Analysis of Factors Affecting Carbon Emissions from Buildings in Sichuan Province

Yue Zhang* and Hao Tang

Chengdu University of Technology, Chengdu, China

Email: zhangyue20240129@163.com (Y.Z.); t394865556@163.com (H.T.)

*Corresponding author

Manuscript received December 17, 2024; revised January 14, 2025; accepted February 4, 2025, published February 25, 2025.

***Abstract*—In the context of energy efficiency management, this paper focuses on unravelling the influencing factors of building carbon emissions in Sichuan Province. To achieve this, this paper measures the carbon emissions from buildings in Sichuan Province from 2010 to 2021 using the emission factor method, identifies the influencing factors of carbon emissions using the IPAT constant equation, and applies grey correlation analysis to calculate the correlation between each influencing factor and carbon emissions. The results show that: (1) the total carbon emissions from buildings in Sichuan Province show a fluctuating growth from 2010 to 2021, in which the carbon emissions decreased significantly in 2015, which is related to the promulgation of relevant policies in 2014. (2) Indirect carbon emissions dominate construction carbon emissions in Sichuan Province. (3) The main factors affecting construction carbon emissions in Sichuan Province, in order of importance, are: urbanisation rate, industry scale, completed area, number of people employed in the construction industry, labour efficiency, GDP per capita, indirect carbon emission intensity, scale effect, technology and equipment rate, gross construction output value, building material consumption intensity, and energy intensity. The results of this paper enrich the research on carbon emissions in Sichuan's construction industry. In the realm of energy-efficiency management, they provide a key basis for selecting indicators to assess the industry's carbon-emission-reduction potential. Additionally, they offer theoretical support for promoting more effective carbon-emission-reduction efforts centered on energy-efficiency improvements in the industry.**

***Keywords*—building carbon emissions, emission factor approach, IPAT (Impact=Population*Affluence x*Technology) constant equation, grey correlation analysis**

I. Introduction

In recent years, the problem of global warming has attracted worldwide attention, and people's attention has begun to shift to the carbon dioxide emissions caused by human activities [1]. As the world's largest carbon emission country, China embodies the role of a big country in the global carbon emission reduction action, and promises to 'achieve carbon peak by 2030, and achieve carbon neutrality by 2060' [2]. In the face of the severe pressure to reduce emissions, it is crucial to study the current status of carbon emissions in China and propose corresponding emission reduction measures to achieve the 'dual carbon' goal. As an important pillar of China's socio-economic development, the construction sector is characterised by high energy consumption and high emissions, with its energy consumption accounting for about 30% of the total energy consumption and carbon emissions accounting for 27.9%–34.3% of the total carbon emissions, and thus the construction sector has brought about tremendous pressure on China's carbon emission reduction [3]. However, the construction industry is considered to have enormous potential for improving energy efficiency and is a key industry that China pays close attention to in its carbon emission reduction efforts. Therefore, it is of great significance to explore the influencing factors of building carbon emissions to analyse the potential of building carbon emission reduction and study the path of carbon emission reduction [4].

Currently, the main methods for measuring building carbon emissions are: the input-output method (SDA, Structural Decomposition Analysis), the whole life cycle method, and the carbon emission factor method. Zhang *et al.* [5] used the full life cycle method to calculate China's building carbon emissions from 2004–2018, and analysed the spatial and temporal evolution characteristics and clustering effects of building full life cycle carbon emissions in each province and the three major regions. Shang *et al.* [6] measured the direct carbon emissions and indirect carbon emissions of buildings in Hainan Province from 1993 to 2013 based on the input-output method. Yu *et al.* [7] measured the total carbon emissions and carbon emissions from fossil energy, secondary energy and building materials of the four major national urban agglomerations based on panel data from 2009–2019 using the carbon emission coefficient method.

