International Journal for Housing Science and Its Applications
Publish August 10, 2025. Volume 46, Issue 4 Pages 5264-5273

https://doi.org/10.70517/ijhsa464366

# Carbon emissions assessment throughout the entire life cycle of ultra-low energy buildings in severely cold regions

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**Abstract** Against the backdrop of increasing concerns about global climate change and environmental protection, the building sector, as an important source of carbon emissions, has gradually become a focus of research. In particular, residential buildings in severe cold regions have more significant carbon emissions due to the long-time heating demand. This paper studies the carbon emissions of ultra-low-energy residential buildings in cold regions, and analyzes different energy consumption and its carbon emissions by establishing a carbon emission measurement model. Firstly, the carbon emission coefficient method is used to measure the carbon emissions of residential buildings in the operation stage. The results of the analysis show that the carbon emissions of buildings in severe cold regions are significantly affected by the type of energy consumption and seasonal changes. In the empirical analysis, the winter carbon emissions of the 150-unit type reached 1408.6 kg in December and January, showing the characteristics of high carbon emissions in winter. In addition, by simulating the carbon emission and thermal comfort of different cities, Wuhan has the highest total carbon emission of 93127.83 kg, while Chengdu and Shanghai are 76216.06 kg and 81730.77 kg, respectively, showing the influence of different geographical climates on carbon emission. The study further used sensitivity analysis to assess the impact of different factors on carbon emissions, and the results showed that factors such as population size, urbanization rate and per capita GDP had a significant positive impact on carbon emissions. The study suggests that in the future, when designing ultra-low-energy buildings, the focus needs to be on optimizing the efficiency of energy use, especially energy management during the winter heating phase, in order to reduce carbon emissions and enhance the sustainability of energy use.

**Index Terms** Cold regions, residential buildings, carbon emission, energy consumption, sensitivity analysis, low energy consumption

## I. Introduction

Facing the greenhouse effect and atmospheric pollution problems, energy saving and emission reduction is of great significance for the improvement of the earth's environment, and most countries are actively carrying out various aspects of engineering technologies that help energy saving and emission reduction, among which energy saving through buildings is an important technical measure [1]-[4]. In China, with the emphasis on passive ultra-low-energy buildings, more and more cities have set off the ultra-low-energy building boom [5], [6]. Ultra-low-energy buildings are buildings that adapt to climatic characteristics and natural conditions to provide a comfortable indoor environment with less energy consumption by means of enclosure structures with higher thermal insulation and airtightness, adopting high-efficiency heat recovery technologies to minimize the heating and cooling demand of the building, and making full use of renewable energy sources [7]-[10]. The technical core of ultra-low-energy buildings is to reduce one-time energy consumption as the goal, through the measures of heat preservation, heat insulation, air tightness, thermal bridge breaking and optimization of HVAC equipment of the enclosure structure, to reduce the energy demand of the building body, to reduce the dependence on the traditional heating and cooling equipment, and to provide a better indoor environment in the form of a building with less energy consumption [11]-[14].

At present, China's ultra-low-energy buildings are mainly distributed in cold regions such as Beijing-Tianjin-Hebei, Henan and Shandong, and a small number of them are distributed in hot-summer and cold-winter regions [15], [16]. As a matter of fact, the cold region is a region with greater potential for energy saving gains from ultra-low energy consumption technologies, but due to the extreme cold and long winters in the cold region, which require high thermal insulation performance and pose a challenge to the performance of windows and doors, the performance of equipment systems, and the safety of thermal insulation installations, the practical cases of large-scale implementation of ultra-low-energy consumption buildings in the cold region are still relatively few [17]-[20]. However, many buildings are heavy on construction, light on management, heavy on envelope structure, light on system operation, heavy on design, light on commissioning, neglecting the energy-saving management of the operation link, which makes the energy-saving effect of the building greatly discounted, resulting in a higher level of energy consumption of the building than the design expectations, and failing to realize the true meaning of ultra-low-energy buildings [21]-[24].

