCV is the average low calorific value, and its unit is kilojoules/kg or kilojoules/cubic meter; CEF is the carbon emission factor, that is, the carbon content per unit heat, in kg/10<sup>6</sup> kilojoules; COF is the carbon oxidation factor, representing the carbon oxidation rate during energy combustion; 44 and 12 are the molecular weights of carbon dioxide and carbon, respectively.

Based on the usage of different energy sources in Hubei Province, carbon emissions are computed and examined in this paper. Nonetheless, the statistical energy balance sheet depicts a multitude of energy sources, so it is too complicated to calculate all the energy sources, which may lead to unnecessary errors due to repeated calculation of data. Referring to Fan (2016) and Rao et al. (2023), the energy types not mainly used for combustion are removed from the energy types provided by the energy balance sheet. The main combustion energy varieties including raw coal, cleaned coal, washed coal, briquette coal, coke, coke oven gas, blast furnace gas, converter gas, other gas, crude oil, gasoline, kerosene, diesel oil, fuel oil, liquefied petroleum gas, refinery dry gas, and natural gas are selected, which are listed in Table 1. The data in the calculation process are from Hubei statistical yearbook from 2000 to 2022 (Hubei Provincial Statistics Bureau 2022). According to Eq. (2), Table 1 displays the relevant carbon emission coefficient for each type of energy.

Table 2 demonstrates the calculated carbon emissions and associated indicators based on the carbon emission calculation

method (1) and the total energy consumption statistics of Hubei Province from 2000 to 2022 (Hubei Provincial Statistics Bureau 2022). As shown in Table 2, the carbon emissions of Hubei Province increased by 234,601,800 tons in 20 years. Even though there have been a few years of reduction, Hubei's carbon emissions have generally been on the increase, increasing at a pace of 5.90% per year on average. From 2000 to 2011, the carbon emissions of Hubei Province increased rapidly. According to the analysis of the social situation, it may be because Hubei Province was located in the hub region of the Yangtze River during this period and its industrialization developed rapidly. Influenced by some policies such as expanding domestic demand and increasing investment, the output value of heavy industries such as ships increased rapidly, which increased energy consumption and led to a rapid rise in carbon emissions. After 2011, the rising trend of carbon emissions slowed down and decreased in some years. The primary explanation is that the government is responding to national objectives of energy-saving and emission reduction, increasing investment in the use of low-carbon environmental protection technologies, and progressively converting to a green and low-carbon circular economy.

The carbon emission intensity index in Table 2 refers to the carbon dioxide emissions created by the increase of each unit of gross national product (GNP), which is primarily used to assess the link between economic growth and the rise of carbon

emissions. The data in Table 2 show that since the “11th Five-Year Plan,” the carbon emission intensity of Hubei Province has been declining with a 7.22% yearly average growth rate, which means that Hubei Province's efforts to reduce emissions and save energy have achieved certain effects.

## Main influencing factors analysis of carbon emission in Hubei Province

“Analysis of carbon emission status in Hubei Province” analyzes the current situation of social development and the trend of carbon emissions in Hubei Province. It has been discovered that the carbon emissions in Hubei Province continue to rise along with the region's population, degree of urbanization, and GDP. To limit the growth benefit of carbon emissions and achieve carbon peaking and carbon neutrality as soon as feasible, it is vital to perform in-depth study on the factors that drive carbon emissions. On the basis of the GDIM decomposition model, this section examines and discusses the elements that affect Hubei Province's carbon emissions, and finally determines the primary contributors of carbon emissions in Hubei Province.

According to the state quo of social and economic growth in Hubei Province, as well as the development tendency from 2000 to 2020 described in “Analysis of carbon emission status

**Table 2** Carbon emission quantity and carbon emission intensity in Hubei Province from 2000 to 2020

Year	Quantity of carbon emissions (ten thousand tons)	Rate of increase	Carbon emission intensity (ton/ten thousand yuan)
2000	10,916.44	-	3.08
2001	10,953.32	0.34%	2.56
2002	12,278.09	12.09%	2.47
2003	13,296.50	8.29%	2.46
2004	15,859.05	19.27%	2.51
2005	21,248.56	33.98%	3.26
2006	23,590.20	11.02%	3.11
2007	23,779.12	0.80%	2.58
2008	23,917.15	0.58%	2.11
2009	25,015.73	4.59%	1.93
2010	27,790.40	11.09%	1.74
2011	30,023.24	8.03%	1.53
2012	28,474.78	-5.16%	1.28
2013	30,591.12	7.43%	1.23
2014	30,353.70	-0.78%	1.11
2015	29,429.02	-3.05%	1.00
2016	28,705.78	-2.46%	0.89
2017	28,800.47	0.33%	0.81
2018	30,273.10	5.11%	0.77
2019	32,359.53	6.89%	0.71
2020	34,376.62	6.23%	0.69

in Hubei Province,” the core of industrial structure in Hubei Province is still in the secondary industry, especially in the industrial sector. As per capita income increases and urbanization accelerates, carbon emissions also increase rapidly. It is required to do more in-depth study on the factors that affect carbon emissions in order to decrease the growing trend of these emissions and advance the construction process of energy conservation and emission reduction.

According to the basic development characteristics of Hubei Province, the possible influencing factors are determined as follows: socio-economic development level, the affluence of the people, population size, urbanization rate, industrial structure, energy intensity, energy consumption structure, and so forth. These influencing factors may promote or inhibit carbon emissions, and their influencing utility may also change over time. Now, we will combine the aforementioned factors to investigate the effects of carbon emission factors in detail.

### The GDIM model

The generalized D<sub>I</sub>visia index method (GDIM) model was proposed by Vaninsky in 2014 (Vaninsky, 2014). In this model, the target variable is decomposed into multiple factor products based on Kaya identity. Thus, this model is suitable for more complete and accurate quantitative decomposition of the impact of various factors on changes in carbon emission trend. The decomposition function of carbon emission target is constructed as follows:

$$\Delta Z = f(x) = f(x_1, x_2, \dots, x_n), \tag{3}$$

$$\Delta Z = Z_1 - Z_0 = \int dZ = \int f'_1 dx_1 + \int f'_2 dx_2 + \dots + \int f'_n dx_n, \tag{4}$$

where  $Z$  is the carbon emission function;  $x_i$  is the  $i$ th driving factor of carbon emission;  $\Delta Z$  is the variation from time 0 to time 1;  $f'_i$  is the partial derivative of the  $i$ th driving factor of the function  $Z$ . Equation (4) can be transformed into the following form:

$$\begin{cases} \Delta Z = \int \nabla Z^T dX \\ \Delta Z[X_i] = \int_L f'_i dX_i = \int_{t_0}^{t_1} f'_i X'_i dt \end{cases} \tag{5}$$

where  $\nabla Z = \langle f'_1, f'_2, \dots, f'_n \rangle$  is the gradient vector of the carbon emission function  $f = (f_1, f_2, \dots, f_n)$ , superscript  $T$  is the transpose matrix,  $dX$  is the diagonal matrix of driving factors  $dx_1, dx_2, \dots, dx_n$ , and  $\Delta Z[X_i]$  is the contribution value of driving factor  $x_i$  to carbon emissions variation  $\Delta Z$ .

Considering the correlation between driving factors, Eq. (6) is introduced to constrain the relationship between driving factors.

$$\Phi_j(x_1, x_2, \dots, x_n) = 0, j = 1, 2, \dots, k. \tag{6}$$

The vector form of Eq. (6) is expressed as follows:

$$\Phi(X) = 0, \tag{7}$$

then

$$\Delta Z[X|\Phi] = \int_L \nabla Z^T (I - \Phi_x \Phi_x^+) dx, \tag{8}$$

where the coordinate of the row vector  $\Delta Z[X|\Phi]$  is the component of the factorial decomposition of the change of carbon emission index  $Z$  in the case of interconnected driving factors.  $\Phi_x$  is the Jacobian matrix of driving factors, and  $\Phi(X)_{ij} = \partial \Phi_j / \partial \Phi_i$ . Superscript “+” denotes generalized inverse matrix;  $I$  is the identity matrix. If the columns of the matrix  $\Phi_x$  are linearly independent, then Eq. (9) is satisfied.

$$\Phi_x^+ = (\Phi_x^T \Phi_x)^{-1} \Phi_x^T. \tag{9}$$

By introducing the specific driving factors of carbon emissions in Hubei Province, Eq. (3) is transformed into the following form:

$$C = \left(\frac{C}{GDP}\right)GDP = \left(\frac{C}{E}\right)E = \left(\frac{C}{P}\right)P, \tag{10}$$

$$\frac{E}{GDP} = \left(\frac{C}{GDP}\right) / \left(\frac{C}{E}\right), \tag{11}$$

$$\frac{GDP}{P} = \left(\frac{C}{P}\right) / \left(\frac{C}{GDP}\right). \tag{12}$$

The specific meanings of the relevant driving factors in the Eqs. (10)–(12) are shown in Table 3.