Scholars have used different methods to analyse the influencing factors of building carbon emissions, mainly including the mean split index (LMDI, Logarithmic Mean Divisia Index) decomposition method, grey correlation analysis method and STIRPAT model [8]. Feng and Wang used the LMDI decomposition method to decompose the carbon emissions from buildings in each region of China, and concluded that the output scale effect of the building sector is the main contributor to the growth of carbon emissions from buildings in each province, that indirect carbon emissions are the main source of carbon emissions from buildings in China, and that the effect of the energy structure of buildings in each province, and the effect of the intensity of the carbon emissions from energy, have a weak positive or negative impact on carbon emissions [9]. Gao Sihui *et al.* used grey correlation analysis to conclude that the factors affecting China's building carbon emissions, in descending order, are: industrial structure, output value of the building sector, GDP per capita, urbanization rate, living standards, energy emission intensity, total population, building energy consumption, area of buildings completed in the building sector, GDP, per capita housing floor area in cities and towns, and the number of people employed in the building sector [10]. Guo *et al.* based on grey correlation analysis derived that the correlation between construction carbon emissions and related factors, from largest to smallest, were technical equipment rate, number of employees, GDP, population size, and total output value of the construction sector [11]. Zhang and others used the STIRPAT model to analyse the influencing factors of construction carbon emissions in Gansu Province, and the results showed that: changes in the number of people employed in the construction sector, urbanisation rate, per capita GDP of the construction sector, gross construction product, and carbon emission intensity all promote the growth of construction carbon emissions, among which the urbanisation rate and the intensity of carbon emissions have a greater impact on the construction carbon emissions; the technological equipment rate of the construction sector increase inhibits the growth of construction carbon emissions, but its influence is smaller [12]. In the past, scholars have mostly explored the factors affecting building carbon emissions from the national level, but there are large differences in the level of building carbon emissions in China among various provinces and regions [3, 4, 6]. Therefore, this paper takes the construction sector in Sichuan Province as the research object, establishes its carbon emission accounting model by using the carbon emission factor method, and measures the carbon emissions of the buildings in Sichuan Province; combines the IPAT model and the literature research to identify the factors affecting its carbon emissions; then uses the grey correlation analysis method to calculate the correlation between the carbon emissions and the factors affecting them; and finally, combines the results of the calculations to evaluate the potential of the factors for carbon emission reduction and puts forward the measures to promote the carbon emission reduction of buildings in Sichuan Province.

II. METHODOLOGY

A. Emission Factor Approach

The emission factor method is derived from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories published by the IPCC, and is one of the widely used measurement methods at present. Its basic idea is to construct the corresponding consumption and emission factor for each emission source based on the carbon emission inventory list, and the product of consumption and emission factor is used as the estimated carbon emission value of the source. The data acquisition and calculation of the emission factor method is relatively simple, and the emission factor of each energy source has already had relatively mature standards for taking values, and most of the relevant indexes have already been provided in the official guidelines of the IPCC, so the calculation results obtained by this method are more accurate and have a higher authority.

B. Grey Correlation Analysis

Grey system theory is a system science theory proposed by Professor Deng Julong in 1982, grey correlation analysis is an analytical method of grey system theory, which is used to solve multifactorial and nonlinear problems, and its basic idea is to judge whether the connection is close or not based on the degree of similarity of the geometrical shape of the sequence curves; the closer the curves are, the greater the correlation between the corresponding sequences are, and vice versa, the smaller the correlation is [13].

China's statistical data are very limited, the existing data are grey, and many of them are subject to several ups and downs, without typical distribution patterns and other problems. Therefore, it is often difficult to be effective using mathematical and statistical methods. Grey correlation analysis then makes up for this shortcoming, it does not have strict requirements on the number of sample size and the regularity of the sample, and the calculation is small, there will not be quantitative results do not match the qualitative analysis results.