This paper focuses on the carbon emissions of ultra-low energy residential buildings in cold regions. Firstly, this paper defines and measures the carbon emissions of residential buildings, and adopts the carbon emission coefficient method to analyze the carbon emissions of different energy types. Then, carbon emissions and thermal comfort of several cities are simulated for different regional climate characteristics to explore the relationship between building energy efficiency and carbon emissions under different climatic conditions. In addition, a sensitivity analysis was conducted in this paper to assess the impact of demographic, economic and technological factors on building carbon emissions through different sensitivity analysis methods. The results of the study provide a scientific carbon emission measurement model for residential buildings in severe cold regions, and provide a theoretical basis for realizing the design and renovation of low-carbon buildings.

## II. Measurement of carbon emissions from residential buildings

### *II. A. Definition of carbon emissions from residential buildings*

(1) Definition of Carbon Emission

Carbon emissions [25] refers to the behavior of human production and business activities in the process of greenhouse gas emissions to the outside world. Greenhouse gases are mainly carbon dioxide and methane.

(2) Definition of residential building

Residential buildings are buildings for people's daily living and living use, the basic place of human habitation, which can be single-family houses, apartment buildings, villas and other forms. Residential buildings can be categorized into urban residential buildings and rural residential buildings. Urban residential buildings are buildings located in cities or established towns for people to live in.

(3) Definition of carbon emissions from residential buildings

In the operation stage of residential buildings, people continuously consume energy to meet their daily needs, thus generating carbon emissions. In the whole life cycle of a residential building, the operation phase accounts for the highest proportion of carbon emissions. In view of this, the carbon emissions from residential buildings studied in this paper refer to the carbon emissions generated by the energy consumed by people to maintain their daily lives, such as heating and ventilation, during the operation phase of residential buildings.

### *II. B. Components of Carbon Emission Measurement for Residential Buildings*

(1) For individual residential buildings

Carbon emissions can be measured for individual buildings using the actual measurement method. The measurement method is mainly to measure the flow rate and concentration of emission gases of a certain building or a small number of buildings by means of testing methods or measuring facilities, so as to obtain the total amount of carbon emissions.

(2) For residential buildings at the macro level such as industries or provinces and cities

The carbon emission coefficient method can be used to measure carbon emissions for residential buildings in the whole industry or larger scope areas. According to the carbon emission coefficient calculation method, the carbon emissions of residential buildings are measured based on their consumption of various energy sources, and the specific calculation formulas are as follows:

$$E = AD \cdot EF \tag{1}$$

$$EF = \frac{44}{12} \cdot o_1 \cdot o_2 \cdot o_3 \tag{2}$$

where $E$ denotes the carbon emissions from energy consumption, $AD$ denotes the amount of table energy consumed, $EF$ denotes the carbon emission factor of the energy source, $o_1$ denotes the average low-level heat production of the energy source, $o_2$ denotes the carbon content per unit calorific value, and $o_3$ denotes the carbon oxidation rate of the energy source.

### *II. C. Carbon Emission Measurement of Ultra-low Energy Consumption Residential Buildings in Cold Regions*

#### II. C. 1) Scope of carbon emission accounting for residential buildings

The whole life cycle of residential buildings can be divided into four stages: production and transportation of building materials, construction, operation, dismantling and disposal, and its carbon emissions mainly come from these four stages, as follows:

(1) Production and transportation of building materials

The carbon emission from the production and transportation of building materials is one of the important sources of carbon emission in the construction industry, which mainly comes from the mining of building raw materials and energy consumption in the production process.

(2) Construction Stage

The construction stage refers to the entire process from the start of construction to the completion of the building, including land leveling, foundation works, main structure, decoration and other links.

(3) Operation Stage

The operation stage after the completion of the building is the longest stage in the whole life cycle of the building. The actual energy consumption, maintenance and management of the building, renewal and renovation are all carried out in this stage.

(4) Demolition and Abandonment Stage

When a building reaches the end of its designed service life or needs to be upgraded, it enters the demolition and abandonment phase. In this stage, the recycling and disposal of building materials is required to minimize the negative impact on the environment.