Furthermore, Eqs. (10)–(12) are transformed into the following forms.

$$\begin{cases} C = GDP \times CG \\ GDP \times CG - E \times CE = 0 \\ GDP \times CG - P \times CP = 0 \\ GDP - P \times GP = 0 \\ E - EG \times GDP = 0 \end{cases} \tag{13}$$

Let the contribution function of factor  $X$  to carbon emission be  $C(X)$ , and construct the Jacobian matrix containing relevant factors according to Eq. (13) as follows.

$$\Phi_x = \begin{bmatrix} CG & GDP & CE & E & 0 & 0 & 0 & 0 \\ CG & GDP & 0 & 0 & -CP & -P & 0 & 0 \\ 1 & 0 & 0 & 0 & -GP & 0 & -P & 0 \\ -EG & 0 & 1 & 0 & 0 & 0 & 0 & -GDP \end{bmatrix}. \tag{14}$$

**Table 3** Variables in Eqs. (10)–(12) and their meanings

Variable symbol	Meanings	Unit
<i>C</i>	The amount of carbon emissions	Ten thousand tons
<i>GDP</i>	Gross domestic product	One hundred million yuan
<i>E</i>	Total energy consumption	Ten thousand tons standard coal
<i>P</i>	Population size	Ten thousand people
$CG=C/GDP$	carbon emission intensity	Tons/ten thousand yuan
$GP=GDP/P$	Per capita GDP	Ten thousand yuan/person
$EG=E/GDP$	Energy consumed per unit of GDP (energy intensity)	Tons/ten thousand yuan
$CE=C/E$	Carbon emissions per unit of energy consumed (carbon intensity of energy consumption)	kg
$CP=C/P$	Per capita carbon emissions	Tons/person

According to Eq. (8), the variation  $\Delta C$  in carbon emissions can be decomposed into the sum of contributions of all process variations, i.e.,

$$\Delta C[X|\Phi] = \int_L \nabla C^T (I-\Phi(x))\Phi^+(x)dx, \tag{15}$$

where  $\nabla C=(GDP\ CG\ 0\ 0\ 0\ 0\ 0\ 0)^T$ . According to Eq. (15), the variation  $\Delta C$  in carbon emissions can be decomposed into the sum of these eight process variations  $\Delta C_{GDP}$ ,  $\Delta C_E$ ,  $\Delta C_P$ ,  $\Delta C_{CG}$ ,  $\Delta C_{GP}$ ,  $\Delta C_{EG}$ ,  $\Delta C_{CE}$ , and  $\Delta C_{CP}$ , which represents the variations of economic development, energy consumption situation, population size, carbon emission intensity, per capita GDP level, energy intensity, carbon intensity of energy consumption, and per capita carbon emissions, respectively.

### Main influencing factors analysis using the GDIM model

Based on the “Tenth Five-Year Plan,” “Eleventh Five-Year Plan,” “Twelfth Five-Year Plan,” and “Thirteenth Five-Year Plan” formulated by China since 2000, we divide the period from 2000 to 2020 into four periods as the time span of the GDIM model, and the values of eight intermediate variations are listed in Table 4.

Substituting the values of eight intermediate variations in Table 4 into the decomposition model (15), then Matlab software is used to perform calculations, then we obtain the final values of the quantitative driving factors of carbon emission as  $x_1 = GDP$ ,  $x_3 =$  energy consumption,  $x_5 =$  population size, and  $Z = CO_2$  emissions. That is, by the GDIM model given in “The GDIM model,” the main influencing factors of carbon emissions are GDP, energy consumption, and population size.

In terms of GDP, the contribution rate of regional GDP and per capita GDP to carbon emissions in Hubei Province has been positive in the past 20 years, contributing 677.1652 million tons of carbon dioxide in total, which has obvious positive effect to carbon emissions. During the “Tenth Five-Year Plan”

and “Eleventh Five-Year Plan,” the contribution rate of GDP in Hubei Province increased greatly. Although the cumulative contribution value is still on the rise, the overall contribution rate has shown a downward trend since the “12th Five-Year Plan.” This result indicates that Hubei has accomplished great successes in green transformation and the establishment of a green and low-carbon circular economy, which reflects the remarkable achievements in carbon emission reduction and control during the “12th Five-Year Plan.”

In terms of population, the population size has a promoting effect on carbon emissions in Hubei Province. Due to the small change range of population size in Hubei Province, the positive driving effect on carbon emissions has been maintained at a low level.

In terms of energy consumption, the rise of total energy consumption plays an obvious role in promoting the carbon emission of Hubei Province, which is an important factor influencing the carbon emission of Hubei Province. During the “Tenth Five-Year Plan” and “Eleventh Five-Year Plan,” the total energy consumption contributed 7489.4 and 109.875 million tons of carbon dioxide, with the contribution value increasing by 31.8%. It shows that the exploitation and utilization of energy is the main factor for the development of Hubei Province during this period. During the “12th Five-Year Plan” and “13th Five-Year Plan,” the total energy consumption contributed 2389.5 and 35.924 million tons of carbon dioxide, respectively. Compared with the “11th Five-Year Plan” stage, the cumulative contribution showed a sharp decline, reflecting that the development of Hubei’s economy has begun to achieve results in the exploration of low-carbon economy and moved to the transition stage of economic transformation. Low-carbon technologies related to energy development and utilization have been effectively developed.

### Carbon emission forecasting via STIRPAT extended model with ridge regression

This section establishes a STIRPAT extended model with ridge regression to predict carbon emissions in Hubei Province based on the key influencing elements of carbon

**Table 4** The values of eight intermediate variations

Year	$\Delta C_{GDP}$	$\Delta C_E$	$\Delta C_P$	$\Delta C_{CG}$	$\Delta C_{GP}$	$\Delta C_{EG}$	$\Delta C_{CE}$	$\Delta C_{CP}$
2001	2907.9	1061.6	2.3	-2855.5	2907.9	-1846.3	-1009.2	52.3
2002	2353.2	2019.8	70.0	-579.3	2280.9	-333.3	-246.0	1701.6
2003	1343.8	134.2	37.9	-40.5	1305.9	-1209.6	1169.0	1265.3
2004	2636.2	2853.4	40.7	353.4	2595.5	217.2	136.2	2948.9
2005	603.8	1420.4	45.6	4785.7	558.2	816.7	3969.1	5343.9
2006	3675.0	2234.9	76.7	-1127.0	3598.3	-1440.1	313.1	2471.4
2007	5046.0	3011.7	147.4	-4841.6	4898.6	-2034.3	-2807.3	57.0
2008	5270.7	1445.4	109.3	-5121.8	5161.4	-3825.3	-1296.5	39.6
2009	3473.2	1677.7	131.0	-2314.3	3342.2	-1795.5	-518.8	1027.9
2010	5502.9	2617.7	146.9	-2728.2	5356.0	-2885.2	157.0	2627.8
2011	5909.5	2601.9	56.1	-3699.1	5965.6	-3307.6	-391.5	2266.5
2012	3721.2	1901.9	6.3	-5295.3	3715.0	-1819.4	-3475.9	-1580.3
2013	3130.9	-3424.1	24.4	-1055.5	3106.5	-6555.0	5499.5	2051.0
2014	2978.7	1156.4	40.4	-3212.5	3019.1	-1822.3	-1390.2	-193.4
2015	2280.7	153.4	113.7	-3205.4	2394.4	-2127.3	-1078.1	-811.0
2016	2830.9	854.1	92.7	-3623.1	2738.2	-1976.8	-1646.3	-884.9
2017	2954.1	-1275.5	76.7	-2850.5	3030.9	-4229.6	1379.1	180.3
2018	3276.7	961.9	59.1	-1705.5	3117.6	-2314.8	609.3	1412.0
2019	3906.3	1204.6	25.6	-2754.8	3880.7	-3701.7	947.0	2125.9
2020	2914.8	1847.3	63.1	-897.7	2851.7	-1067.5	169.8	1953.9

emissions in Hubei Province obtained in “Main influencing factors analysis of carbon emission in Hubei Province.”

**STIRPAT extended model**

In the field of carbon emission forecasting, Dietz and Rosa (1994) made improvements to the impact (I) affected by population (P), affluence level (A), and technology (T) (IPAT) model and developed STIRPAT stochastic model (Dietz and Rosa, 1994; Wang et al., 2013), which solved the problem that the driving influence of every factor on carbon emission in the IPAT model presented the same proportional change relationship. The model expression is as follows:

$$I = aP^b A^c T^d e, \tag{16}$$

where *a* is the model coefficient, *I* (impact) represents environmental pressure, *P* (population) represents population size, *A* (affluence) represents affluence degree, and *T* (technology) represents technology level. *b*, *c*, and *d* are the elasticity coefficients of population size, affluence degree, and technology level respectively, and *E* is the model error term. In order to better eliminate the possible heteroscedastic influence in the model and better measure the driving effect of each factor on carbon emissions, the model is logarithmic processed, and expression (17) is obtained.

$$\ln I = \ln \alpha + b(\ln P) + c(\ln A) + d(\ln T) + \ln e. \tag{17}$$

There are few independent variables set in STIRPAT model (17), which only include three influencing aspects: population size, affluence degree and technological level. Considering the complexity of carbon emission prediction, with the purpose of strengthening the STIRPAT model’s accuracy and universality, we expanded the model based on the development reality of Hubei Province.

As can be seen from “Main influencing factors analysis using the GDIM model,” the decomposition of the factors influencing carbon emissions according to the GDIM model proves that factors such as GDP, population size, energy intensity have an impact on carbon emissions in Hubei Province. Thus, Hubei’s total population, per capita GDP, and energy intensity serve as the STIRPAT model’s representations of the province’s population size, level of wealth, and technological advancement, respectively. In addition, combined with the analysis of the development status of Hubei Province in “Analysis of carbon emission status in Hubei Province,” several new extension factors of STIRPAT model are explored as follows.

- (1) In terms of population, with the reform of the housing policy implementation in Hubei Province, promoting the regional population transfer from rural to urban, promoting the development of the urban basic measures of construction, combined with the energy consumption and utilization improve the carbon emissions to a great extent. Thus, urbanization rate is added as a



supplement in the population scale factor, and as one of the extension factors of STIRPAT model.