Grey correlation analysis is done in the following steps:

1) *Confirm the analysis of the sequence*

Determine the reference sequence that reflects the behavioral characteristics of the system:

$$X_0 = (x_{0(1)}, x_{0(2)}, \cdots x_{0(n)})^T \tag{1}$$

Determine the comparative sequence that affects the behavior of the system:

$$\begin{gathered} X_1, X_2, \cdots X_m \\ X_1 = (x_{1(1)}, x_{1(2)}, \cdots x_{1(n)})^T \\ \cdots \\ X_m = (x_{m(1)}, x_{m(2)}, \cdots x_{m(n)})^T \end{gathered} \tag{2}$$

2) *Preprocess the data*

$$x'_{it} = \frac{x_{it}}{\frac{1}{n}\sum_{t=1}^{n} x_{it}} (i = 0, 1, \cdots, m; t = 1, 2, \cdots n) \tag{3}$$

3) *Calculate the correlation coefficients between each indicator in the comparative sequence and the reference sequency*

$$\begin{gathered} a = \min_{i=1}^{m} \min_{t=1}^{n} |x'_{it} - x'_{0t}| \\ b = \max_{i=1}^{m} \max_{t=1}^{n} |x'_{it} - x'_{0t}| \\ \gamma(x'_{0t}, x'_{it}) = \frac{a + \rho b}{|X'_i - X'_0| + \rho b} \end{gathered} \tag{4}$$

where $\boldsymbol{\rho}$ is the resolution coefficient, generally taken as 0.5.

4) *Calculate the grey relational degree* γ'

$$\gamma'(X_0, X_i) = \frac{1}{n}\sum_{t=1}^{n} \gamma(x'_{0t}, x'_{it}) \tag{5}$$

5) *Analyze the results by comparing the degrees of correlation.*

III. DATA

In this paper, the relevant data of Sichuan Province from 2007 to 2021 are selected for analysis. The terminal consumption of each energy source in the construction sector in Sichuan Province is taken from the regional energy balance table in the China Energy Statistical Yearbook; the consumption of each building material, the gross construction output value, and the technical equipment rate are taken from the China Construction Industry Statistical Yearbook; the default carbon dioxide emission factor of each energy source for combustion is taken from the '2006 IPCC Guideline Catalogue for National Greenhouse Gas Inventories'; the average low-level heat generation of each energy source is taken from the 'General Principles for Calculation of Comprehensive Energy Consumption General Rules for Calculation of Comprehensive Energy Consumption (GB/T2589-2020); correlation coefficients of asphalt are from Standard for Calculation of Carbon Emissions from Buildings; carbon emission factors of electricity are from Study on Carbon Dioxide Emission Factors of China's Regional Electricity Grids (2023); and the number of employed persons in the construction sector in Sichuan Province, the urbanisation rate, the GDP per capita, the regional economic output value, and the construction area are from the Statistical Yearbook of Sichuan Province.

IV. Empirical Results

A. Carbon Emissions Measurement

At present, there is no data related to carbon emissions in the relevant indicators published by the national and provincial governments, so it is impossible to obtain building carbon emissions directly, so it is necessary to construct a carbon emission accounting model to measure building carbon emissions in Sichuan Province. In this paper, building carbon emissions are divided into two parts: direct carbon emissions and indirect carbon emissions. Direct carbon emissions refers to the carbon emissions of various energy sources directly consumed by the building's own activities, this paper selects the energy terminal consumption of raw coal, coke, gasoline, paraffin, diesel, natural gas, electricity to measure the direct carbon emissions; indirect carbon emissions refers to the carbon emissions induced by the building sector to produce other industries, this paper takes the consumption of steel, cement, timber, glass, aluminium for the measurement of indirect carbon emissions. The measurement model is as follows:

$$C = C_{dir} + C_{ind} \tag{6}$$

$$C_{dir} = \sum_{i=1}^{8} C_i \cdot NCV_i \cdot CEF_i + C_e \cdot a + C_a \cdot b \cdot c \tag{7}$$