#### II. C. 2) Indicator selection and data sources

(1) Principles of Carbon Accounting Options

Energy accounting options should be representative. Residential buildings use many types of energy in the operation stage, and it is impractical to treat every type of energy as an option for carbon emission accounting, so it is necessary to select the main energy sources for accounting. Carbon emission accounting for residential buildings requires a large amount of data support, and in selecting carbon emission accounting options, it is necessary to consider the reliability and availability of data to ensure the accuracy of the calculation results.

(2) Types of energy consumption and data sources

Due to different energy structures in different regions and provinces, the types of energy consumed in the operation phase of residential buildings are different and varied. This paper analyzes the literature and conducts field surveys, and selects 11 types of energy, including raw coal, coal, coke, gasoline, kerosene, diesel, liquefied petroleum gas (LPG), natural gas, heat, and electricity, as the accounting options for the carbon emissions of residential buildings in severe cold regions.

#### II. C. 3) Carbon Emission Measurement Modeling for Residential Buildings

The carbon emissions generated by residents' life during the operation phase of residential buildings are mainly divided into carbon emissions from living energy consumption and carbon emissions from electricity energy consumption. The total carbon emissions from residential buildings in cities and towns in severe cold areas also include carbon emissions from centralized heating heat consumption in winter, and the specific calculation formula is as follows:

$$C = C_1 + C_2 + C_3 \tag{3}$$

where $C$ is the total carbon emission from urban residential buildings in the cold region, $C_1$ is the carbon emission from domestic energy consumption, $C_2$ is the carbon emission from electric power energy consumption, and $C_3$ is the carbon emission from centralized heating thermal energy consumption in the north.

(1) Measurement of carbon emissions from domestic energy consumption

According to the carbon emission coefficient method, the formula for calculating carbon emissions from living energy consumption consumption of urban residential buildings is as follows:

$$C_1 = \sum_{i=1}^{k} s_i \cdot a_i \tag{4}$$

where $k$ is the number of energy types, $s_i$ is the consumption of the $i$ th type of energy, and $a_i$ is the carbon emission coefficient of the $i$ th type of energy.

(2) Measurement of carbon emissions from electricity energy consumption consumption

Electricity consumption refers to the total amount of electricity used by an individual, organization or country in a certain period of time. Electricity energy is a kind of secondary energy, which needs to be generated through the conversion of primary energy such as coal, natural gas, hydro wind and so on. The specific formula for calculating carbon emissions from electricity energy consumption is as follows:

$$C_2 = e \cdot d \tag{5}$$

where $e$ denotes the electricity consumption and $d$ denotes the electricity carbon emission coefficient.

(3) Measurement of carbon emissions from thermal energy consumption and consumption

In this paper, the total of “total hot water heating” and “total steam heating” are chosen to represent the heat consumed by centralized heating in urban residential buildings in cold regions. The formula for calculating the carbon dioxide produced by centralized heating in urban residential buildings in cold regions in winter is as follows:

$$C_3 = (h_1 + h_2) \cdot q_h \tag{6}$$

where $h_1$ is the total amount of steam heat supply, $h_2$ is the total amount of hot water heat supply, and $q_h$ is the thermal carbon emission factor.

## III. Results of the simulation and accounting of carbon emissions from the operation of residential buildings

The simulated carbon emissions of each household type month by month are shown in Fig. 1. The total carbon emissions of the five types of households show the trend that the larger the size of the household type, the larger the average household carbon emissions, such as the 150 household type, which has the highest carbon emissions of the whole year, which is 1408.6 kg, between December and January. In addition, carbon emissions in winter are much higher than those in other seasons, and the annual peak of carbon emissions occurs in November-January; in summer, there are small peaks in July and August, but the carbon emissions are much smaller than the total in winter; and the evidenced operational carbon emissions in spring and fall are generally low, and there is a trough of carbon emissions in March, April, and October. The reason for this phenomenon is closely related to changes in temperature. Because users will turn on the air conditioner to cool down when it is too hot in summer, and turn on the air conditioner to warm up when it is too cold in winter, but the process of heat production spends more electricity than the process of cooling down, thus showing the phenomenon of lower carbon emissions in summer than in winter.