- (2) In terms of economic scale, the development of industry, especially the second industry, has performed a crucial part for carbon emissions. In the industrial structure of Hubei Province, the second industry relies on the energy consumption and utilization (Zhang et al. 2023; Chu and Xiao 2023), the second industry has a carbon intensity that is much greater compared to the first and third industries. The industrial structure in Hubei Province has significant influence on carbon emissions. Therefore, the industrial composition that reflects the contribution of secondary industry is also taken as one of the extension factors of STIRPAT model.
- (3) In terms of energy consumption, coal continues to dominate Hubei Province’s energy consumption structure, while conventional fossil fuels still take the lead. The production of carbon dioxide mainly depends on the utilization and combustion of carbon-containing energy. With the development and utilization of various forms of clean energy, the emissions of carbon dioxide will be greatly reduced (Zhang et al. 2022; Chen et al. 2023). Therefore, this paper takes coal as the representative of traditional fossil energy, and the proportion of coal consumption in energy consumption (which is called energy structure) is regarded as one of the extension factors of STIRPAT model.

In summary, the STIRPAT model (17) is extended by above extension factors, i.e., urbanization rate, industrial structure, and energy structure, and its logarithmic expression is shown in the following Eq. (18):

$$\ln C = \ln a + b(\ln P) + c(\ln A) + d(\ln T) + f(\ln U) + g(\ln I) + h(\ln S) + \ln e, \tag{18}$$

where the meanings of variable symbols in Eq. (18) are shown in Table 5.

According to STIRPAT extended model (18), we will comprehensively study the driving effects of six influencing factors, i.e., total population, per capita GDP, energy intensity, urbanization rate, industrial structure and energy structure, on carbon emissions in Hubei Province. Specifically, the effects and benefits of each driving factor are investigated from the model coefficients, their mutual promotion and restriction factors are discussed, and the influence of their comprehensive benefits on carbon emissions is evaluated.

### Re-regression the STIRPAT extended model via ridge regression

For the STIRPAT extended model proposed in “STIRPAT extended model,” the least square linear regression may not solve the multicollinearity problem. In order to avoid the interference of multicollinearity and preserve the information of influencing factors to a greater extent, the ridge regression model is introduced to re-regression the STIRPAT extended model.

Ridge regression was proposed by Hoerl and Kennard (1970). A regular penalty term is added to optimize the regression coefficient of carbon emission. The carbon emission driving coefficient function of ridge regression optimization is defined as follows:

$$\begin{cases} \hat{\beta} = \arg \min \|X\beta - y\|_2^2 \\ s.t. \\ \|\beta\|_2^2 \leq c \end{cases}, \tag{19}$$

where  $X$  is an input characteristic matrix composed of each driving factor index of carbon emission,  $y$  is an output matrix of carbon emission, and  $\beta$  is the coefficient vector of the model.  $\|\beta\|_2^2 \leq c$  is the regularization term, and  $C$  is a constant greater than 0, which measures the strength of the control penalty. According to Lagrange multiplier method,

**Table 5** The meanings of variable symbols in STIRPAT extended model

Variable symbol	Meanings	Unit
$C$	The amount of carbon emissions	Ten thousand tons
$P$	Total population (total population of Hubei Province)	Ten thousand people
$A$	Per capita GDP (the ratio of gross regional product to total population)	Ten thousand yuan/person
$T$	Energy intensity (the ratio of energy consumption to gross regional product)	Tons/ten thousand yuan
$U$	Urbanization rate (the ratio of urban population to total population)	%
$I$	Industrial structure (the ratio of the output value of the secondary industry to the gross regional product)	%
$S$	Energy structure (the ratio of coal consumption to total energy consumption)	%

$\ln a$  is the model coefficient,  $\ln e$  is the model error term,  $b, c, d, f, g,$  and  $h$  are the elasticity coefficients of each variable

Eq. (19) is transformed into an unconstrained penalty function optimization problem expressed by Eq. (20).

$$\begin{aligned} \min & \|X\beta - y\|_2^2 + \lambda \|\beta\|_2^2 \\ \text{s.t.} & \\ & \begin{cases} \|\beta\|_2^2 = \sqrt{\sum_i x_i^2} \\ \lambda > 0 \end{cases} \end{aligned} \tag{20}$$

To calculate the coefficient  $\hat{\beta}$  of STIRPAT extended model, the coefficient function is defined as follows:

$$f(\beta) = \|X\beta - y\|_2^2 + \lambda \|\beta\|_2^2. \tag{21}$$

Set  $\partial f(\beta)/\partial \beta = 0$ , we have

$$X^T(X\beta - y) + \lambda\beta = (X^T X + \lambda I)\beta - X^T y = 0. \tag{22}$$

From Eq. (22), the analytical solution of the coefficients of STIRPAT model can be obtained as follows:

$$\hat{\beta} = (X^T X + \lambda I)^{-1} X^T y, \tag{23}$$

where  $\lambda$  is the ridge parameter and  $I$  is the identity matrix.

According to Eq. (23), the effect of the ridge regression estimation varies with the ridge parameter  $\lambda$ , and  $\lambda \in (0, 1]$  generally. The selection methods of ridge parameter  $\lambda$  include ridge trace method, variance inflation factor method and residual sum of squares method. According to the prediction accuracy requirement of STIRPAT extended model, the combination of ridge trace method and residual sum of squares method is selected to determine ridge parameter.

### Ridge regression results of STIRPAT extended model

Due to many influencing factors selected in the STIRPAT extended model (18) in “STIRPAT extended model,” there may be correlation between different factors, resulting in

the problem of multicollinearity, which distorts the coefficient of the model, affects the accuracy of the model, and leads to errors in the prediction of carbon emissions. Therefore, in this paper, the least square linear regression (Wang et al. 2023; Wei et al. 2023) is first conducted on STIRPAT extended model to analyze the collinearity of all influencing factors in the model. The regression outcomes are displayed in Table 6.

As shown by the regression outcomes in Table 6, the influencing factors exhibit severe multicollinearity, and certain variable values fail the test. Therefore, the model coefficients fitted by least square linear regression cannot be guaranteed to be accurate. Table 7 shows the results of the correlation test that was further performed on all influencing elements in the STIRPAT expanded model.

The correlation test findings in Table 7 indicate that the factors in STIRPAT extended model have significant correlation with each other, and the least square linear regression cannot solve the multicollinearity problem. Thus, the ridge regression model given in “Re-regression the STIRPAT extended model via ridge regression” to re-regression the STIRPAT extended model (18).

For model (18) in “STIRPAT extended model,” the iteration step of the ridge parameters of the ridge regression is set as 0.01, and the iteration interval is (0, 1]. The ridge trace map of the change trajectory combination of standard regression coefficient  $\hat{\beta}(\lambda)$  corresponding to different ridge parameter  $\lambda$  is obtained, as shown in Fig. 1.

According to the ridge trace map Fig. 1, combined with residual sum of squares method, when  $\lambda = 2.46$ , the goodness of fit is  $R^2 = 0.957$ , the standard regression coefficients of each factor variable tend to be stable, and the fitting effect is good. The analysis results of ridge regression are shown in Table 8. Among them, the explanatory variables of the regression model all passed the test, and the  $F$ -test coefficient of the model was significant. In addition, Table 8 also calculates the non-standardized treatment results of the regression coefficients.

**Table 6** Results of least square linear regression

	Unstandardized coefficient		Standardized coefficient <i>Beta</i>	<i>t</i>	<i>p</i>	<i>VIF</i>	<i>R</i> <sup>2</sup>
	<i>B</i>	Standard error					
Constant	-22.493	64.61	—	-0.348	0.733	—	0.977
ln <i>P</i>	2.669	7.587	0.094	0.352	0.730	42.507	
ln <i>A</i>	1.191	0.338	2.684	3.518	0.003***	349.225	
ln <i>T</i>	1.485	1.221	0.125	0.252	0.805	147.568	
ln <i>U</i>	0.307	0.302	2.126	4.91	0.000***	112.43	
ln <i>I</i>	-0.772	0.261	-0.146	-2.961	0.010**	1.463	
ln <i>S</i>	-0.179	0.339	-0.063	-0.528	0.606	8.582	

\*\*\*, \*\*, and \* represent the significance level of 1%, 5%, and 10% respectively

As shown by the ridge regression results in Table 8, the corresponding regression equation of STIRPAT extended model is obtained as follows.

$$\ln C = -137.523 + 16.573 \ln P + 0.124 \ln A - 0.035 \ln T + 0.268 \ln U + 0.378 \ln I + 0.131 \ln S \quad (24)$$

Equation (24) shows that in the STIRPAT extended model, from large to small, the following explanatory factors have an impact on carbon dioxide emissions: total

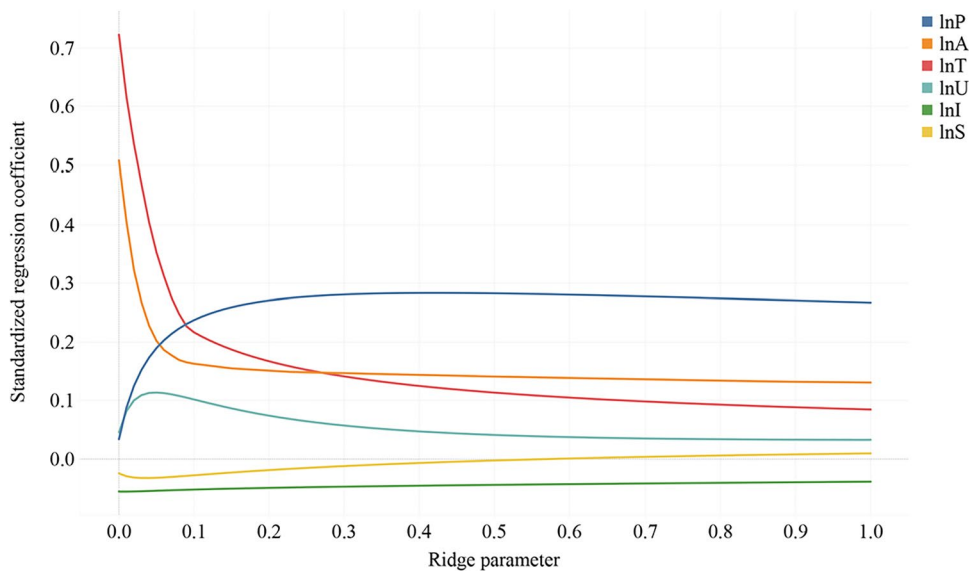
population, energy structure, industrial structure, rate of urbanization, per capita GDP, and energy intensity.

