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Scenario Prediction of Carbon Emission Peak of Urban Residential Buildings in China's Coastal Region: A Case of Fujian Province

Yanyan Ke [1], Lu Zhou [1], Minglei Zhu [2], Yan Yang [1], Rui Fan [1] and Xianrui Ma [3,*]

[1] College of Harbour and Coastal Engineering, Jimei University, Xiamen 361021, China
[2] School of Innovation and Entrepreneurship Education, Chongqing University of Posts and Telecommunications, Chongqing 400065, China
[3] College of Economics and Management, Southwest University, Chongqing 400715, China
* Correspondence: maxianrui@swu.edu.cn

Abstract: With the acceleration of China's urbanization process, the importance of energy conservation and emission reduction in the building sector has become increasingly prominent. The effective control of carbon emissions in coastal provinces has a decisive impact on achieving the carbon emissions peak target nationwide. Based on the analysis of the influencing factors, this study establishes an urban residential buildings carbon emission prediction model by combining the IPAT model and the ridge regression model. In addition, the prediction model is combined with scenario analysis to simulate the evolution of carbon emission trends of urban residential buildings in Fujian Province from 2018 to 2050 under different scenarios. The results show that total population, urban living area, residents' consumption expenditure, urbanization rate, per capita GDP, and energy structure are key factors affecting carbon emissions from urban residential buildings in coastal cities. Only under the ultra-low carbon model scenario can Fujian's urban residential buildings achieve the carbon peak goal in 2027 (13.4748 million tons of CO_2), which requires a reduction of 59.67% compared to that under the baseline model scenario. This study can provide an effective reference for energy conservation and emission reduction work of the regional scale and even the national scale.

Keywords: urban residential buildings; STIRPAT model; scenario analysis method; influencing factors; control policy

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1. Introduction

The problem of global warming is becoming increasingly prominent. A report by the United Nations Intergovernmental Panel on Climate Change (IPCC) shows that the average global warming from 1951 to 2010 was approximately 0.7 °C, of which the contribution of greenhouse gas (GHG) emissions was above 0.5 °C. Greenhouse gases are mainly caused by human activities [1,2]. Global carbon emissions have been increasing from 2000 to 2020 and are still increasing to date [3]. Therefore, the Paris Agreement proposes that the global average temperature rise in this century should be controlled within 2 °C. The IPCC Sixth Assessment Report (AR6) proposes that it is possible to achieve this goal if net zero carbon dioxide (CO_2) emissions are achieved by 2050 [4,5]. According to the statistics of the World Energy Statistical Yearbook, in 2020, the carbon emissions of the Asia Pacific region will account for more than half of the global total emissions, of which China will contribute 30.7%, far more than other regions. Currently, more countries and regions have proposed carbon neutral targets [6]. China also promises to strive to achieve the goal of "double control" of carbon emission intensity and total amount. Therefore, it is essential to find scientific and reasonable carbon emission reduction measures to successfully achieve the 2030 carbon peak target.

The building sector plays an important role in addressing global warming [7,8]. According to the 2021 Report on the Status of the Global Construction Industry, the building sector accounts for 36% of the global end energy consumption and 37% of energy-related CO_2 in 2020 [9]. The building sector has great potential to reduce carbon emissions, which can reduce carbon dioxide emissions about by 50%. It is estimated that by 2050, China's building sector will reduce its carbon emissions by approximately 56% [10,11]. In 2016, China's building energy consumption accounted for 20.6% of the national energy consumption, and the CO_2 generated by buildings accounted for 19% of the national total energy CO_2 emissions [12]. Greenhouse gas emissions will further increase with the continuous growth of energy consumption in the building related field [13]. Therefore, achieving energy conservation and emission reduction in the building sector is key to achieving the "Dural carbon" goal. Due to the continuous growth of the number of residential buildings, they gradually become the main source of carbon emissions [14,15].

The coastal provinces become the main source of carbon emissions due to their developed economy, large population, large living area and other reasons. Behind the economic development is the high proportion of energy consumption and emissions. In 2020, coastal provinces will account for 13.6% of the national land area, 56.4% of the national GDP, 46.5% of the permanent population, and 49.31% of energy consumption [16]. From 2005 to 2019, the carbon emissions in coastal areas accounted for 45–50% of the national total [17]. Although the proportion of carbon emissions in coastal areas began to decline in 2017, the huge proportion of emissions is still a huge challenge for China to achieve the goals of "carbon neutrality" and "carbon peak". On the other hand, coastal provinces, depending on their degree of development and geographical location, put forward a carbon peak scheme standard in terms of architecture, which is much higher than that of inland cities. In October 2021, the State Council issued the Action Plan for Carbon Peak by 2030, which highlighted that Beijing-Tianjin-Hebei, Yangtze River Delta, Guangdong-Hong Kong-Macao Greater Bay Area, and other regions should actively play a leading role in helping China to achieve economic, energy conservation, and emission reduction goals. In the 14th Five-Year Plan of the coastal provinces, Zhejiang Province proposed to vigorously promote green and low-carbon production and lifestyle, and the proportion of non-fossil energy in primary energy increased to 24%. Shandong Province proposes to build a "hydrogen corridor" and vigorously develop green buildings. Hainan Province proposes that the installed weight of clean energy is about 80%. Carbon dioxide per unit GDP of Hebei Province decreased by 4.2%. Jiangsu Province and Fujian Province put forward the goal of "achieving carbon peak ahead of schedule". Fujian Province strives to accelerate the low-carbon transformation of the construction industry by strengthening top-level design and overall planning, establishing and improving the low-carbon construction policy and system, improving the carbon emission accounting system in the construction field, building a diversified incentive mechanism for building carbon emission reduction, and establishing a low-carbon technology innovation mechanism in the construction field.

Thus, it can be seen, the carbon peaking and carbon neutralization of China's coastal provinces can not only promote the sustainable development of coastal areas, but also play a significant role in the green and low-carbon transformation of the national economy and the enhancement of international competitiveness [18]. In order to guide the sustainable development of urban residential buildings and provide differentiated governance measures, we consider coastal provinces as the research object and propose the following three issues:

① What were the characteristics of the historical carbon emissions from residential buildings in coastal provinces?

② Based on the current situation, what are the evolutionary trajectories and the peak situation of residential building carbon emissions in coastal provinces?

③ What are the factors affecting whether residential buildings in coastal provinces can achieve the carbon peak goal?

