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Research on Energy Efficiency and Carbon Reduction in the Construction Industry under the "Dual Carbon" Goal

-- Taking Jiangsu Province as an Example

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Abstract: This article focuses on the issue of building carbon emissions reduction in Jiangsu Province. Based on the building energy balance equation and the mathematical model of air conditioning work, weighted evaluation and principal component analysis methods are used to evaluate the energy efficiency of buildings, and the carbon emissions of the entire construction process in Jiangsu Province in 2023 are predicted. To achieve the "dual carbon" strategic goal, it is recommended that Jiangsu Province pay attention to the use of green and environmentally friendly materials and equipment in the design and construction process of low-carbon buildings, strengthen energy management and monitoring, encourage the use of renewable energy, improve building energy efficiency, and reduce energy consumption and carbon emissions. At the same time, the government should increase financial subsidies to support innovation in environmental protection technology and the development of low-carbon industries, promote the formation of a good atmosphere for society to participate in low-carbon energy conservation, and thus promote the sustainable development of the construction industry in Jiangsu Province.

Keywords: Dual carbon, Low carbon buildings, Annual carbon emissions, Building energy balance equation, Mathematical model of air conditioning operation.

1. Introduction

The "dual carbon" goal refers to China achieving carbon peak (i.e. no increase in total carbon dioxide emissions) by 2060 and achieving carbon neutrality (i.e. total carbon dioxide emissions equal to or lower than total absorption) within the following years. In this context, the construction industry needs to actively explore low-carbon, energy-saving, and environmentally friendly building forms to reduce negative impacts on the environment. Due to the fact that buildings are an important source of global energy consumption and greenhouse gas emissions, especially in countries like China with a large population and rapid economic development, the energy consumption and carbon emissions of buildings are particularly prominent. Research on reducing the use of chemical energy, improving energy efficiency and reducing carbon dioxide emissions in the whole cycle of building materials and equipment manufacturing, construction and building use.

2. Specific Issues and Analysis Ideas

2.1. Specific problems to be solved

Question 1: There is now a single story flat roof single building with a length of 4 meters, a width of 3 meters, and a height of 3 meters. The wall is a brick concrete structure, with a thickness of 30 centimeters (thermal conductivity coefficient of $0.3W/m^2K$). The roof is reinforced concrete with a thickness of 30 centimeters (thermal conductivity coefficient of $0.2W/m^2K$), and the total area of doors and windows is 5 square meters (thermal conductivity coefficient of $1.6W/m^2K$). The ground is made of concrete (thermal conductivity coefficient of $0.25W/m^2K$). The monthly average temperature (in degrees Celsius) of the building's geographical location over a period of 365 days is shown in the table below.

Table 1. Monthly Average Temperature (Unit: Celsius)

Month	1	2	3	4	5	6	7	8	9	10	11	12
Average Temperature	-1	2	6	12	22	28	31	32	26	23	15	2

Assuming that the temperature inside the building needs to be maintained at 18-26 degrees Celsius, it is necessary to adjust the temperature through electricity when the temperature is not suitable. Consuming one degree of electricity is equivalent to 0.28 kilograms of carbon emissions. Please calculate the annual carbon emissions of the building through air conditioning (assuming that the Coefficient of performance of air conditioning heating is 3.5 and the Coefficient of performance of refrigeration is 2.7). (Try to use the conditions given in this question to calculate carbon emissions, without considering other losses.)

Question 2: Throughout the entire lifecycle of residential buildings (construction, operation, demolition), there are many factors that affect carbon emissions, such as building design standards, climate, production and transportation of building materials, regional differences, energy consumption during construction and demolition, decoration style, usage energy consumption, building type, etc. Please search and analyze the data, establish a mathematical model, identify indicators that are highly correlated with the above factors and easy to quantify, and comprehensively evaluate the carbon emissions of residential buildings throughout their entire life cycle based on these indicators.

Question 3: On the basis of Problem 2, respectively consider the carbon emissions in the three stages of the building life cycle, find relevant data, establish a mathematical model, comprehensively evaluate the carbon emissions of residential buildings in 13 Prefecture-level city in Jiangsu Province in 2021, and verify the effectiveness of the evaluation model.