The information on the impact of STIRPAT parameters on carbon emissions may be found in Table 8's ridge regression results. The elasticity coefficient of total population in Hubei Province on carbon emissions from 2000 to 2020 is 16.573, which has the biggest influence on level of carbon emissions. Although the total population in Hubei Province only grows slowly in the past 20 years, the population not only in terms of its impact on carbon emissions, its growth

**Table 7** Correlation test of influencing factor variables

	lnP	lnA	lnT	lnU	lnI	lnS
lnP	1.000	0.928	-0.841	0.878	-0.082	-0.624
lnA	0.928	1.000	-0.978	0.989	-0.240	-0.827
lnT	-0.841	-0.978	1.000	-0.989	0.315	0.877
lnU	0.878	0.989	-0.989	1.000	-0.250	-0.842
lnI	-0.082	-0.240	0.315	-0.250	1.000	0.446
lnS	-0.624	-0.827	0.877	-0.842	0.446	1.000

**Fig. 1** Ridge trace map



**Table 8** Analysis results of ridge regression

	$\lambda = 2.46$		Standardized coefficient <i>Beta</i>	<i>t</i>	<i>p</i>	$R^2$	<i>F</i>
	Unstandardized coefficient <i>B</i>	Standard error					
Constant	-137.523	21.404	—	-6.434	0.000***		
lnP	16.573	2.489	0.276	6.798	0.000***		
lnA	0.124	0.015	0.049	8.247	0.000***		
lnT	-0.035	0.041	-0.016	-0.864	0.037**	0.965	25.081***
lnU	0.268	0.152	0.067	1.787	0.000***		
lnI	0.378	0.391	0.092	0.972	0.023**		
lnS	0.131	0.262	0.054	0.501	0.042**		

\*\*\*, \*\*, and \* represent the significance level of 1%, 5%, and 10% respectively

can make corresponding energy consumption, GRP, and urbanization rate rise, thereby indirectly lead to carbon dioxide emissions continue to rise, causing the population to have a considerable effect on carbon emissions. To balance the factors and eliminate the multicollinearity, so the model coefficient of total population is bigger. The elasticity coefficient of energy intensity is  $-0.035$ , which is the only variable in the model that has a negative impact on carbon emissions, in line with the analysis results of the GDIM extended model. Although the reduction of energy intensity means that the economic development mode of Hubei Province gradually realizes low-carbon development, it indicates that the average annual growth rate of GDP in Hubei Province is greater than the average annual growth rate of energy consumption. However, as a relative indicator, energy intensity decreases while energy consumption and GDP increase, indicating that carbon emissions will increase with the decrease of energy intensity. The model coefficients of the four explanatory variables, energy structure, industrial structure, urbanization rate, and per capita GDP, are consistent with the conclusions of the GDIM extended model, which is positive on carbon emissions.

In order to intuitively study the effectiveness of regression equation (24) of STIRPAT extended model, the fitting prediction analysis was carried out based on the data of statistical yearbook from 2000 to 2020 in Hubei Province. The fitting results are shown in Fig. 2. The error analysis of STIRPAT extended model is carried out according to the actual and predicted values, and Table 9 shows the results. The STIRPAT extension model with ridge regression is effective in solving the elastic coefficient of the model, the error is within a reasonable range, and the prediction accuracy is high. Thus, the regression equation obtained has practical significance.

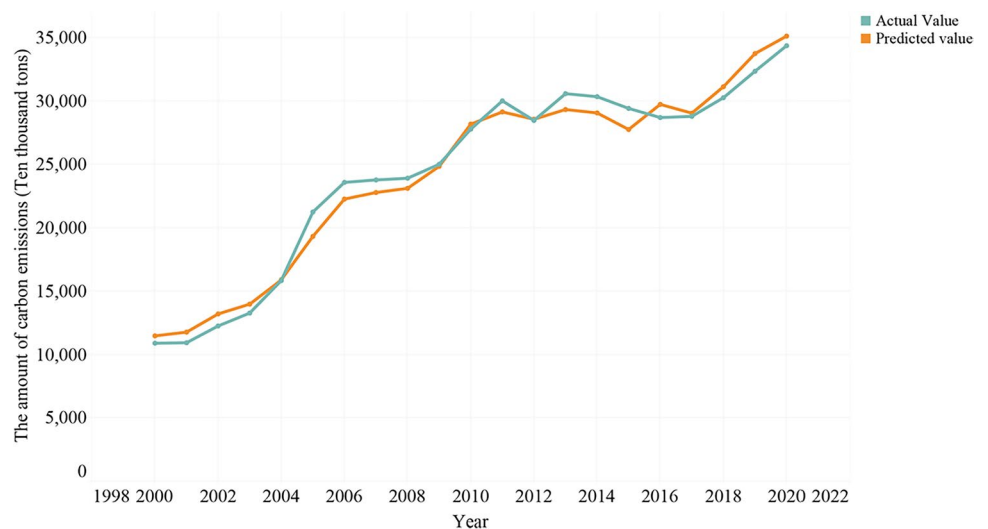
**Table 9** Regression error analysis of STIRPAT extended model

Year	Error/ten thousand tons	Error rate
2000	-580.327	5.32%
2001	-836.616	7.64%
2002	-949.391	7.73%
2003	-704.779	5.30%
2004	-42.3383	0.27%
2005	1926.595	9.07%
2006	1320.395	5.60%
2007	991.6922	4.17%
2008	799.2513	3.34%
2009	165.992	0.66%
2010	-397.846	1.43%
2011	872.2248	2.91%
2012	-96.7135	0.34%
2013	1252.098	4.09%
2014	1281.421	4.22%
2015	1663.341	5.65%
2016	-1039.43	3.62%
2017	-253.012	0.88%
2018	-867.538	2.87%
2019	-1395.61	4.31%
2020	-757.598	2.20%

### Forecast of emission peak value and carbon peak time in Hubei Province

In “Main influencing factors analysis of carbon emission in Hubei Province” and “Carbon emission forecasting via STIRPAT extended model with ridge regression,” through the decomposition of driving factors of carbon emissions, we found that the main factors affecting carbon emissions in Hubei

**Fig. 2** Fitting prediction analysis of carbon emissions in Hubei Province from 2000 to 2020



Province include population scale, economic scale, energy intensity, urbanization level, industrial structure, and energy structure. To further research on the future trend of carbon emissions in Hubei Province, in this section, the scenario analysis method (Rahman et al. 2021) is applied to set the variables of STIRPAT extended model with ridge regression established in “Carbon emission forecasting via STIRPAT extended model with ridge regression,” so as to predict and analyze carbon emissions’ peak value and peak time in Hubei Province, and discuss the path to achieve carbon neutrality.

## Scenario analysis setup of carbon emission

### The basic idea of scenario design

Under the general trend of energy conservation and emission reduction, the future development goal of Hubei Province will be to establish a green and low-carbon circular economic system. Therefore, in this paper, in combination with the trend of The Times and the relevant policies and measures issued by the state and Hubei Province, we set the growth rate of six influencing factors in STIRPAT extension model: total population (P), per capita GDP (A), energy intensity (T), urbanization rate (U), industrial structure (I), and energy structure (S). Four scenarios were set for the carbon emission prediction of Hubei Province: extensive development scenario, benchmark scenario, low-carbon development scenario, energy conservation, and carbon control scenario. Moreover, different scenario paths will be designed under different scenario environments to measure and compare the carbon emission trend, emission peak value, and carbon peak time of each development path under the same scenario.

### Scenario parameter setting

In the scenario analysis method, based on the national economic resources development policy and the regional development plan of Hubei Province, the scenario parameter setting of each influencing factor of STIRPAT extension model. In this paper, based on STIRPAT extension model, the scenario analysis method is proposed to predict the carbon emissions’ peak value and peak time in Hubei Province. According to the “Outline of the 14th Five-Year Plan and Long-term Goals of Hubei Province” (hereinafter referred to as the “Outline of the 14th Five-Year Plan”) and other relevant policies, the six influencing factors, total population (P), per capita GDP (A), energy intensity (T), urbanization rate (U), industrial structure (I), and energy structure (S), are set parameters in three scenarios, that is, low, medium, and high.