To solve these problems, this study proposes a historical carbon emission reduction assessment, carbon emission scenario analysis and low-carbon path research for urban residential buildings in coastal provinces for the first time. The scope of study covers China's coastal provinces, including Liaoning Province, Jiangsu Province, Zhejiang Province, Fujian Province and other nine provinces, as well as Guangxi Zhuang Autonomous Region, Shanghai, Tianjin municipality directly under the Central Government and Hong Kong and Macao Special Administrative Region. The specific research area is shown in Figure 1. We choose Fujian Province as the representative province for data measurement of coastal provinces. Fujian Province, as the main body of Haixi Economic Zone and pilot province of the building energy conservation supervision system, has proposed the goal of achieving carbon peak by 2030. Predicting the carbon emissions of urban residential buildings in Fujian Province has important practical significance and value for coastal provinces, which can help propose corresponding emission reduction paths and achieve China's "Dural carbon" goal as soon as possible. Specifically, in combination with the relevant policies recently issued by the Fujian Province, and against the background of the goal of achieving carbon peak by 2030, this study selects the relevant carbon emission data in the economic development field from 2000 to 2017 in the Fujian Statistical Yearbook, and considers the impact of total population, urbanization rate, per capita GDP, resident consumption expenditure, energy structure, and urban living area on carbon emissions from urban residential buildings in the Fujian Province. Based on this, the scenario analysis method is used to set the ultra-low carbon, low-carbon, baseline, and high-carbon models to predict the changing trend of carbon emissions of urban residential buildings in Fujian Province from 2018 to 2050, providing corresponding policy references for coastal provinces.

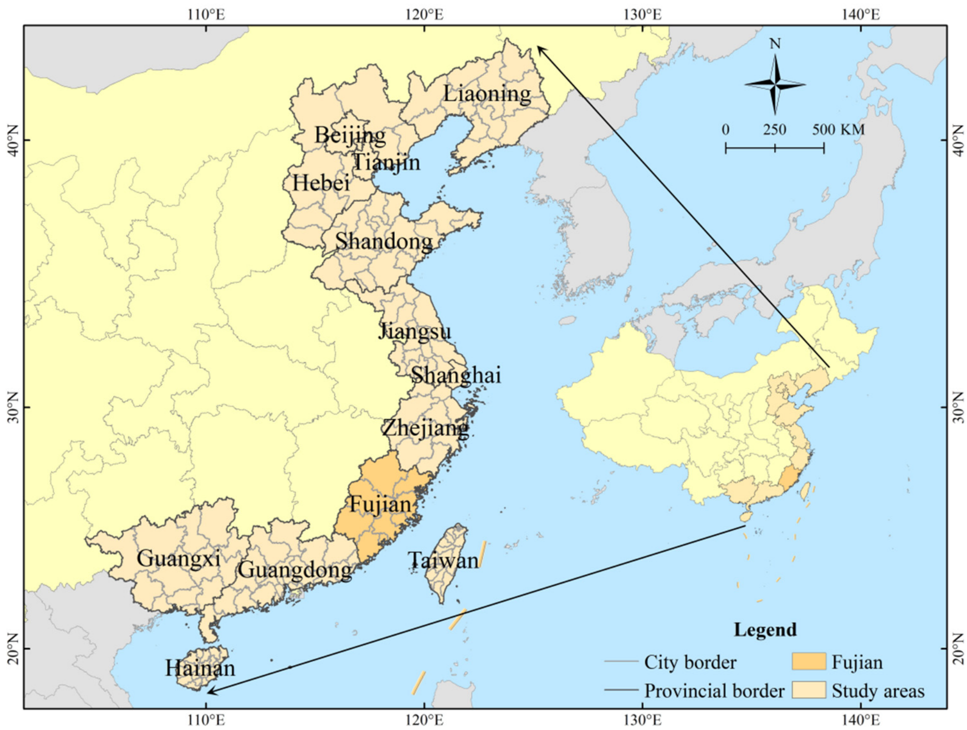

Figure 1. The location of study areas.

The innovative contribution of this study to the existing literature lies in the following three aspects: First, this study attempts to explore the key factors that affect the carbon emissions of urban residential buildings in coastal provinces in combination with the current construction situation in coastal provinces and rank the importance to fill the gap in the existing research on this issue. Second, from the perspective of research, this study is different from the existing research. Existing research focuses on carbon emissions from the national level, urban agglomeration, or single city perspective, while this research focuses on urban residential buildings in coastal provinces, which can provide theoretical support and policy reference for the green and low-carbon development in the construction industry in China's coastal provinces. This will also help promote the coordinated development between urbanization and building carbon emission reduction and provide a useful reference for achieving low-carbon sustainable development. Third, we establish a building carbon emission prediction model, combining with the STIRPAT model and scenario analysis methods, and the model is used to simulate the evolution of carbon emission trends of urban residential buildings by considering the uncertainty of variables.

The rest of the paper is arranged as follows. We review the literature in Section 2. The research methods and data sources are introduced in Section 3. The results and analyses are presented in Section 4. Section 5 discusses the different scenarios and provides policy recommendations. Section 6 present the discussions and conclusions.

2. Literature Review

Due to the huge potential of residential buildings in energy conservation and emission reduction, many scholars have focused on carbon emissions from residential buildings. The research perspectives on carbon emissions in the construction industry worldwide are mainly divided into three aspects: micro, meso, and macro. The micro aspect focuses on the entire life cycle of buildings, which has become an important tool to evaluate the carbon emissions of buildings since 1990 [19]. Foreign research showed that the energy consumption of civil buildings during their life is nearly 40%, and the proportion of energy consumption in the operation phase is as high as 80% of the entire life cycle [20,21]. In 1995, Suzuki [22] calculated the carbon emissions and life cycle energy consumption of residential buildings. Adalberth [23] presented the calculation formula of energy consumption at different stages of the entire life cycle of a building. Domestic scholars, You [24] and others, have collated and calculated the carbon emissions of buildings throughout their life cycle. Yu et al. analyzed the influencing factors of carbon emissions from residential buildings based on the life cycle assessment (LCA) theory [25]. However, there is no uniform standard and conclusion for the division of stages of the entire life cycle of buildings, the determination of carbon emission boundaries, and the differences in carbon emission inventories. At the meso level, most studies compare the carbon emissions of single buildings of different types or regions. For example, Mao et al. measured and compared the carbon emissions of green buildings of different star ratings [26]. Wu et al. compared the carbon emissions of green buildings and non-green buildings [27]. Macro level research is relatively rich, selecting regions, countries, and even the whole world as research objects. For example, Wang et al. [28] used Caoyang New Village in Shanghai as an example to study the relationship between residential mode and carbon emissions. Shi et al. [15] investigated the impact of climate and economy on carbon emissions of cities in southern and northern China. Marwa Dabaieh et al. [29] selected Egyptian residential buildings as their research object, aiming to develop carbon map tools and measure the carbon footprint of Egyptian residential buildings. Nematchoua et al. [30] selected tropical climate regions as their research object, compared them to temperate regions, and studied the difference in carbon emissions reduction that can be implemented by residential building reconstruction in different regions.