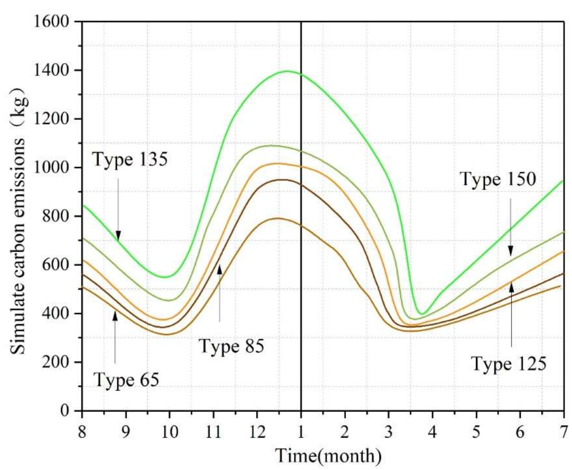


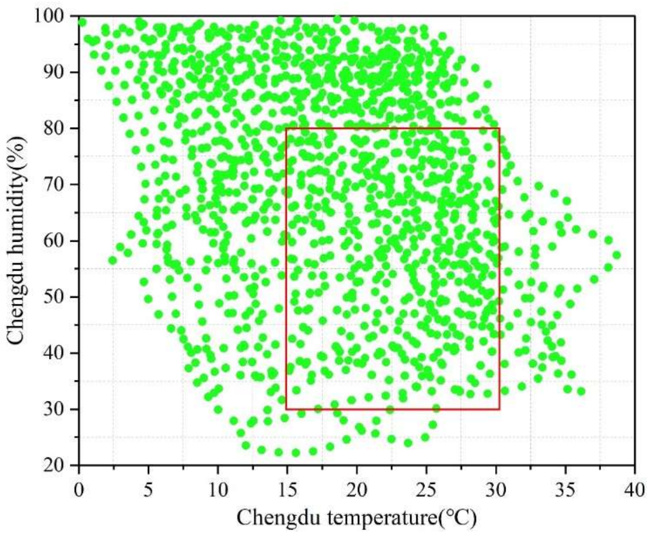

Figure 1: Each household model operates carbon emissions month by month

## IV. Integrated Sensitivity Analysis of Carbon Emissions and Thermal Comfort in Residential Buildings

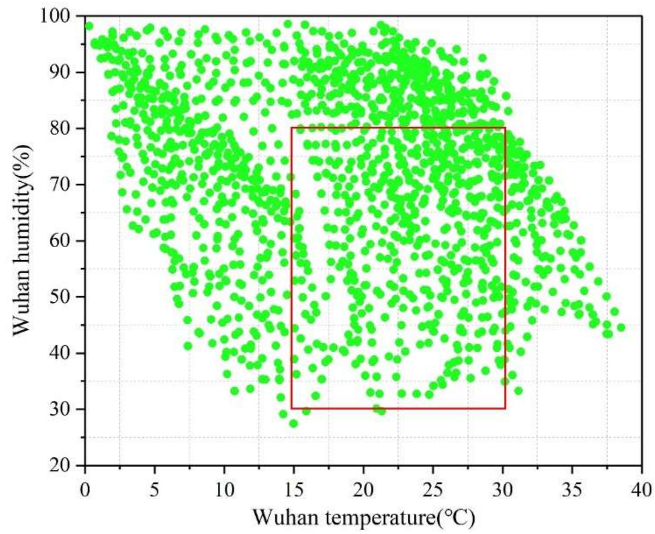
### *IV. A. Weather analysis*

Three typical cities in the hot summer and cold winter regions were selected to calculate their thermal comfort and carbon emissions using the same building model simulation, with the only variable being the EPW weather file from EnergyPlus. The data in the anomaly and whisker line intervals are taken from periods of higher or lower temperatures, most of which are periods of unnatural ventilation; while the data located in the boxed intervals are periods of natural ventilation.