**(1) Total population (P)** According to the Population Development Plan of Hubei Province (2018–2030) issued by

Government of Hubei Province, the general trend of population development in Hubei Province during 2018–2030 is as follows: The population size tends to be stable and is expected to reach a peak of 60.9 million during 2028–2030. However, due to the impact of COVID-19, the resident population in Hubei Province dropped from 59.270 million in 2019 to 57.753 million in 2020. Although the two-child policy has been fully implemented in Hubei Province, the potential of population growth is weakened because of the decrease in the number of women of childbearing age and the aging of the population, which makes it difficult for the population to reach the expected size. Combined with the previous average annual population growth rate of Hubei Province, the population growth rate is set to be 0.60% in 2021–2025, 0.55% in 2026–2030, and  $-0.10\%$  in 2031–2040 under the medium mode, and the growth rate of different years in the low and high mode is adjusted accordingly.

**(2) Per capita GDP (A)** The Hubei Province’s per capita GDP in 2020 was 80,803 yuan, increasing by 13.8% compared with 2019, and the annual average rate of increase from 2000 to 2020 was 13.96%. In the “Outline of the 14th Five-Year Plan,” the economic aggregate of Hubei Province will cross 6 trillion yuan in 2025. Planning is expected in 2035, Hubei basically realized socialist modernization, and the per capita GDP reached the level of medium developed economies. According to The World Economic Situation and Outlook issued by United Nations and the confirmation of the rich world’s standard, take the arithmetic average, the level of moderately developed economies is around \$20,000 to \$30,000. According to this standard, the growth rate of per capita GDP is set at 6.5% in 2021–2025, 7.3% in 2026–2030, and 8.6% in 2031–2040 under the medium mode. Accordingly, the growth rate set for different years under the low and high modes is adjusted accordingly.

**(3) Energy intensity (T)** In the 14th Five-Year Plan for Energy Conservation and Emission Reduction issued by The State Council, the main targets of energy intensity are as follows: By 2025, the national energy consumption per unit of GDP will be 13.5% lower than that of 2020, and the total amount of energy consumption will be under reasonable control. 14th Five-Year Plan for ecological and environmental protection in Hubei Province has proposed that the goal of 2025 is to complete the targets and tasks issued by the state. According to the “Outline of the 14th Five-Year Plan,” the government will play an “innovation card” to achieve an average annual growth of 7% in the whole society’s R&D investment, an annual growth of more than 10% in the number of high-tech enterprises, and promote the low-carbon technologies development. Based on this standard, the energy intensity growth rate is set to be  $-5.5\%$  in 2021–2025,  $-6.2\%$  in 2026–2030, and  $-7.1\%$  in 2031–2040

under the medium mode, and the growth rate in different years under the low and high modes is adjusted accordingly.

**(4) Urbanization rate (U)** According to the “Outline of the 14th Five-Year Plan,” Hubei Province plans to promote a new pattern of people-centered urbanization and guide the development of small towns, and the permanent residents’ urbanization rate will reach 65% by 2025. According to the Population Development Plan of Hubei Province (2018–2030), the population of Hubei Province will continue to gather in urban areas during 2018–2030, and the urbanization level will steadily improve. The urban population is expected to grow to 42.6 million by 2030, with an urbanization rate of 70%. According to this standard, the growth rate of urbanization rate is set to be 1.2% in 2021–2025, 0.8% in 2026–2030, and 0.6% in 2031–2040 under the medium mode. Based on this standard, the growth rate in different years under the low and high modes is adjusted accordingly.

**(5) Industrial structure (I)** According to the “14th Five-Year Plan” of ecological and environmental protection of Hubei Province, the industrial structure is dominated by heavy industry, and the level of green and low-carbon development needs to be improved. Since the “12th Five-Year Plan” came out, the annual average rate of the secondary industry in Hubei Province is –3.14%. According to the “Outline of the 14th Five-Year Plan,” Hubei Province will implement new development concepts, promote green industrial upgrading, and optimize industrial structure. According to the development status and future goals of Hubei Province, the growth rate of industrial structure is set as –3.5% in 2021–2025, –4.0% in 2026–2030, and –4.5% in 2031–2040 in the medium mode, and the growth rate of different years in the low and high modes is adjusted accordingly.

**(6) Energy structure (S)** The 14th Five-Year Plan for energy conservation and emission reduction issued by The State Council proposes to implement clean and efficient coal utilization projects and promote green and low-carbon

transformation of the energy system. By 2025, non-fossil energy will take up about 20% of total energy consumption and coal consumption will be reduced by about 10%. The “14th Five-Year Plan” of ecological environmental protection in Hubei Province points out that the resource conditions of wind power and photovoltaic power in Hubei Province are not optimal, it is difficult to change for the coal-based energy structure in the short term, and it is also difficult to be efficiently solved for the structural problems in the short term. Combined with the emission reduction target and the current circumstances of Hubei Province, the growth rate of energy structure is set as –2.5% in 2021–2025, –3.6% in 2026–2030, and –4.8% in 2031–2040 under the medium mode, and the growth rate in different years under the low and high modes is adjusted accordingly.

To sum up, the set parameters for the six influencing factors of total population (P), per capita GDP(A), energy intensity (T), urbanization rate (U), industrial structure (I), and energy structure (S) according to the development status and future policy planning of Hubei Province are shown in Table 10.

**Scenario design of carbon emission**

Among the six influence factors in the STIRPAT extended model, the total population, per capita GDP, and urbanization rate are the factors that increase carbon emissions, the rise of these indicators will lead to the rise of carbon emissions. However, the decline of industrial structure and energy structure will promote the reduction of carbon emission in Hubei Province. Although the elasticity coefficient of energy intensity is negative and plays a role in reducing carbon emissions, the relative energy consumption increases with the decline of energy intensity, which fundamentally indicates the increase of carbon emissions. Combined with the effects of various influencing factors, this paper combined the different change parameters of six influencing factors according to the development status of Hubei Province

**Table 10** Parameter setting of influencing factors in different scenario modes

Mode	Years	The growth rate parameters of the influencing factors					
		<i>P</i>	<i>A</i>	<i>T</i>	<i>U</i>	<i>I</i>	<i>S</i>
Low	2021–2025	0.50%	5.5%	–4.6%	1.1%	–2.5%	–2.0%
	2026–2030	0.45%	6.3%	–5.4%	0.7%	–3.0%	–3.1%
	2031–2040	0.05%	7.6%	–6.3%	0.5%	–3.5%	–4.3%
Medium	2021–2025	0.60%	6.5%	–5.5%	1.2%	–3.5%	–2.5%
	2026–2030	0.55%	7.3%	–6.2%	0.8%	–4.0%	–3.6%
	2031–2040	–0.10%	8.6%	–7.1%	0.6%	–4.5%	–4.8%
High	2021–2025	0.70%	7.5%	–6.1%	1.3%	–4.0%	–3.0%
	2026–2030	0.65%	8.3%	–6.9%	0.9%	–4.5%	–4.1%
	2031–2040	–0.12%	9.6%	–7.8%	0.7%	–5.0%	–5.3%

and the planning policies formulated by the government. Specifically, four scenarios are set for the social and economic development of Hubei Province: extensive development scenario, benchmark scenario, low-carbon development scenario, and energy conservation and carbon control scenario. Moreover, different scenarios are subdivided into multiple development paths to compare the impact of different change trends of influencing factors on carbon emissions. Each scenario is explained as follows.

**(1) Extensive development scenario** This scenario is based on the assumption that in order to pursue rapid economic development, the government temporarily sacrifices environmental protection indicators, continues to maintain the development mode of “heavy” industrial structure and energy utilization and consumption, and promotes economic growth with the development of heavy industry, so as to catch up with the pace of advanced developing economies. In this scenario, Hubei Province will invest funds to expand its industrial advantages and take the secondary industry as the core of its industrial structure for a long time. With the research and development of core industrial technologies, the energy consumption structure is still centered on fossil energy, but the ratio of non-fossil energy consumption is gradually increasing. At the same time, with the two-child policy and housing policy in full operation, the total population and urbanization rate of Hubei Province may show a rapid growth trend. This scenario reflects the socio-economic development and carbon emission status of Hubei Province under the trend of relaxed environmental constraints and extensive development.

**(2) Benchmark scenario** Baseline scenario refers to the assumption that Hubei Province regards social and economic development as the priority, continue to maintain the existing social and economic development situation without a proactive response to climate change, and promotes the efficiency improvement of energy consumption and utilization only relying on the development of social economy itself. This scenario reflects the socio-economic development and carbon emission status of Hubei Province under the natural development trend.

**(3) Low-carbon development scenario** This scenario is based on the assumption that the social development situation of Hubei Province is developing in accordance with the goals set by the relevant development plans and policies of Hubei Province and the national government. According to the 14th Five-Year Plan of Hubei Province and 2035 Long-term Target Outline, the government will take effective measures to improve the rate of energy utilization, optimize industrial structure and improve energy structure, stabilize scientific research funding for low-carbon and environment-friendly technologies, carry

out a new round of scientific and technological revolution and industrial transformation, and promote scientific and technological innovation to generate new growth drivers. Under the low-carbon and environmental protection development mode, the comprehensive strength of the province has been steadily developed, and the carbon emissions have been gradually controlled. This scenario reflects the socio-economic development and carbon emission status of Hubei Province under the control of its own regional development policies.

**(4) Energy conservation and carbon control scenario** This scenario means that Hubei Province gives priority to energy conservation and carbon control and realizes green environmental protection and low-carbon development, slows down its economic development trend, and thinks more deeply about the control of energy consumption and carbon emissions. Hubei Province will increase investment in low-carbon energy-saving technology research and development funds, introduce new technologies and models of low-carbon energy control under the relevant national policies, and encourage push the application of low-carbon and environmentally friendly technologies. This scenario reflects the situation of socio-economic development and carbon emission in Hubei Province under the support of national policy and the shift of development focus.