The prevalence of carbon emission research creates an endless emergence of research on building carbon emissions, influencing factors, and prediction methods. Among a variety of methods for studying carbon emissions, the most representative is the IPAT model proposed by Ehrlich, which has been used to investigate the drivers of different industries, followed by the STIRPAT model proposed by York et al. [31] and combined with the scenario analysis method for prediction. In this regard, Richard York and others abroad proposed the STIRPAT model and ecological resilience measures, which more accurately explain the sensitivity of environmental impact to driving forces [32]. Gao et al. used the STIRPAT model to study and proposed that the residential building area has a dilution effect on the energy consumption per square meter [33]. Ma et al. [34] used the STIRPAT model to discuss the influencing factors of energy consumption and carbon emissions of public buildings in China from 2000 to 2015. Zhang and Song discussed the impact of tax and environmental regulatory factors on carbon emissions [35,36]. Dong and Li conducted research on the impact of digital economy on carbon emissions [37,38]. Huo et al. [39–42] studied the macro and micro driving factors of the building carbon emissions and established dynamic scenario simulation model to predict the future evolutionary trend of the building carbon emissions at different scales considering the uncertainty. Another commonly used model for studying carbon emissions is the decomposition analysis model. For instance, Yang et al. [43] used the LMDI model to explore the driving forces of carbon emissions and found that economic activities have the greatest influence on carbon emissions.

In summary, the research on building carbon emissions worldwide is mainly concentrated at the national and provincial scales, and the research focuses on the influencing factors of carbon emissions, while the research on the prediction of urban residential building carbon emissions in coastal provinces is less. Therefore, we selected the Fujian Province as the representative area for data measurement of coastal provinces. Fujian is not only an excellent student of green development in China's ecological civilization construction but also an important component of coastal economic provinces. Taking Fujian Province as an example, forecasting the carbon emissions of urban residential buildings is of great practical significance and value for the carbon emission reduction path and dual carbon goals of coastal provinces.

3. Research Methods

3.1. Determination of Influencing Factors

The carbon emission factor method was used to determine carbon emissions. Various energy carbon emission coefficients and calculation methods and formulas were obtained from the carbon emissions trading website data and IPCC.

After screening, the relevant research documents [11,44–53] on carbon emissions were counted for influencing factors. The top seven influencing factors mentioned with the highest frequency were ranked from large to small: total population, industrial structure, GDP per capita, urbanization rate, energy structure, residents' consumption expenditure, and urban living area.

Here, the influencing factors are preliminarily selected as the following variables, in addition to the results of limited literature statistics, there are also the following reasons. First, the residential buildings in coastal cities are based on the total population for carbon emission intensity statistics, and the total population and GDP per capita are the common factors that affect carbon emissions from previous literature. Second, coastal provinces have unique geographical advantages, and their urbanization speed is increasing, which has led to the optimization of consumption type, scale, and industrial proportion. This should be considered as the influencing factor of carbon emissions from urban residential buildings in coastal provinces. Third, the huge changes in the consumption structure of residents in coastal provinces in the past decade have also had a noticeable impact on carbon emissions, and previous studies have also shown that changes in energy, industrial structure, and urban residential area are equally important to the carbon emissions of provincial cities. In combination with the research conclusions drawn by many scholars and relevant environmental characteristics of coastal provinces, seven common influencing factors are selected: total population (P), per capita GDP (G), resident consumption level (R), urbanization level (U), residential area (S), energy structure (E) and industrial structure (I) [11,39–48].

3.2. Models

According to the factors selected above, the STIRPAT model is selected to analyze the factors affecting the carbon emissions of urban residential buildings in Fujian Province one by one. The STIRPAT model is an extension of the IPAT model (where is environmental capacity, is population, represents wealth level, and represents technology level). This model assesses the relationship between the three independent variables and dependent variables of population, property and technology. This paper constructs the STIRPAT model, and uses regression analysis to estimate the influence of the selected carbon emission influencing factors on the change of the building carbon emission intensity of urban residents in Fujian Province. The STIRPAT model is modified from the IPAT model, as shown in Equation (1).

$$I = \propto P^b A^C T^d e \quad (1)$$

where I is environmental pressure, P is population size, A is affluence, and T is technical level. $\propto$ is the coefficient of the model, b, c and d are the indexes of population, wealth and technical level, and e is the error term.

Based on the STIRPAT model, the explanatory variables of this study are the total population (P), urban rate (U), per capita GDP (G), household consumption expenditure (R), energy structure (E), and industrial structure (I) of Fujian Province, a total of six variables. To this end, the STIRPAT model expression built is as shown in Equation (2).

$$C = \alpha P^{\beta_1} U^{\beta_2} G^{\beta_3} R^{\beta_4} E^{\beta_5} I^{\beta_6} e \quad (2)$$

Based on the STIRPAT model, regression analysis is used to estimate the impact of various factors on the carbon emissions of residential buildings in Fujian Province.During the establishment of the STIRPAT model for industrial structure (I), the standardization coefficient of its beta is only 0.016, which is too wide and stable compared with the other five values, indicating that it is not significant. Therefore, the STIRPAT expansion model for carbon emissions from residential buildings in Fujian Province is constructed after removing the influence factor of industrial structure through analysis, as shown in Equation (3).

$$lnC = \alpha + \beta_1 lnP + \beta_2 lnU + \beta_3 lnG + \beta_4 lnR + \beta_5 lnE + \beta_6 lnS + e \quad (3)$$

where, α is a constant term, $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6$ represents the elasticity coefficient of the total population, urbanization rate, per capita GDP, household consumption expenditure, energy structure, urban living area, and industrial structure, respectively, and e is an error term.