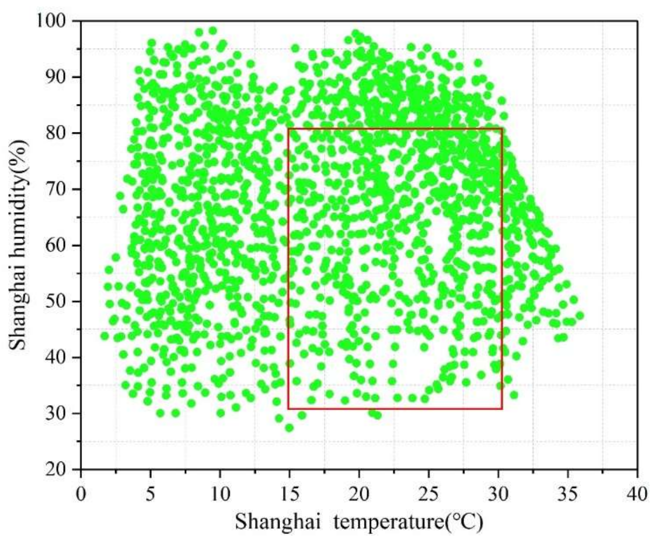
In order to better analyze the meteorological data of different cities, Fig. 2 shows the scatter plot of temperature and humidity in typical cities, where (a) to (c) represent Chengdu, Wuhan and Shanghai, respectively, and the red rectangles in the figure represent the thermal comfort zones. The red rectangles represent the thermal comfort zones. The same thermal comfort zones are used for comparative observation, but the actual thermal comfort zones of each city are different in the calculation. After removing non-natural ventilation time and unoccupied time, the number of points that do not fall into the box (thermal comfort zone) is calculated and counted as the number of uncomfortable hours per year.




(a)Chengdu




(b)Wuhan




(c)Shanghai

Figure 2: Typical urban temperature and humidity scatter diagram

### *IV. B. Analysis of Carbon Emission Simulation Results for Different Cities*

The carbon emissions and total hours of thermal discomfort in typical cities are shown in Table 1. Wuhan, located in the central region, has the highest annual total carbon emission of 93127.83 kg, and the total carbon emission gradually decreases from the center to the west and to the east. The western city of Chengdu has a carbon emission of 76216.06 kg, a decrease of 18.16%. The carbon emissions of the easternmost city, Shanghai, were 81,730.77 kg, a decrease of 12.24%. The trend of carbon emissions from refrigeration in summer is the same as the total emissions, and Wuhan, Chengdu and Shanghai have the highest carbon emissions from refrigeration in summer, reaching 50565.61 kg, 15780.54 kg and 42449.10 kg respectively, with Chengdu and Shanghai having a decrease of 29.75% and 19.12% respectively compared to Wuhan. The carbon emission of heating in winter is smaller than that of cooling in summer, so hot summer and cold winter areas should focus on strengthening the cooling performance of air conditioners. In terms of the annual thermal discomfort index, Chengdu's annual discomfort hours are as high as 670.70h, while Shanghai's annual thermal discomfort hours are much lower than those of other cities, only 278.73h.

Table 1: Typical urban carbon emissions and thermal discomfort total hours

| Index | Chengdu | Wuhan | Shanghai |
|---|---|---|---|
| Total carbon emissions(Kg·$CO_2$) | 76216.06 | 93127.83 | 81730.77 |
| Refrigerating carbon emissions(Kg·$CO_2$) | 35520.36 | 50565.61 | 42449.10 |
| Heating emissions(Kg·$CO_2$) | 15780.54 | 16996.61 | 14140.27 |
| Annual discomfort hours(h) | 670.70 | 618.27 | 278.73 |

### *IV. C. Analysis of results of different sensitivity analysis methods*

Scientific sampling of input parameters is an important process in sensitivity analysis, using Simlab software, sampling samples were generated based on the input parameters and their ranges, and discrete value samples were generated by five different sampling methods, eFAST, Sobol, LHS, Random and M orris. Out of these, 1900 samples were taken by eFAST, 1670 samples were taken by Sobol, 2050 samples were taken by LHS, 2040 samples were taken by Random and 300 samples were taken by Morris. JEPlus builds the model in EnergyPlus after receiving the samples created by Simlab, and the total simulation time is 550 h. The simulation results are sent back to Simlab for sensitivity analysis, and the sensitivity analysis indices are shown in Table 2.