The above specific scenario settings are shown in Table 11.

## Prediction result analysis of carbon emissions

### Scenario prediction analysis

According to the four scenarios set for Hubei Province’s carbon emissions and various carbon emission paths under different scenarios, and based on the constructed STIRPAT extended model with ridge regression in “Carbon emission forecasting via STIRPAT extended model with ridge regression,” the emission peak value and carbon peak time in Hubei Province from 2021 to 2040 are predicted. The prediction results of Hubei Province’s carbon emissions from 2021 to 2040 under each scenario are shown in Fig. 3. From the prediction results of STIRPAT extended model with ridge regression, the peak values and peak times of carbon emission in Hubei Province are different under different scenarios, and the carbon emission’s peak times in vary development paths is also different under different scenarios.

- (1) Under the extensive development scenario, the carbon emissions of paths 1, 2, and 3 will not reach the peak before 2040, and path 4 will reach the peak in 2039, reaching 496.73 million tons.

**Table 11** Specific path settings for each scenario

Scenario settings	Scenario path	<i>P</i>	<i>A</i>	<i>T</i>	<i>U</i>	<i>I</i>	<i>S</i>
Extensive development scenario	Path 1	M	H	L	M	L	L
	Path 2	M	H	L	M	L	M
	Path 3	H	M	M	H	L	M
	Path 4	H	H	M	H	L	M
Benchmark scenario	Path 5	M	M	L	M	L	L
	Path 6	M	M	L	M	L	M
	Path 7	M	M	M	M	M	L
	Path 8	M	M	M	M	M	M
Low-carbon development scenario	Path 9	M	M	H	M	M	M
	Path 10	M	H	H	M	H	M
	Path 11	H	M	M	H	M	H
	Path 12	H	H	M	H	H	H
Energy conservation and carbon control scenario	Path 13	L	L	H	L	H	H
	Path 14	M	L	H	L	H	H
	Path 15	M	L	H	M	H	H
	Path 16	H	L	H	H	H	H

*L*, *M*, and *H* represent low, medium and high modes respectively

- (2) Under the benchmark scenario, the carbon emissions of the four development paths all reach the peak, and the peak values are 45,370 tons, 46,665 tons, 43,695 tons, and 421,090,000 tons in the order of paths, and the peak times are in 2036, 2037, 2035, and 2034, respectively. Although the carbon emission of the four paths all reach the peak, it does not meet the target condition of carbon peak before 2030.
- (3) Under the low-carbon development scenario, all the four development paths will reach the peak of carbon emission, and the peak value are 39,073 tons, 38,807 tons, 38,415 tons, 382,221 tons in the order of paths, and the peak times are in 2033, 2032, 2030, and 2030, respectively. Among them, path 5 and path 6 both achieve the target of carbon peak in 2030 and before.
- (4) Under the energy conservation and carbon control scenario, all the four development paths will achieve the peak target of carbon emission before 2030. According to the order of development paths, their peak values are 36181 tons, 36716 tons, 36318 tons, and 367.8 million tons respectively, and the peak times are in 2025, 2028, 2027, and 2028, respectively. It can be found that under the scenario of energy conservation and carbon control, there is little difference in the peak carbon emission of each development path, but the peak times are different.

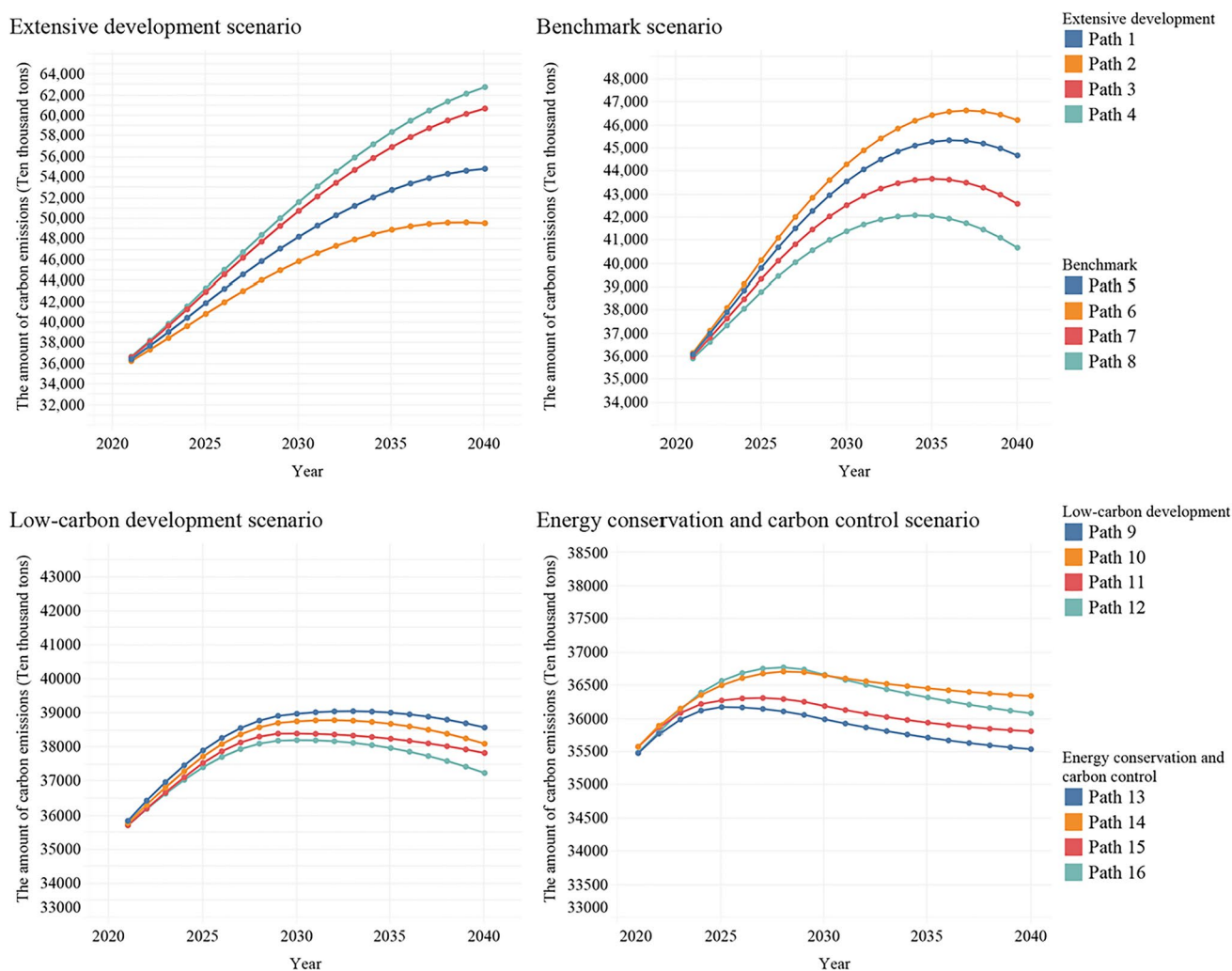
### Comparative analysis of scenarios

In “Scenario prediction analysis,” the STIRPAT extended model with ridge regression is used to predict the emission peak values and carbon peak times in Hubei Province under different situations and different development paths.

However, based on the state formulates about carbon emissions to achieve peak value more than 2030 years ago and to realize of the carbon neutral target more than 2060 years ago, how to achieve the carbon peak target in advance and reduce the target of carbon peak by considering the carrying capacity of resources and environment, and environmental protection needs of Hubei Province, is still a problem that needs to be further discussed. By comparing different scenarios, we further analyze the impact of the growth of total population and per capita GDP, the rise of urbanization rate, and the decline of energy intensity, industrial structure, and energy structure on carbon emissions in Hubei Province.

Under the extensive development scenario, the secondary industry maintained a high proportion in the industrial structure of Hubei Province, and the per capita GDP and urbanization rate increased rapidly. Due to the focus on economic development and neglect of energy consumption, the energy intensity index has a slow downward trend. Because of the swift growth of population and economy, the population gradually moves to the cities and towns, and the carbon emission shows a rising trend in the development paths 1, 3, and 4. Although the rate of increase gradually slowed down, it did not reach a peak before 2040. Although path 2 achieves the carbon peak, it reaches the peak later and has a high peak value. This shows that although the economy is developing quickly, the fund for scientific and technological innovation is gradually abundant and the energy consumption structure is improved, the “heavy” industrial structure makes it impossible to effectively decrease the energy intensity. The effects of industrial structure on carbon emission in Hubei Province are greater than that of energy structure. Carbon





**Fig. 3** Prediction results of carbon emissions in Hubei Province for different paths under different scenarios from 2021 to 2040

emission cannot be effectively controlled, which indicates that it is inadvisable to pursue economic development unilaterally while ignoring environmental protection.

Under the baseline scenario, all the four development paths achieved carbon peak, but the peak time was far after 2030, and the peak value was higher, indicating that the greenhouse gas pollution in Hubei Province was not negligible at this time. In this scenario, the population growth rate, urbanization rate, and per capita GDP are set in a medium mode, and then the changes of industrial structure, energy structure, and energy intensity are further compared. By observing the trend change of carbon emission, it is found that the optimization and improvement of industrial structure and energy structure in Hubei Province have obvious inhibitory effect on the rise of carbon emission. However, by analyzing the carbon emission situation under this scenario, the role of spontaneous regulation of carbon emission in Hubei Province according to socio-economic development is not significant.