3.3. Forecast Scenario Setting

In order to predict the carbon emissions of urban residential buildings in Fujian Province and propose suggestions on energy conservation and emission reduction, four scenarios are set: ultra-low carbon, low-carbon, baseline carbon, and high-carbon. When setting the growth model of each variable, this paper takes relevant policies and laws of economic development into consideration in order to ensure that the setting of each factor is more scientific and reasonable in accordance with the future development plan of Fujian Province and the current social situation.

In order to predict the carbon emissions of urban residential buildings in Fujian Province from 2018 to 2050, and considering that China's national and provincial planning policies generally set targets based on five years, this study will take this as the basis to carry out prediction and analysis from 2018 in the 13th five-year plan to 2050 at the end of the 19th five-year plan, which is divided into seven stages. Take the existing data as the benchmark value, calculate the annual average change rate, that is, the percentage change of the current year compared with the previous year, as the change parameter of each variable, and relax or increase the parameter setting of high carbon mode or low carbon mode according to the four scenarios set. For example, the average annual growth rate of the population, the People's Government of Fujian Province, in the notice on the population development plan of Fujian Province (2016–2030) issued in 2018, said that the expected development goal of the population of Fujian Province will reach 41.5 million by 2030, and the urbanization rate of the permanent population will reach 75%, that is, the urban permanent population will reach 31.125 million by 2030. In the past five years, the average annual growth rate of Fujian's population has been around 2%. Therefore, this paper sets the average annual growth rate of urban population under the baseline carbon emission scenario to 2%, while the low carbon emission scenario is set to 1%, and the high carbon emission scenario is set to 3%, which remains unchanged under the ultra-low carbon model. According to the prediction of the United Nations on China's population, the growth rate of China's population will gradually decrease, rea ching a peak in 2030, and then the growth rate will be negative. Therefore, it is predicted that the population growth rate of the baseline carbon emission scenario will be set to zero in 2030, and then the growth rate will be negative. The specific settings are summarized in Table 1.

Table 1. Carbon emission scenarios of urban residential buildings in Fujian Province.

	Stage Situation	2021–2025	2026–2030	2031–2035	2036–2040	2041–2045	2046–2050
Growth rate of total population	Ultra-low carbon	−1.00%	−2.00%	−2.50%	−3.00%	−3.250%	−3.50%
	Low-carbon	0.00%	−1.00%	−1.50%	−2.00%	−2.250%	−2.50%
	Baseline carbon	1.00%	0.00%	−0.50%	−1.00%	−1.250%	−1.50%
	High-carbon	2.00%	1.00%	0.50%	0.00%	−0.250%	−0.50%
Urbanization growth rate	Ultra-low carbon	68.50%	72.00%	75.00%	76.00%	76.500%	77.00%
	Low-carbon	69.50%	73.00%	76.00%	77.00%	77.500%	78.00%
	Baseline carbon	70.50%	74.00%	77.00%	78.00%	78.500%	79.00%
	High-carbon	71.50%	75.00%	78.00%	79.00%	79.500%	80.00%
GDP growth rate per capita	Ultra-low carbon	9.00%	8.00%	7.00%	6.00%	5.000%	4.00%
	Low-carbon	10.00%	9.00%	8.00%	7.00%	6.000%	5.00%
	Baseline carbon	11.00%	10.00%	9.00%	8.00%	7.000%	6.00%
	High-carbon	12.00%	11.00%	10.00%	9.00%	8.000%	7.00%
Resident Growth rate of consumption expenditure	Ultra-low carbon	5.00%	4.00%	3.00%	2.00%	1.000%	0.00%
	Low-carbon	6.00%	5.00%	4.00%	3.00%	2.000%	1.00%
	Baseline carbon	7.00%	6.00%	5.00%	4.00%	3.000%	2.00%
	High-carbon	8.00%	7.00%	6.00%	5.00%	4.000%	3.00%
Proportion growth rate of coal energy	Ultra-low carbon	40.00%	38.00%	37.00%	36.00%	35.000%	34.00%
	Low-carbon	42.00%	40.00%	39.00%	38.00%	37.000%	36.00%
	Baseline carbon	44.00%	42.00%	41.00%	40.00%	39.000%	38.00%
	High-carbon	46.00%	44.00%	43.00%	42.00%	41.000%	40.00%
Growth rate of urban residential area	Ultra-low carbon	2.50%	2.00%	1.50%	1.00%	0.500%	0.00%
	Low-carbon	3.50%	3.00%	2.50%	2.00%	1.500%	1.00%
	Baseline carbon	4.50%	4.00%	3.50%	3.00%	2.500%	2.00%
	High-carbon	5.50%	5.00%	4.50%	4.00%	3.500%	3.00%

3.3.1. Baseline Scenario

Under the scenario, all influencing factors follow the current trends in Fujian Province, which are not impacted by other emission reduction measures. This scenario is the basis of other scenarios.

3.3.2. Low-Carbon Scenario

Under the scenario, the factors which promote the carbon emissions of urban residential buildings will change at a rate lower than the baseline scenario. This means that the government will increase the intervention in low-carbon energy conservation of urban residential buildings, such as slowing down the urbanization process and promoting technological progress.

3.3.3. Ultra-Low Carbon Scenario

This scenario shows that Fujian Province vigorously implements energy-related policies. The factors which might promote the carbon emissions of urban residential buildings will change at a rate lower than the low-carbon scenario, aiming to explore the evolution of carbon emissions under the most stringent policies.

3.3.4. High-Carbon Scenario

Under high-carbon scenario, the factors which promote carbon emissions will increase at a rate higher than the baseline scenario. This scenario can simulate the evolving trend of carbon emissions of urban residential buildings in the worst situation.

3.4. Data Sources

The carbon emission data from 2000 to 2018 used in this study are estimated using the China building energy consumption calculation model (CBECM) [54]. In addition, the seven influencing factors (total population, per capita, urbanization rate, household consumption expenditure, energy structure, urban living area) obtained in the last section, as well as the industrial structure, excluded due to the low applicability of the model, are all from Fujian Statistical Yearbook.

4. Analysis and Results

4.1. Analysis of Influencing Factors

This paper forecasts the carbon emission model of urban residential buildings in Fujian Province based on the emission model of total building carbon emissions established by STIRPAT model. Based on the above data obtained in Fujian Statistical Yearbook, the ridge regression model is calculated using SPSSPRO 1.1.0 software, and the ridge regression results analysis (as shown in Table 2) and the thermodynamic diagram results are shown in Figure 2.