$$C_{ind} = \sum_{i=1}^{5} C_j \cdot d_j \cdot (1 - \alpha_j) \tag{8}$$

In the above equation: C_{dir} indicates total direct carbon emissions from buildings (tonnes); C_{ind} shows total indirect carbon emissions from buildings; C_i indicates the end–use consumption of the ith energy source of the building (in tonnes); C_j indicates the amount of building materials consumed for the jth building; NCV_i denotes the average low-level heating value of the i th energy source (kJ/kg); CEF_i denotes the default CO_2 emission factor for the i th energy source (kg/kJ); C_e indicates end-use consumption of building electricity ($10^8 kW \cdot h$); a indicates the CO_2 emission factor for electricity (kg/kWh); C_a indicates end-use consumption of construction petroleum asphalt (tonnes); b indicates the carbon content per unit calorific value of petroleum asphalt (tC/TJ); c denotes the carbon emission factor per unit calorific value of petroleum asphalt (tCO_2/TJ); d_j denotes the carbon emission factor of the j th building material (kg/kg or kg/m^3); and α_j denotes the recovery factor for the j th building material. Average low-level heat generation and carbon emission factors for energy are shown in Table 1:

Table 1. Average low-level heat generation and carbon emission factors for energy

Type of Energy	Average low-level heat generation (kJ/kg or kJ/m^3)	carbon emission factors ((kJ/kg))
Raw coal	20934	95977.2
Coke	28470	10700
Petrol	43124	7033.3
Diesel	43124	71500
Diesel oil	42705	74066.7
Gas	35608.5	56100

The carbon content per unit calorific value of bitumen is $22.0 tC/TJ$, and its carbon emission factor per unit calorific value is $79.05 \, tCO_2/TJ$. The carbon emission factors for electricity in Sichuan Province in 2010, 2012, 2018 and 2020 were $0.289 \, kg/kWh$, $0.248 \, kg/kWh$, 0.103, $0.117 \, kg/kWh$. Carbon emission factors and recovery factors for major building materials are shown in Table 2.

Table 2. Carbon emission factors and recovery factors for major building materials

Types of building materials	Carbon emission factor (kg/kg or kg/m^3)	Recovery factor
Steel	1.789	0.80
concrete	0.822	/
lumber	−842.800	0.85
nylon	1.130	0.80
aluminium	2.600	0.85

From Eqs. (6) to (8), the direct carbon emissions, indirect carbon emissions and total carbon emissions from buildings in Sichuan Province from 2010 to 2021 are calculated as shown in Table 3:

Table 3. Carbon Emission Measurement Results in Sichuan Province, 2010–2021

Year	Direct carbon emissions (tonnes)	Imdirect carbon emissions (tonnes)	Total carbon emissions (tonnes)
2010	296.72	10253.77	10550.49
2011	378.54	12520.32	12898.86
2012	524.77	18640.49	19165.27
2013	506.79	20520.95	21027.74
2014	613.72	22651.35	23265.07
2015	658.72	10038.77	10697.48
2016	781.35	11129.84	11911.19
2017	859.67	14357.83	15217.50
2018	931.30	17964.25	18895.55
2019	987.10	18467.02	19454.13
2020	1008.45	19326.95	20335.39
2021	1005.27	19058.87	20064.14

As can be seen from Fig. 1, the total carbon emissions from buildings in Sichuan Province from 2010 to 2021 show a fluctuating growth trend, in which the total carbon emissions from 2011–2014 show a year-on-year growth trend, and the total carbon emissions in 2014 reached the highest value in these 12 years, and the carbon emissions in 2015 declined sharply, and thereafter continued to increase year by year until 2020, but the increase compared with the pre-2015 period has slowing down, with a slight decline in total carbon emissions by 2021. Among them, the significant decline in carbon emissions in 2015 was mainly due to Sichuan Province's active response to the 2014–2015 energy conservation and emission reduction and low-carbon development actions, promoting building energy conservation and carbon reduction, and carrying out in-depth green building actions. At the same time, it has increased efforts to eliminate backward production capacity, strictly controlled total coal consumption, accelerated the clean and efficient use of coal, and vigorously developed non-fossil energy.

As can be seen from Fig. 1, carbon emissions from buildings in Sichuan Province mainly come from indirect carbon emissions, which account for about 95%, and the trend of change is basically the same as the total carbon emissions, indicating that the indirect carbon emissions from buildings make the greatest contribution to the total amount of carbon emissions, which is the key to exploring the potential of carbon emission reduction in buildings as well as the path of carbon emission reduction.