Under the low-carbon development scenario, we can accelerate the adjustment of industrial structure and gradually improve energy utilization efficiency, so as to achieve obvious effect of promoting carbon emission reduction. Although path 11 and path 12 are ahead of path 9 and path 10 in terms of population growth and urbanization, path 11 has obvious measures in terms of energy structure. Increased research and development of energy conservation and environmental protection technologies and the use of new energy resources have reduced the percentage of coal consumption and inhibited the role of population growth in promoting carbon emissions. Based on path 11, path 12 optimizes the industrial structure, accelerates industrial transformation, and the proportion of secondary industry decreases. This scenario has achieved high-quality development, steadily increased per capita GDP, and reached the carbon peak by 2030, which has realized the simultaneous development of social economy and environmental protection, and formed a sound low-carbon development system.

Under the scenario of energy conservation and carbon control, the growth of per capita GDP remains at a low level, the proportion of coal in the energy consumption structure continues to increase and decline, and the percentage of secondary industry in the industrial structure is also steadily declining. These changes may sacrifice social and economic development to some extent. At the same time, the energy intensity is also increasing and decreasing, which indicates that Hubei Province should change the traditional energy consumption structure, reduce the combustion of fossil energy, increase capital investment to develop new clean energy, and promote the reform of industrial structure. These requirements put forward high requirements and challenges for the key energy consumption industries in Hubei Province. Under this scenario, Hubei Province takes the lead in achieving the goal of carbon emission peak from a strategic height. Development path 13 is nearly 5 years ahead of the national goal of achieving peak carbon by 2030. As a central province in central China, Hubei Province has made important contributions to the national goal of achieving carbon peak and promoting carbon neutrality.

Through the above comparative analysis, under the different development paths of each scenario, path 12 is the most consistent with the carbon emission peak path of Hubei Province. Under this path, the social and economic growth of Hubei Province is stable, energy-saving and emission reduction technology is promoted and applied, and the environment and ecology are protected accordingly, presenting a win-win situation of economic and ecological benefits.

## Conclusions and policy implications

In this paper, in order to study the carbon emission and change trend of Hubei Province under the target of emission peak and carbon neutrality, the carbon emission factors of Hubei Province were decomposed by GDIM method, and a STIRPAT extended model combined with scenario analysis method is established to forecast the emission peak value and carbon peak time in Hubei Province. The results show that industrial structure, energy structure, and urbanization level have significant effects on carbon emissions in Hubei Province, and Hubei Province's carbon emissions peaked first in 2025, with a peak value of 361.81 million tons. Compared and analyzed the carbon emission situation of different development paths in each scenario, corresponding suggestions and policy implications on carbon reduction and control according are provided for Hubei Province as follows, which provides theoretical basis and decision support for Hubei's green and low-carbon economic system to achieve peak carbon and carbon neutralization. At the same time, it also provides certain reference significance for the formulation of energy-saving and emission reduction policies in other regions of China, which help to achieve the industry's cleaner production and sustainable development of society in China.

**(1) Optimize industrial structure and promote technological innovation** The industrial structure of Hubei Province is dominated by the secondary industry, and the industrial energy consumption remains high, especially the traditional industries with high-energy consumption, which have a non-negligible impact on carbon emissions. According to the contribution rate of GDIM decomposition in Table 4, the rise of total energy consumption has an obvious promotion effect on carbon emission. The coefficient of industrial structure (lnI) in the STIRPAT extended model (24) is 0.378, indicating that the high proportion of secondary industry promotes carbon dioxide emission. And scene comparative analysis indicates that the continuous optimization of industrial structure has an obvious negative impact on the increase of carbon emission. Therefore, Hubei Province should give priority to reducing the percentage of the secondary industry, and carry out green transformation and upgrading of the secondary industry. Firstly, we can start from the traditional chemical industry and other high energy consumption industries to carry out low-carbon technology transformation and upgrading to reduce energy consumption. Secondly, the government can focus on developing efficiency and improving efficiency, change the growth mode of the secondary industry driven by industrial scale expansion and energy consumption, and vigorously develop green and environmental protection industries. Thirdly, the government can integrate modern high and new technologies, use artificial intelligence technology to expand production efficiency, eliminate unnecessary production procedures, reduce energy consumption, and promote the transformation and upgrading of traditional industries toward intelligent and green development. In addition, Hubei Province is close to mountains and rivers. Taking Wuhan City as an example, relying on the advantages of the Yangtze River basin, the government can vigorously develop the service industry based on tourism, deeply integrate the advantages of modern internet, develop the commodity economy of the primary industry, and reduce the percentage of the secondary industry's output value.

In addition, the transformation and upgrading of industrial structure, technological innovation is the breakthrough, the establishment of high and new technology development system is conducive to the reduction of carbon emissions. The government should increase the investment of scientific research funds, fully combine the advantages of many universities in Hubei Province, introduce innovative talents, do a good job in the incentive mechanism, and encourage the talents of universities to focus on research. Furthermore, the government can vigorously build major scientific and technological basic measures and high-level laboratories, and serve high-level science and technology to become self-reliant and self-reliant.

**(2) Energy structure innovation, and energy-saving and efficiency increasing** According to the results obtained by applying the GDIM model in "Main influencing factors

analysis of carbon emission in Hubei Province,” it can be seen from Table 4 that, in terms of energy, energy intensity has a detrimental impact on carbon emissions, and the reduction of the carbon intensity of energy consumption can effectively help reduce carbon emissions. In terms of economy, the reduction rate of carbon emission intensity is also maintained at a relatively high level. Therefore, Hubei Province should improve its energy efficiency. Hubei Province has many industries and a large amount of energy consumption, and its energy utilization efficiency cannot be ignored. It is imperative to accelerate the reform of energy consumption, improve the carbon emission decentralization system piloted, formulate strict energy constraint indicators, and restrain unreasonable energy consumption. In addition, Hubei Province has a wide area, which can optimize the energy transmission channel and reduce the energy loss in the transmission link. Moreover, coal is the main body of energy consumption in Hubei Province, so the government should encourage the clean and efficient utilization of coal and accelerate the construction of large-scale power projects which are clean and efficient coal.

According to the STIRPAT extended model (24), the coefficient of energy intensity is  $-0.035$ , and the coefficient of energy structure is  $0.131$ , indicating that energy intensity conforms to the GDIM analysis result and plays a promoting role in reducing carbon emissions. The carbon emission prediction result obtained in Fig. 3 combined with scenario analysis method shows that on the basis of path 7, path 8 improves the optimization rate of energy structure and can effectively inhibit carbon emissions. At the present time, the energy consumption structure of Hubei Province is still centered on traditional fossil energy represented by coal consumption, which leads to high-carbon emissions. Under this background, the government should vigorously develop clean and safe and efficient new energy technology, mining the solar energy, hydrogen power, hydropower, wind energy, biomass energy, and other new clean energy, and enlarge the coverage of gas zone. Furthermore, depending on the regional advantage that Hubei Province is located in the Yangtze River basin, the government can scale up the exploitation and utilization of comprehensive water use technologies, while accelerating the spread of green vehicles such as electric cars. For buildings with a certain height, the government can install solar energy equipment to decrease the consumption of high-carbon energy in daily life, so as to accelerate the optimization of the energy structure.

**(3) Guide population development and maintain a balance between urban and rural areas** From the decomposition outcomes and the regression coefficients of the STIRPAT extended model (24), population size plays a significant role in promoting carbon emissions. At present, population aging leads to productivity decline, and energy intensity

rose problem must be solved. With the two-child policy and three-child and the urban housing policy in full operation, Hubei’s population is likely to surge in a short period of time. Therefore, it is important to properly guide population development and migration. In order to prevent the population from rising too fast and out of control, causing excessive pressure on resources and the environment, the relevant departments of population and birth planning should formulate corresponding plans, control the ratio between the birth rate and the death rate, and avoid the imbalance of the ratio. According to regression eq. (24), the coefficient of urbanization rate is  $0.268$ , indicating that the rise of urbanization rate is also an important positive driving factor of carbon emissions. Housing policies and a rise in population is bound to bring the improvement of urbanization level, and increase the consumption of energy. Cities and towns should strengthen environmental governance and protection, increase the coverage of vegetation to alleviate greenhouse gas emission pollution caused by the rise of urban population, popularize low-carbon knowledge, and actively encourage low-carbon life. With the migration of population, rural departments can take this opportunity to formulate measures to restore green ecology and promote carbon emission reduction guided by rural areas.

Due to the complexity of the carbon emissions’ contributing factors, the problem of carbon emission forecasting still needs to be discussed and analyzed. In the future, we will further expand and optimize the STIRPAT extended model established in this paper to achieve higher accuracy of prediction.

**Acknowledgments** We would like to thank the editor and the anonymous reviewers for their helpful comments.

**Author contribution** Congjun Rao: conceptualization, methodology, data curation. Qifan Huang: methodology, software, writing—original draft. Lin Chen: visualization, investigation, validation. Mark Goh: formal analysis, supervision, writing—review and editing. Zhuo Hu: conceptualization, methodology.

**Funding** This work is supported by the National Natural Science Foundation of China (Nos. 72071150, 61703317, 72102171).

**Data availability** The datasets generated and analyzed during the current study are available in the [Hubei Provincial Statistics Bureau] repository, [<https://tjj.hubei.gov.cn/tjsj/sjksxc/tjnj/qstjnj/>].

## Declarations

**Ethical approval and consent to participate** There no ethical approval and patient consent to participate are required for this study.

**Consent for publication** The authors confirm that the final version of the manuscript has been reviewed, approved, and consented for publication by all authors.