Table 2. Analysis of ridge regression results of influencing factors.

	lnS	*lnG*	*lnE*	*lnU*	*lnP*	*lnR*
lnS	1.000 (0.000 ***)	0.995 (0.000 ***)	−0.441 (0.067 *)	0.996 (0.000 ***)	0.978 (0.000 ***)	0.996 (0.000 ***)
lnG	0.995 (0.000 ***)	1.000 (0.000 ***)	−0.449 (0.062 *)	0.994 (0.000 ***)	0.981 (0.000 ***)	0.998 (0.000 ***)
lnE	−0.441 (0.067 *)	−0.449 (0.062 *)	1.000 (0.000 ***)	−0.423 (0.080 *)	−0.560 (0.016 **)	−0.458 (0.056 *)
lnU	0.996 (0.000 ***)	0.994 (0.000 ***)	−0.423 (0.080 *)	1.000 (0.000 ***)	0.977 (0.000 ***)	0.996 (0.000 ***)
lnP	0.978 (0.000 ***)	0.981 (0.000 ***)	−0.560 (0.016 **)	0.977 (0.000 ***)	1.000 (0.000 ***)	0.988 (0.000 ***)
lnR	0.996 (0.000 ***)	0.998 (0.000 ***)	−0.458 (0.056 *)	0.996 (0.000 ***)	0.988 (0.000 ***)	1.000 (0.000 ***)

Note: ***, **, and * represent the significance level of 1%, 5%, and 10%, respectively.

As shown in Figure 2, there is a good correlation among the total population, urbanization rate, GDP per capita, resident consumption expenditure, energy structure, and urban living area. Therefore, the six independent variables that have been modified and determined are fitted with the ridge regression model again, and K = 0.154 was determined according to the variance expansion factor method. The ridge trace map and the final model analysis results are shown in Figure 3 and Table 3.

The standardized coefficient value of the urban living areas in Fujian Province is, Beta = 0.233 > 0.05. Thus, this independent variable plays an important role in the carbon emissions of Fujian Province and should be included in the carbon emissions considerations of this study. In addition, the new ridge regression results show that the significance value of the regression model based on the independent variables, *lnS*, *lnP*, *lnE*, *lnG*, *lnU*, and *lnR* is 0.000 (removed), showing significance at the level, rejecting the original hypothesis, and indicating that there is a regression relationship between the independent and dependent variables (*lnC*). Simultaneously, the goodness of fit of the model is relatively excellent (R^2 = 0.928), thus, the model met the requirements.

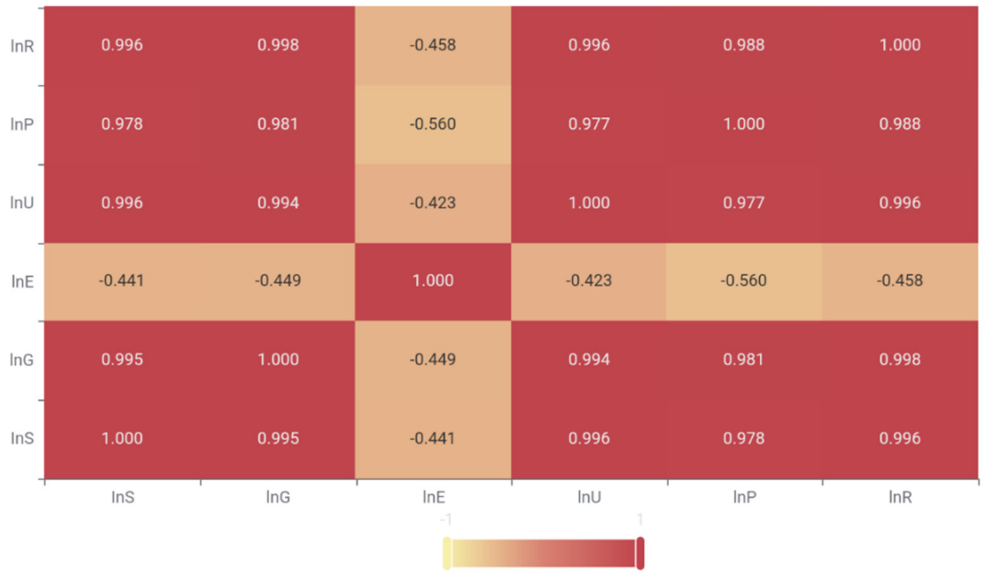

Figure 2. Thermodynamic diagram analysis of influencing factors.

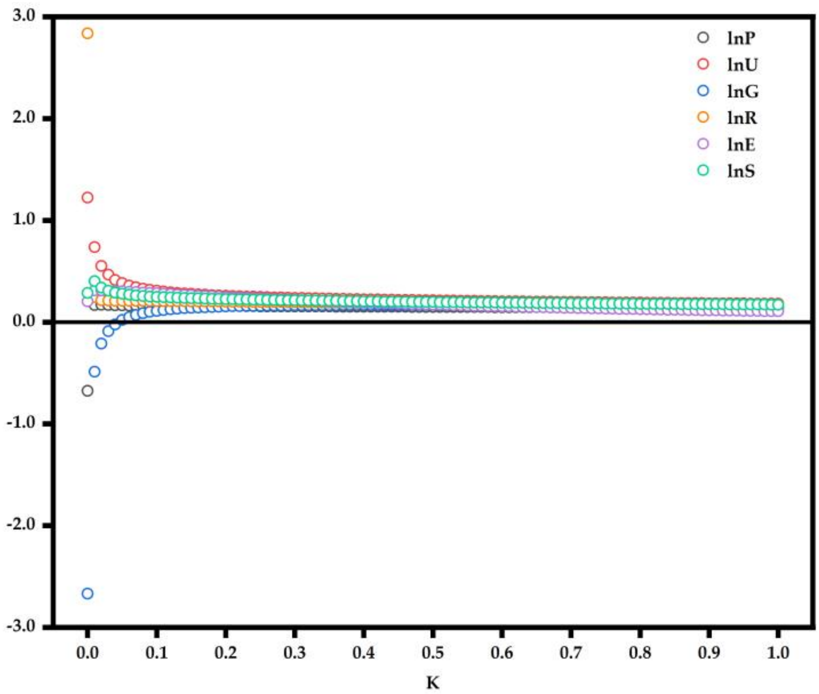

Figure 3. Ridge trace map of influencing factors.