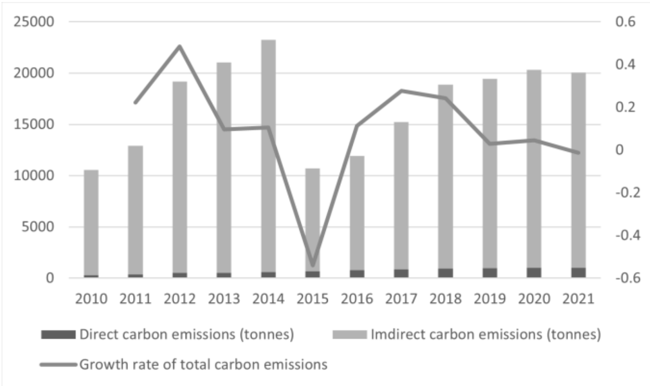

Fig. 1. Total building carbon emissions and annual growth rate in Sichuan province, 2010–2021.

B. Analysis of Factors Affecting Carbon Emissions

Reviewing the previous literature on carbon emission influencing factors, combined with the IPAT constant equation, this paper classifies the building carbon emission influencing factors into three categories, which are demographic factors, economic factors and technological factors. As shown in Table 4:

Table 4. Factors affecting carbon emissions from buildings in Sichuan Province

	Factor	Meaning
Demographic factors	Number of persons in construction sector (X_1)	/
	Urbanisation rate (X_2)	Urban population/total population
Economic factors	GDP per capita (X_3)	/
	Industrial scale (X_4)	Gross construction output/gross regional economic output
	Scale effect (X_5)	Construction area/building output
	Completed area (X_6)	/
	Gross construction output (X_7)	/
Technical factor	Energy carbon intensity (X_8)	Energy CO_2 emissions/gross building value
	Technology readiness rate (X_9)	Net value of owned machinery and equipment at the end of the year/number of persons employed in the construction sector
	Intensity of consumption of building materials (X_{10})	Consumption of building materials/gross construction output
	Labour efficiency (X_{11})	Gross construction output/number of persons employed in the construction sector
	Indirect carbon intensity (X_{12})	Indirect CO_2 emissions/gross building value

The carbon emissions of Sichuan Province were taken as the reference series, and the influencing factors X1–X12 were taken as the comparative series, and the grey correlation was calculated by applying Eqs. (1)–(6). The results are showed in Table 5.

Table 5. Grey correlation calculation results

Factor	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}
Relatedness	0.784	0.817	0.739	0.805	0.727	0.802	0.684	0.624	0.710	0.683	0.782	0.728

The calculation results in Table 5 show that the correlation between the carbon emission influencing factors identified in this paper and the total amount of carbon emissions is in the range of 0.62–0.82, which is a strong correlation, indicating that the selection of indicators is reasonable and reliable, and providing a strong basis for the selection of indicators for evaluating the potential of carbon emission reduction in Sichuan Province's buildings.

The correlation of urbanisation rate, industrial scale, completed area, and the number of employees in the construction sector are at the top of the overall indicator system. Generally speaking, an increase in the level of urbanisation promotes the demand for housing, transport and other infrastructure construction, leading to an increase in the scale of the construction industry and the area of completion, as well as an increase in the number of people employed in the construction sector, which leads to a continuous increase in the carbon emissions from the construction sector.

The higher correlation of labour efficiency is due to the sloppy management mode of the construction sector. The sloppy management model makes it impossible for enterprises to clearly grasp the situation of workers, which greatly reduces the labour efficiency and increases the cost investment. Therefore, shifting the management mode of the construction sector from crude to intensive will strongly improve labour efficiency and promote the construction sector to shift to a low-carbon mode.

Indirect carbon emission intensity and technical equipment rate also have a high correlation with carbon emissions, this is because of the low level of construction development in Sichuan Province, the construction materials are still mainly traditional energy-intensive materials, so that the indirect carbon emission intensity of the construction is much higher than the direct carbon emission intensity, which accounts for a great proportion of the total carbon emissions, and the overall low level of technical equipment of the construction enterprises in Sichuan Province, and the low investment in technical equipment, which results in the rate of technical equipment has a certain influence on carbon emissions also have a certain impact.