**Competing interests** The authors declare no competing interests.

## References

- Cansino JM, Romun R, Ordonez M (2016) Main drivers of changes in CO<sub>2</sub> emissions in the Spanish economy: a structural decomposition analysis. *Energy Policy* 89:150–159
- Chai ZY, Yan YB (2022) Carbon emissions index decomposition and carbon emissions prediction in Xinjiang from the perspective of population-related factors, based on the combination of STIRPAT model and neural network. *Environ Sci Pollut Res* 29(21):31781–31796
- Chen H, Qi SZ, Tan XJ (2022) Decomposition and prediction of China's carbon emission intensity towards carbon neutrality: from perspectives of national, regional and sectoral level. *Sci Total Environ* 825:153839
- Chen L, Dong T, Nan GF, Xiao QZ, Xu M, Ming JR (2023) Impact of the introduction of marketplace channel on e-tailer's logistics service strategy. *Manag Decis Econ*. <https://doi.org/10.1002/mde.3850> (in press)
- Chu JJ, Xiao XP (2023) Benefits evaluation of the Northeast Passage based on grey relational degree of discrete Z-numbers. *Inform Sci*. <https://doi.org/10.1016/j.ins.2023.02.085> (in press)
- Dietz T, Rosa EA (1994) Rethinking the environmental impacts of population, affluence and technology. *Hum Ecol Rev* 25:13–21
- Ding Q, Xiao XP, Kong DK (2023) Estimating energy-related CO<sub>2</sub> emissions using a novel multivariable fuzzy grey model with time-delay and interaction effect characteristics. *Energy* 263:126005
- Ehrlich P, Holdren I (1971) Impact of population growth. *Science* 171:3–6
- Ehrlich PR, Holden JP (1972) One dimensional economy. *Bull At Sci* 28(5):18–27
- Fan FY (2016) Study on influencing factors and emission reduction policies of Beijing. China University of Geosciences (Beijing), Beijing
- Gao MY, Yang HL, Xiao QZ, Goh M (2022) A novel method for carbon emission forecasting based on Gompertz's law and fractional grey model: evidence from American industrial sector. *Renew Energy* 181:803–819
- Gao XW, Zhu Y (2020) Do research inputs constrain carbon emission from carbon emission factors based on LMDI model and STIRPAT model? *Resour Ind* 22(6):37–45
- Ge XX, Qi W (2020) Analysis of CO<sub>2</sub> emission drives based on energy consumption and prediction of low carbon scenarios: a case study of Hebei Province. *Pol J Environ Stud* 29(3):2185–2197
- Guan MJ, Yuan YH, Ruan MX, Wang Z (2021) Influencing factors and peak forecast of energy carbon emission in Shanxi based on STIRPAT model. *China Coal* 47(9):48–55
- Hoerl AE, Kennard RW (1970) Ridge regression: biased estimation for nonorthogonal problems. *Technometrics* 12:55–67
- Hu XY (2018) Empirical study on the impact of urbanization on carbon dioxide emissions. Beijing Institute of Technology, Beijing
- Huang JB, Li XH, Wang YJ, Lei HY (2021) The effect of energy patents on China's carbon emissions: evidence from the STIRPAT model. *Technol Forecast Soc Chang* 173:121110
- Hubei Provincial Statistics Bureau (2022) Statistical yearbook of Hubei Province: <https://tjj.hubei.gov.cn/tjsj/sjksxcx/tjnj/qstjnj/index.shtml>. Accessed 30 Nov 2022
- IPCC (2019) 2019 Refinement to the 2006 IPCC guidelines for national greenhouse gas inventories: <https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories>. Accessed 20 Feb 2023
- Liu JL, Yu QH, Chen YY, Liu JG (2022a) The impact of digital technology development on carbon emissions: a spatial effect analysis for China. *Resour Conserv Recycl* 185:106445
- Liu YP, Han YL (2021) Impacts of urbanization and technology on carbon dioxide emissions of Yangtze River Economic Belt at two Stages: Based on an extended STIRPAT model. *Sustainability* 13:276
- Liu YS, Yang M, Cheng FY, Tian JZ, Du ZQ, Song PB (2022b) Analysis of regional differences and decomposition of carbon emissions in China based on generalized Divisia index method. *Energy* 256:124666
- National Development and Reform Commission (2022) “14th Five-year Plan” for Circular Economy Development: [https://www.ndrc.gov.cn/xwdt/tzgg/2022107/t20210707\\_1285530.html?code=&state=123](https://www.ndrc.gov.cn/xwdt/tzgg/2022107/t20210707_1285530.html?code=&state=123). Accessed 27 Mar 2022
- Qian M, Gao L (2020) Industrial carbon emission factors in Shaanxi Province based on GDIM. *Resour Ind* 22(2):18–24
- Rahman SM, Kim J, Laratte B (2021) Disruption in circularity? Impact analysis of COVID-19 on ship recycling using Weibull tonnage estimation and scenario analysis method. *Resour Conserv Recycl* 164:105139
- Rao CJ, Gao MY, Wen JH, Goh M (2022a) Multi-attribute group decision making method with dual comprehensive clouds under information environment of dual uncertain Z-numbers. *Inform Sci* 602:106–127
- Rao CJ, Wang C, Hu Z, Xiao XP, Goh M (2022b) Gray uncertain linguistic multiattribute group decision making method based on GCC-HCD. *IEEE Trans Comput Soc Syst*. <https://doi.org/10.1109/TCSS.2022.3166526> (in press)
- Rao CJ, Zhang Y, Wen JH, Xiao XP, Goh M (2023) Energy demand forecasting in China: a support vector regression-compositional data second exponential smoothing model. *Energy* 263:125955
- Ren F, Long DH (2021) Carbon emission forecasting and scenario analysis in Guangdong Province based on optimized Fast Learning Network. *J Clean Prod* 317:128408
- Shan X (2021) Influencing factors of China's carbon emissions based on LMDI method and STIRPAT model. *Energy Conserv* 40(5):54–57
- Sun W, Huang CC (2022) Predictions of carbon emission intensity based on factor analysis and an improved extreme learning machine from the perspective of carbon emission efficiency. *J Clean Prod* 338:130414
- Vaninsky A (2014) Factorial decomposition of CO<sub>2</sub> emissions: a generalized Divisia index approach. *Energy Econ* 9:387–400
- Wang HP, Zhang Z (2022) Forecasting Chinese provincial carbon emissions using a novel grey prediction model considering spatial correlation. *Expert Syst Appl* 209:118261
- Wang J, Rao CJ, Goh M, Xiao XP (2023) Risk assessment of coronary heart disease based on cloud-random forest. *Artif Intell Rev* 56:203–232
- Wang P, Wu WS, Zhu BZ, Wei YM (2013) Examining the impact factors of energy-related CO<sub>2</sub> emissions using the STIRPAT model in Guangdong Province, China. *Appl Energy* 106:65–71
- Wei X, Rao CJ, Xiao XP, Chen L, Goh M (2023) Risk assessment of cardiovascular disease based on SOLSSA-CatBoost model. *Expert Syst Appl* 219:119648
- Wen JH, Hong LJ, Dai M, Xiao XP, Wu CZ (2023) A stochastic model for stop-and-go phenomenon in traffic oscillation: on the prospective of macro and micro traffic flow. *Appl Math Comput* 440:127637
- Xi JP (2021) Speech at the General Debate of the Seventy-fifth Session of the United Nations General Assembly. *People's Daily* Accessed 23 Sep 2021
- Xie ZQ, Gao XN (2020) Decomposition and prediction of direct residential carbon emission indicators in Guangdong Province of China. *Ecol Indic* 115:106344
- Yang LX, Xia H, Zhang X, Yuan S (2018) What matters for carbon emissions in regional sectors? A China study of extended STIRPAT model. *J Clean Prod* 180:595–602
- Yin C, Mao SH (2023) Fractional multivariate grey Bernoulli model combined with improved grey wolf algorithm: application in short-term power load forecasting. *Energy* 269:126844
- Yue T, Long R, Chen H, Zhao X (2013) The optimal CO<sub>2</sub> emissions reduction path in Jiangsu Province: an expanded IPAT approach. *Appl Energy* 112:1510–1517

- Zhang M, Guo H, Sun M, Liu SF, Forrest J (2022) A novel flexible grey multivariable model and its application in forecasting energy consumption in China. *Energy* 239:122441
- Zhang YL, Zhang QY, Pan BB (2019) Impact of affluence and fossil energy on China carbon emissions using STIRPAT model. *Environ Sci Pollut Res* 26(18):18814–18824
- Zhang YX, Guo H, Sun M, Liu SF, Forrest J (2023) A novel grey Lotka–Volterra model driven by the mechanism of competition and cooperation for energy consumption forecasting. *Energy* 264:126154
- Zhou Y, Chen MX, Tang ZP, Zhao Y (2022) City-level carbon emissions accounting and differentiation integrated nighttime light and city attributes. *Resour Conserv Recycl* 182:106337
- Zhu B, Xu C, Wang P, Zhang L (2022a) How does internal carbon pricing affect corporate environmental performance? *J Bus Res* 145:65–77
- Zhu B, Ye S, Wang P, Chevallier J, Wei YM (2022b) Forecasting carbon price using a multi-objective least squares support vector machine with mixture kernels. *J Forecast* 41(1):100–117
- Zhu C, Chang Y, Li XD, Shan MY (2022c) Factors influencing embodied carbon emissions of China's building sector: an analysis based on extended STIRPAT modeling. *Energ Buildings* 255:111607

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.