Table 2: Sensitivity analysis index

| Type | Sampling method | Sensitivity index |
|---|---|---|
| Based on the sensitivity method of regression | LHS, Random | PEAR |
| | | PCC |
| | | SRC |
| Based on the return sensitivity index (rank transform) | LHS, Random | SPEA |
| | | SRRC |
| | | PRCC |
| Regional sensitivity analysis | LHS, Random | Smirmov |
| Sensitivity method based on variance | SOBOL | SOBOL |
| | FAST | First-Fast |
| | FAST | Total-Fast |
| Filter based sensitivity method | Morris | Morris |

### *IV. D. Analysis of variance results and F-test results*

The F-test values for the different sensitivity results are shown in Figure 3. Although the average dataset does not necessarily represent the most accurate sensitivity values, it can represent the most average and reliable values, both to avoid the effect of the large differentiation of impact parameters by FAST and SOBOL and to minimize the effect of over-rating of unimportant impact parameters in Smirnov. The first-order F-eFAST has the smallest variance value (0.0038) among all sampling methods, followed by Sobol (0.048), R-SRRC, R-PCC, and LHS-PCC,whose F-values range from 0.0038- 0.072, the above are the sensitivity analysis methods that are more differentiated from the mean data set.LHS-PEAR, LHS-SPEA, LHS-SRRC, and Morris have F-test values above 0.6.LHS -PEAR and LHS-SPEA were closest to the mean data set in the variance test, reaching 0.7876 and 0.7246, respectively.Therefore, the results of the F-tests are recommending the PEAR and SPEA sensitivity analysis methods based on Latin Hypercubic Sampling as the more reliable sensitivity analysis methods to obtain the closest to the data to the mean value.

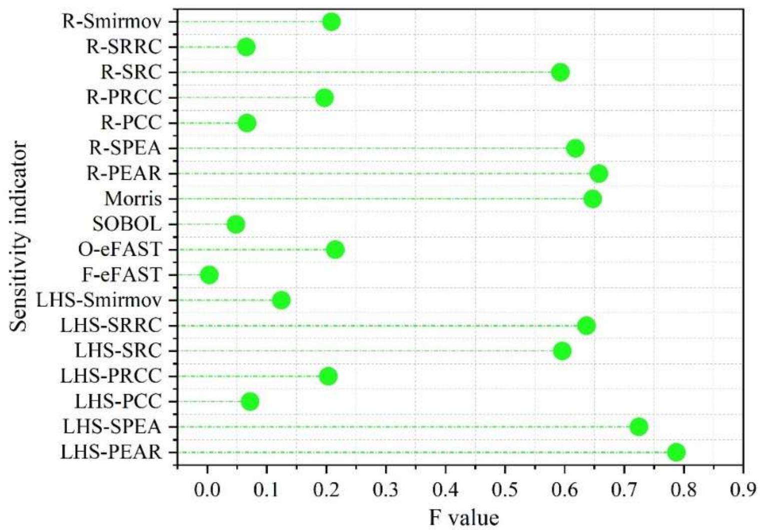



Figure 3: *F* test value of different sensitivity results

## V. Modeling of factors influencing carbon emissions from buildings

The carbon emissions of the whole life cycle of a building can be divided into material production stage, construction stage, operation stage and demolition stage according to different stages. According to the existing literature research, the material production stage and operation stage account for 96% of the carbon emission of the building. Since the carbon emission of the material production stage is greatly influenced by the carbon emission coefficient of the building materials [26], and the carbon emission coefficient of the building materials is closely related to the level of the material production technology, which belongs to the industrial category, therefore, this paper only researches the carbon emission influencing factors of the operation stage.