Table 3. Final model construction results.

K = 0.154	**Nonstandard Coefficient B**	**Standard Error**	**Standardization Coefficient Beta**			**Adjustment**		
constant	−18.166	4.169	-	−4.357	0.001 ***			
lnP	1.488	0.475	0.157	3.136	0.009 ***			
lnU	1.026	0.141	0.275	7.255	0.000 ***			
lnE	1.178	0.338	0.262	3.486	0.005 ***	0.928	0.889	23.618 (0.000 ***)
lnS	0.357	0.058	0.233	6.145	0.000 ***			
lnR	0.19	0.021	0.204	8.906	0.000 ***			
lnG	0.109	0.029	0.141	3.722	0.003 ***			

Note: *** represent the significance level of 1%. Dependent variable: lnC.

As shown from the above analysis, the carbon emission indicators of residential buildings in Fujian Province remain stable when K = 0.154, and R^2 = 0.928, the regression equation fitting effect is significant, and the final result of the model is shown by Equation (4):

$$lnC = -18.166 + 1.488lnP + 1.206lnU + 0.109lnG + 0.19lnR + 1.178lnE + 0.357lnS \quad (4)$$

4.2. Carbon Emission Prediction

The peak time and value of carbon emissions under different scenarios are summarized in Table 4.

Table 4. Peak time and peak value of carbon under different scenarios.

Scene	Ultra-Low Carbon Scenarios	Low-Carbon Scenarios	Reference Scenarios	High-Carbon Scenarios
Peak time	2027	2035	2044	Not reaching the peak
Peak value	1347.48 Mt	1971.57 Mt	3340.59 Mt	6947.75 Mt

The forecast trend of carbon emission under different scenarios is shown in Figure 4.

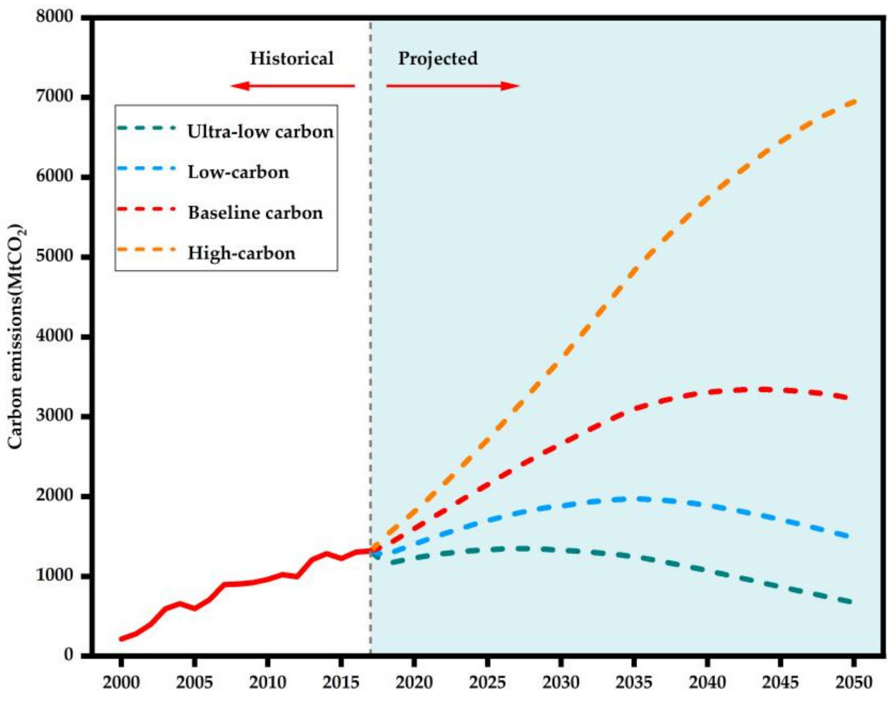

Figure 4. Predicted carbon emissions of urban residential buildings in Fujian Province from 2018 to 2050.

To test the accuracy and reference of the predictions in this study, the carbon emissions of urban residential buildings in Fujian Province in 2018 and the three scenarios under the prediction model were analyzed for error, as shown in Table 5.

As shown in Table 5, in the analysis results of STIRPAT model and scenario analysis method used in this study, the error between the predicted values of the low-carbon and high-carbon models in 2018, and the actual carbon emission value, is controlled within 9%, which is relatively accurate. In particular, the carbon emission index error rate under the baseline model is as low as 0.1065%, indicating that urban residential buildings in Fujian Province are currently developing according to the baseline model. However, the error rate between the ultra-low carbon model and the actual carbon emissions has reached 16.22%, and the error rate of the predicted value of the low-carbon model is lower than that of the high carbon model, indicating that the current carbon emissions of urban residential buildings in Fujian Province are moving towards the low-carbon model. The error values of the other three models are relatively small, which proves that the predicted values in this study are reliable.

Table 5. Inspection table of carbon emission prediction value of urban residential buildings in Fujian Province in 2018.

Particular Year	Actual Carbon Emission Value	Predicted Value of Ultra-Low Carbon Model	Predicted Value of Low-Carbon Model	Predicted Value of Reference Model	Predicted Value of High-Carbon Model
2018	1378.91	1155.252146	1264.57	1380.38	1502.91
Error rate	0.0000%	16.2199%	8.2920%	0.1065%	8.9926%

4.3. Sensitivity Analysis Results of Influencing Factors

When different influencing factors change, the corresponding peak carbon emissions of urban residential buildings in Fujian Province and life prediction will be affected. This study adopts the single factor sensitivity analysis method to conduct a sensitivity analysis on the above key influencing factors, and 1% change prediction analysis on each factor. The results show that the total population, urban living area, and resident consumption expenditure, among the six influencing factors, have a greater impact on peak carbon emissions (Table 6). The order of influence of the six key factors is as follows: total population > urban living area > residents' consumption expenditure > urbanization rate > GDP per capita > energy structure.

Table 6. Prediction of peak growth rate of carbon emission from urban residential buildings in Fujian Province under different scenarios.