V. Conclusion

In this paper, carbon emissions are measured based on relevant statistical data of the construction sector in Sichuan Province from 2010 to 2021, carbon emission influencing factors were identified using the IPAT constant equation, and the correlation between each influencing factor and carbon emissions is calculated using grey correlation analysis. The results show that: (1) the total carbon emissions from buildings in Sichuan Province showed a fluctuating growth from 2010 to 2021, and in 2015, the carbon emissions decreased significantly. (2) Indirect carbon emissions dominate in construction carbon emissions in Sichuan Province. (3) The influencing factors of construction carbon emissions in Sichuan Province, in descending order, are urbanisation rate, industrial scale, completed area, the number of employees in the construction sector, labour efficiency, GDP per capita, indirect carbon emission intensity, scale effect, technology and equipment rate, gross construction output value, building material consumption intensity, and energy intensity.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Zhang Yue conducted the research and wrote the paper; Zhang Yue and Tang Hao analyzed the data; both authors had approved the final version.

References

[1] J. Qin and N. Gong, "The estimation of the carbon dioxide emission and driving factors in China based on machine learning methods," *Sustainable Production and Consumption*, vol. 33, pp. 218–229, 2022.

[2] C. Piovani, "The "Greening" of China: Progress, limitations, and contradictions," *Journal of Contemporary Asia*, vol. 47, no. 1, pp. 93–115, 2017.

[3] B. Xu and B. Lin, "Reducing carbon dioxide emissions in China's manufacturing industry: A dynamic vector autoregression approach," *Journal of Cleaner Production*, vol. 131, pp. 594–606, 2016.

[4] H. Chen and C. Lu, "Research on the spatial effect and threshold characteristics of new-type urbanization on carbon emissions in China's construction industry," *Sustainability*, vol. 15, no. 22, 2023.

[5] Z. Y. Zhang, X. L. Yang, B. Q. Cai *et al.*, "Research on the spatial and temporal evolution characteristics of carbon emission in China's construction industry based on the whole life cycle," *Journal of Xi'an Electronic Science and Technology University (Social Science Edition)*, vol. 33, no. 1, pp. 24–33, 2023.

[6] C. J. Shang, J. Cai, Y. R. Liu *et al.*, "Research on carbon emission accounting analysis and prediction of construction industry in Hainan Province," *Environmental Engineering*, vol. 34, no. 4, pp. 161–165, 2016.

[7] Y. Z. Yu, P. Y. Shen, and Y. T. Li, "Spatial differentiation of carbon emissions from the construction industry and its decomposition effects in national-level urban agglomerations," *Xinjiang Finance and Economics*, vol. 4, pp. 19–28, 2022.

[8] Z. Ke and Y. Yin, "Tail risk alert based on conditional autoregressive VaR by regression quantiles and machine learning algorithms," 2024.

[9] B. Feng and X. Q. Wang, "Research on decoupling carbon emissions and influencing factors of construction industry in Chinese provinces," *China Population-Resources and Environment*, vol. 25, no. 4, pp. 28–34, 2015.

[10] S. H. Gao, Y. S. Liu, X. T. Li *et al.*, "Research on the influencing factors and prediction of carbon emission in China's construction industry," *Henan Science*, vol. 37, no. 8, pp. 1344–1350, 2019.

[11] Z. Guo, and J. Yin, "Carbon emission FORECAST of construction industry based on grey theory," *Academic Journal of Computing Information Science*, 2022.

[12] X. P. Zhang, S. F. Gao, C. L. Fu, "Carbon emissions from the construction industry and its influencing factors in Gansu Province based on the STIRPAT model," *Development Research*, vol. 6, pp. 171–176, 2016.

[13] Z. X. Wang and Q. Li, "Modelling the nonlinear relationship between CO_2 emissions and economic growth using a PSO algorithm-based grey Verhulst model," *Journal of Cleaner Production*, vol. 207, pp. 214–224, 2019.