### *V. A. Model for measuring carbon emissions from buildings*

Carbon emissions from buildings in the operation stage mainly come from building energy consumption, and carbon emissions from energy consumption are calculated based on energy consumption and carbon emission coefficients of different energy sources. According to the existing research experience, the energy carbon emissions in the operation stage are mainly counted in residential buildings and public buildings; in residential buildings, they are divided into urban residential buildings and rural residential buildings; considering that a large amount of energy consumption is needed to carry out winter heating in Henan Province in winter, the carbon emissions in the operation stage are divided into four parts, namely, urban residential buildings, rural residential buildings, public buildings and winter heating, for calculating the carbon emissions of the operation stage of the building:

$$Y = \sum_{j=1}^{n} Q_{1j} + \sum_{j=1}^{n} Q_{2j} + \sum_{j=1}^{n} Q_{3j} + \sum_{j=1}^{n} Q_{4j} \tag{7}$$

where $Y$ is the total carbon dioxide emissions in the operation stage, $j$ denotes the carbon emissions of energy in category $j$, $Q_{1j}$ is the carbon dioxide emissions of energy consumption in category $j$ of urban residential buildings, $Q_{2j}$ is the carbon dioxide emissions of energy consumption in category $j$ of rural residential buildings, and $Q_{3j}$ CO2 emissions from energy consumption in public buildings, category $j$, $Q_{4j}$ CO2 emissions from energy consumption in winter heating, category $j$.

### *V. B. Analysis of factors affecting carbon emissions*

(1) Selection of influencing factors

In order to study the influence factors of regional carbon emissions, this paper studies from the macro aspect. Based on the existing research results, it is found that the influencing factors of building carbon emissions are mostly analyzed from the dimensions of population, economy and technology. Based on the principles of science, authenticity and data availability, this paper chooses population dimension indicators (number of resident population, urbanization rate), economic dimension indicators (per capita GDP, per capita tertiary industry value added), and technology dimension indicators (carbon emissions per unit of building area) as the influencing factors of building carbon emissions.

(2) Modeling of influencing factors of building carbon emission

The IPAT model for environmental stress control [27] is formulated as $I = P \times A \times T$ , where $I$ is the dependent variable, which represents the impact of each factor on the environment; $P, A, T$ are the three influencing factors, $P$ is the demographic factor, $A$ is the degree of affluence, and $T$ is the technological factor. Since the IPAT model is a constant equation that only responds to the influence factors acting singularly on the environment in the form of a product, in order to overcome the limitations of this model, Dietz and Rosa improved the IPAT model into a model for environmental impact assessment (STIRPAT), which applies the elasticity coefficients to solve the influence of each influence factor on the environment, with the formula $I = aPbAcTde$ , where, $a$ denotes the model coefficients, $b$ denotes the population driving force index, $c$ denotes the affluence index, $d$ denotes the technology driving force index, and $e$ is the model error. The STIRPAT model [28] is a nonlinear model with multiple indicator factors, which is usually treated logarithmically.

Combining the dependent variable and five influencing factors in this paper, the model of influencing factors of building carbon emission is constructed, and it is taken as natural logarithm:

$$\ln Y = a + b\ln X_1 + c\ln X_2 + d\ln X_3 + e\ln X_4 + f\ln X_5 + m \tag{8}$$

where $Y$ denotes the CO2 emission in the building operation stage, $X_1$ denotes the population size, $X_2$ denotes the urbanization rate, $X_3$ denotes the per capita GDP, $X_4$ denotes the per capita value of value added of the tertiary industry, $X_5$ denotes the carbon emission per unit of building area, $a$ denotes the constant term, $b, c, d, e$ denote the coefficients of each indicator, and $m$ denotes the error term.

# VI. Empirical analysis of the STIRPAT model of carbon emission influencing factors

## *VI. A. Ordinary Least Squares Results*

The results of ordinary least squares regression are shown in Table 3. From the table: $R^2$=1, the analysis of the results of the F-test can be obtained, the significance P-value = 0.0000, presenting significance at the level of 0.001, the model meets the requirements. For variable covariance performance, all variables VIF>10, there is a covariance relationship, in order to eliminate the problem of multiple covariance for ridge regression analysis.