	Ultra-Low Carbon Scenarios		Low Carbon Scenarios		Baseline Scenarios		High-Carbon Scenarios	
	Peak Year	Carbon Reaches Peak Value (Mt)	Peak Year	Carbon Reaches Peak Value (Mt)	Peak Year	Carbon Reaches Peak Value (Mt)	Peak Year	Carbon Reaches Peak Value (Mt)
Increase of influencing factors (0%)	2027	1347.481042	2035	1971.574415	2044	3340.586066	None	6947.754937
Annual average growth rate of total population 1%	2034	1636.496518	2035	1956.923812	None	5258.105544	None	11275.74645
Urbanization rate Average annual growth rate 1%	2027	1367.26318	2035	2034.0931	2044	3384.310649	None	7036.874316
Average annual growth rate of GDP per capita 1%	2027	1360.900188	2035	2006.994065	2044	3430.937489	None	7177.288349
Average annual growth rate of residents' consumption expenditure 1%	2028	1372.805102	2035	2036.105922	2045	3506.518417	None	7368.400278
Average annual growth rate of coal energy 1%	2027	1347.885983	2035	1982.954949	2044	3380.17423	None	6949.801097
Average annual growth rate of urban residential area 1%	2026	1301.848962	2035	2097.428666	2046	3670.947194	None	7771.955995

5. Prediction and Analysis of Emission Scenarios

Based on the setting of the rate of various influencing factors under different scenarios, the carbon emissions of urban residential buildings in Fujian Province were predicted. As shown in Figure 3, there are great differences in the value and the time of carbon emission peaks in different scenarios. The peak carbon emission of urban residential buildings in Fujian Province is 2027–2044, with a large span, and the peak carbon emission is approximately 134,748–33,405,900 tons. The ultra-low carbon, low-carbon, and baseline models will reach their peaks in 2027, 2035 and 2044, respectively, while the high-carbon model will reach 41.2074 Mt of carbon emissions in 2050, with rapid growth and no peak.

5.1. Carbon Emission Scenario under the High-Carbon Model

Under the scenario of the high-carbon model, carbon emissions of urban residential buildings in Fujian Province have been in a growth state in the prediction of carbon emissions and have not reached the peak before 2050. In this case, the per capita GDP of Fujian Province in 2050 is predicted to be as high as 2,055,315 yuan, which is much higher than the predicted value under the other three models, and 25 times the actual per capita GDP of Fujian Province in 2017, meeting the requirements of a developed country. Moreover, the total population reached its peak in 2040, 1.39 times the actual population in 2017. Under the combination of the six influencing factors, the predicted carbon emission in 2050 is high (69.4775 Mt), and 5.27 times the actual carbon emission value of urban residential buildings in Fujian Province in 2017, and there is no peak value during the study period. Under this economic development mode, certain energy-saving and emission reduction effects may be achieved. However, the emission reduction rate is far lower than the increase rate of carbon emissions caused by the sacrifice of various factors. If there is no huge breakthrough in energy-saving and emission reduction technologies or methods of controlling growth factors in the future, the carbon emission situation in Fujian Province will become extremely severe and passive.

5.2. Carbon Emission Scenarios under the Baseline Model

Under the baseline scenario, the predicted carbon emission of urban residential buildings in Fujian Province in 2018 is 13.8038 Mt, which is the closest to the real carbon emission value of 13.7891 Mt. In this scenario, the carbon peak will occur in 2044, with a carbon emission peak value 33.4059 Mt. The growth of the total population made it impossible to reach the peak in the study period. The residents' consumption expenditure and urban living area delayed the peak year, and the other three factors only affected the carbon peak. Six years after reaching the peak, the carbon emissions began to show a downward trend, but the decline was slow. The carbon emission under the baseline model is very close to the current carbon emission of urban residential buildings in Fujian Province, which is more consistent with the current pace of economic and technological development and energy use in Fujian Province. However, from the predicted peak years, there is still much space for energy conservation and emission reduction in Fujian urban residential buildings to achieve the goal of reaching the carbon peak in Fujian Province by 2030 under the baseline model. The task is arduous, and the situation is grim. While maintaining the steady progress of the economy and people's living standards in Fujian Province, the predicted value of reaching the peak in 2044 also brings huge pressure on energy conservation and emission reduction. The Fujian provincial government needs to strengthen top-level design, optimize the industrial structure, change the consumption structure of residents, improve the residents' awareness of energy conservation and emission reduction, and accelerate the development of new energy to reach the carbon peak by 2030.

5.3. Carbon Emission Scenario under the Low-Carbon Model

Under the low carbon model, the peak value in 2035 will be 19.7 Mt CO_2, and the predicted carbon emissions in 2050 will be 14.8 Mt CO_2. The average annual growth rate of carbon emissions in the 17 years from 2018 to 2035 is approximately 0.0265%, while the average annual growth rate from 2018 to 2050 is approximately 0.005%. The annual growth rate of carbon emissions from urban residential buildings in Fujian Province has declined to a certain extent under the low-carbon model. It is predicted that the per capita GDP in 2035 will be 442,992 yuan, 5.29 times that of 2017, which can be included in the category of moderately developed countries. The urbanization rate has also been achieved in the national development policies and the development steps of the Fujian Provincial government. The urbanization rate is predicted to reach 78% in 2050, and more than 3/4 of the population will achieve the urbanization goal. The predicted population of Fujian Province in 2035 will reach approximately 39,063,100, which is slightly less than the actual population of Fujian Province in 2017, in line with the situation that foreign scholars have speculated, which is that China's population growth rate will be negative after 2030. In the low-carbon model, the building carbon summit appears, and the six influencing factors do not change the carbon peak year, but only change the carbon emission values. Therefore, the predicted peak year is 2035, which will not meet the strategic arrangement of reaching the peak by 2030.

5.4. Carbon Emission Scenario under Ultra-Low Carbon Model

Under the ultra-low carbon model, the predicted carbon emissions of urban residential buildings in 2018 reached 11.5525 Mt, which is far from the actual value. However, from the prediction results, only under the ultra-low carbon model can Fujian reach the goal of carbon peak by 2030. Under this model, the total population will decrease from 40,812,600 in 2018 to 20,264,400 in 2050, with the population decreasing by approximately half the base number. The decrease in population growth will trend until a large negative growth is predicted under the current population policy. However, it does not rule out changes in population policy adjustment. Therefore, in the ultra-low carbon model, more focus should be on the control of other influencing variables. For example, in terms of energy structure, coal consumption is expected to decrease from approximately 43% to 34%. Under this scenario, Fujian Province is required to achieve the highest utilization rate of clean energy, thus, the use of clean energy, such as wind and solar energy should be increased. An onshore wind power development policy should be opened in an orderly manner. Simultaneously, the use of offshore wind power should be vigorously implemented. Relevant policies to reward enterprises that use clean energy, improve the autonomy of enterprises in low-carbon emission reduction, and increase the investment in scientific research funds to increase energy utilization should be implemented, to change the carbon emission model of Fujian Province. Simultaneously, the urban system should be adjusted to coordinate the development of large, medium, and small cities and towns and achieve the goal of advancing the peak year of carbon in Fujian Province and saving energy, and reducing emissions.