Table 3: Common least squares regression results

| Variable | Nonnormalized coefficient | | Normalization factor | *t* | *P* | *VIF* | $R^2$ | Adjust $R^2$ | *F* |
|---|---|---|---|---|---|---|---|---|---|
| | B | SE | Beta | | | | | | |
| Constant | -3.9299 | 0.1038 | | -37.8002 | 0 | | 1 | 1 | F=31282685.502<br>P=0.0000 |
| $X_1$ | 0.0233 | 0.0149 | 0.0022 | 1.5035 | 0.1771 | 446.3156 | | | |
| $X_2$ | 0 | 4E-4 | 0 | -0.3618 | 0.728 | 16.3071 | | | |
| $X_3$ | -0.001 | 0.032 | -0.0019 | -0.044 | 0.9663 | 362067.4676 | | | |
| $X_4$ | -0.0013 | 0.0059 | -0.0019 | -0.2028 | 0.8466 | 16897.4842 | | | |
| $X_5$ | 1.0048 | 0.0324 | 0.8079 | 31.5707 | 0 | 184138.6426 | | | |

## *VI. B. Ridge regression results and analysis*

Ridge regression analysis is an improved algorithm for the least squares method, which solves the problem of multicollinearity, and the results of ridge regression are shown in Table 4. The variance expansion factor method determines that the standardized regression coefficient region is stable at K=0.0407, and the smaller K the better the stability. Based on the F-test significance P-value = 0.0000, presenting significance at the 0.001 level, the original hypothesis is rejected, indicating that there is a regression relationship between the independent variables and the dependent variable. Meanwhile, the model's goodness-of-fit $R^2$ is 0.9999, and the model performs very well.

According to the regression coefficients of the model, it can be seen that: the regression coefficients of population size, urbanization rate, per capita GDP, per capita added value of tertiary industry and carbon emissions per unit of building area are positive, then the increase of all these factors will contribute to the increase of carbon emissions from the operation of the residential buildings in the severe cold region. In view of this, we should pay more attention to the development of new energy sources to suppress the increase of carbon emissions from the operation of residential buildings.

Table 4: Ridge regression

| Variable | Nonnormalized coefficient | | Normalization factor | $t$ | $P$ | $R^2$ | Adjust $R^2$ | $F$ |
|---|---|---|---|---|---|---|---|---|
| | B | SE | Beta | | | | | |
| Constant | -14.0003 | 3.1083 | | -4.5326 | 0.0000 | 0.9999 | 0.9997 | F=195.273 P=0.0000 |
| $X_1$ | 1.7122 | 0.3754 | 0.1423 | 4.35 | 0.0000 | | | |
| $X_2$ | 0.1814 | 0.1084 | 0.0748 | 1.6604 | 0.1202 | | | |
| $X_3$ | 0.1608 | 0.017 | 0.1839 | 10.0482 | 0.0000 | | | |
| $X_4$ | 0.1408 | 0.0119 | 0.1812 | 12.6379 | 0.0000 | | | |
| $X_5$ | 0.3906 | 0.0277 | 0.3131 | 14.435 | 0.0000 | | | |

## VII. Conclusion

The carbon emissions of ultra-low-energy residential buildings in severe cold regions are closely related to factors such as building area, types of energy consumption, and climatic conditions. The empirical study shows that the 150-unit model has the highest carbon emission in winter, amounting to 1408.6 kg, and the carbon emission in winter is much higher than that in other seasons, especially in the peak period from November to January. In the comparison of different cities, Wuhan has the highest carbon emission of 93127.83 kg, while Chengdu and Shanghai have 76216.06 kg and 81,730.77 kg, respectively, indicating that climatic factors have a significant impact on carbon emission. For summer cooling demand, Chengdu and Shanghai decreased their carbon emissions by 29.75% and 19.12% respectively compared to Wuhan, which shows the difference in energy demand between different cities.

In addition, the ridge regression analysis reveals that factors such as population size, urbanization rate, per capita GDP and carbon emissions per unit of building area have a significant positive effect on building carbon emissions. Therefore, it is important to promote the development of new energy technologies and the improvement of building energy-saving technologies to reduce the carbon emissions of residential buildings. Policy-level support for low-energy building design should be strengthened and the application of green building materials and technologies should be promoted in order to reduce building carbon emissions and facilitate the realization of the goal of carbon neutrality.

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