From the above analysis, it is shown that the carbon emission of the ultra-low carbon scenario is significantly reduced compared with other models, which has the lowest carbon emissions peak and the earliest peak time under the commitment of achieving carbon emissions peak by 2030. The situation in Fujian Province at this stage is more consistent with the baseline carbon emission model, and with the focus of the Fujian Province on energy conservation and emission reduction, it has gradually moved closer to the low-carbon model. Judging from the results of the study and the implementation of existing policies, the current energy policies have contributed to the mitigation of carbon emissions from urban residential buildings. However, to achieve the goal of peaking carbon dioxide emissions by 2030, the implementation of relevant policies still needs to be strengthened. Based on the analysis of influencing factors, appropriate programs should be developed as far as possible to achieve carbon peak target of urban residential buildings.

6. Conclusions and Policy Implications

In this study, using Fujian Province as the study area, we explored the key influencing factors of carbon emissions from urban residential buildings in coastal provinces and analyzed the carbon peak under different scenarios. The main findings are as follows:

(1) From the literature survey, seven factors influencing urban residential buildings in Fujian Province were determined. The method of ridge regression was used to analyze the best fit degree. The industrial structure factors that have less impact on the carbon emissions of Fujian Province were excluded, and the influencing factors of urban living area were introduced, and the ridge regression analysis was conducted again. Finally, the six major influencing factors of carbon emissions affecting the urban living area of Fujian Province were determined, and a single factor sensitivity analysis on the prediction results was conducted. The total population, urban living area, residents' consumption expenditure, urbanization rate, per capita GDP, and energy structure were determined as the key influencing factors, ranked from high to low.

(2) By studying the relevant policies of Fujian Province in recent years, and processed the collected relevant data for modeling, and finally calculated the STIRPAT model with good fit using SPSSPRO software. The scenario analysis method was used to divide the carbon emissions of Fujian Province into four model scenarios: ultra-low carbon, low-carbon, baseline, and high-carbon. The peak carbon emissions of urban buildings in Fujian Province from 2018 to 2050 are predicted, and the following conclusions were drawn: Only the ultra-low carbon scenario can realize the 2030 carbon peak commitment of the urban residential buildings in advance. Under the baseline model, the carbon emissions will peak in 2044. In the low-carbon scenario, the turning point of the carbon emissions peak time will appear in 2035. Under the ultra-low carbon model, the carbon emissions will peak in 2027, which is in line with the goal of Fujian Province to reach the peak carbon by 2030. Whether there is a peak in the high-carbon model remains to be studied. Based on this, the corresponding countermeasures are proposed for reference.

Several gaps that exist in this study can be addressed in the future. First, the influencing factor parameters of carbon emissions in coastal provinces can be further expanded. With the diversification of research, more and more independent variables that affect the results of carbon emissions may appear, such as household income, per capita living area, digital economy, and so on. Next, when carrying out the regression, we need to consider more aspects of the impact, and the adopted analysis model may be further adjusted. Second, the single factor analysis method is used in the sensitivity analysis. Our research focuses on the prediction of carbon emission prospects of urban residential buildings in coastal provinces. This research has successfully carried out model construction and peak prediction, but we have not carried out very detailed uncertainty discussion on the research results. In the future, we can further discuss the uncertainty of research results through multi-factor sensitivity analysis or dynamic rather than static methods. In addition, the scope of future research can be further extended to the field of public buildings and rural buildings, which is more global for the construction industry to formulate carbon emission strategies.

Based on the above findings, the paper proposes the following policy recommendations:

(1) Pay close attention to the change trend of the total population and advocate the concept of green energy use of residents. The above research shows that the change of total population is the most important factor affecting urban residential buildings. With the change of China's fertility policy, Fujian Province should have a clear development plan for the total population and control the total population and growth rate within an appropriate range. At the same time, we should change the consumption structure of residents in Fujian Province from high carbon and high energy consumption to low carbon and high-quality consumption. The government can provide consumers with more low-carbon options through cooperation with enterprises, and use various

publicity means to guide the masses to form low-carbon awareness, and promote the green transformation of individual consumption behavior.

(2) Improve energy utilization efficiency and realize the transformation of energy structure. It can be seen from the above research that the reduction of coal energy proportion is the key factor affecting urban residential buildings. The government needs to first improve the efficiency of energy use through technological progress, develop centralized photovoltaic power generation projects according to local conditions, cultivate photovoltaic industries such as "complementary fishing and lighting", and actively carry out the centralized promotion of rooftop distributed photovoltaic throughout the county (city, district). We will promote the development of offshore wind power in an orderly manner and plan to build a far-reaching offshore wind power base. Actively explore new marine energy such as wave energy and tidal energy, promote the complementation of source, network, load, storage and multi-energy, and lay out and build a number of integrated projects of scenery and storage. Develop nuclear power safely and steadily. Make rational use of biomass energy. We will promote the construction of pumped storage power stations in an orderly manner and accelerate the large-scale application of new types of energy storage. Promote the development of the whole chain of hydrogen energy "production, storage and transportation". If clean energy is fully developed and used safely, it can solve the problems of environmental pollution and carbon emissions caused by excessive energy consumption from the source, which is of great significance.

(3) Cooperate with multi-factor governance to achieve ultra-low carbon model. Total population, urban living area, residents' consumption expenditure and other paths, multi-factor governance can realize the early transformation of the carbon emission model of coastal cities into ultra-low carbon model, which is conducive to the early realization of the carbon peak goal of coastal provinces. According to the results of sensitivity analysis, in the ultra-low carbon model, urbanization rate, per capita GDP and energy structure do not affect the peak year, but only affect the peak carbon. The total population, residents' consumption expenditure and urban residential area have an impact on the peak and peak years, and urban residents' consumption expenditure has brought the carbon peak years ahead of time, while the other two factors have a delayed effect. Only by cooperating with multi-factor governance can we enter the ultra-low carbon model as soon as possible and achieve the goal of "Dural carbon".

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