Question 4: Accurate carbon emission prediction can provide important reference basis for formulating emission reduction policies and optimizing low-carbon building design. Establish a carbon emission prediction model, based on historical data of carbon emissions throughout the construction process in Jiangsu Province, to predict the carbon emissions throughout the construction process in Jiangsu Province in 2023

Question 5: Please provide policy recommendations for building carbon reduction in Jiangsu Province based on the previous discussion.

2.2. Analysis of the Question

First of all, the difficulty of this problem is that it is necessary to use the given data and relevant coefficients to calculate the Heat transfer coefficient, heat transfer, power consumption and carbon emissions, establish the energy balance equation of the building, and calculate the energy consumption and emissions of the building in different months in combination with the mathematical model of air conditioning work, so as to obtain the annual carbon emissions. Secondly, it is necessary to consider the "Carbon footprint" of the entire life cycle of residential buildings to evaluate their carbon emissions, and select quantitative indicators with high correlation with carbon emissions for evaluation. Carbon footprint refers to the total amount of greenhouse gases released by a product, service or activity in its entire life cycle, including direct and indirect emissions. Furthermore, it is necessary to collect carbon emissions from residential buildings in 13 prefecture level cities in Jiangsu Province for comprehensive evaluation, and verify the effectiveness of the model to complete the prediction of carbon emissions in Jiangsu Province in 2023.

3. Establishment of the Model

3.1. Model Assumptions

(1) The temperature difference between indoor and outdoor buildings is 1 ℃, which means that the indoor temperature needs to be maintained within the range of 1 ℃ above or below the monthly average temperature.

(2) The air inside the building is static and does not consider factors such as natural ventilation.

(3) The thermal conductivity coefficients of building floors, walls, and roofs are constant and do not change with temperature.

(4) The thermal conductivity coefficient of building doors and windows is also Changshu, without considering factors such as the sealing of doors and windows.

3.2. Symbols and Meanings

The symbols and meanings used in the established model are shown in Table 2.

Table 2. Symbols and meanings

Symbol	Meaning
U	Heat transfer coefficient, a scale representing intensity during heat transfer
Q	Heat transfer, the quantitative magnitude of energy transfer that occurs due to temperature differences
P	Quantity of electricity
n	Total hours
COP	Air conditioning heating Coefficient of performance
EER	Air conditioning refrigeration Coefficient of performance

3.3. Model Establishment

3.3.1. Question 1

According to relevant parameters, the change in energy inside a building is equal to the amount of external environmental energy transported internally plus the amount of internal energy dissipated outward. Among them, it involves parameters such as thermal conductivity, thickness, and area of building structural materials. Assuming the indoor temperature is T_i, the outdoor temperature is T_o, the total area of indoor structural materials is A, the thermal conductivity coefficient is k, and the thickness is d, then:

Model A:

The amount of external environmental energy transported internally: $Q_{in}=\mathrm{A} * \mathrm{k} * \frac{(\mathrm{T_O}-\mathrm{T_i})}{\mathrm{d}}$.

The amount of internal energy lost to the outside: $Q_{out} = U * A * (T_i\text{-}T_{out})$.

Model B:

Assuming that the Coefficient of performance (COP) of air conditioning heating is 3.5 and the Coefficient of performance (EER) of refrigeration is 2.7, the following formula can be used to describe the power and energy consumption of air conditioning cooling and heating:

Power during cooling: $P_{cooling}=\frac{Q_{cooling}}{EER}$.

Power during heating: $P_{heating}=\frac{Q_{heating}}{COP}$.

Where, $Q_{cooling}$ and $Q_{heating}$ represent the energy released during air conditioning cooling and heating, respectively.

3.3.2. Question 2

Establish a comprehensive evaluation model for carbon emissions during the life cycle of residential buildings, using the following steps:

Model C:

(1) Determine evaluation indicators and divide them into the following aspects based on actual situations: energy consumption during building design and construction, energy consumption during building material production and

transportation, energy consumption during use, decoration style, and building type.

(2) Collect data for each indicator.

(3) Quantification of indicators. ① The quantification of energy consumption during building design and construction is the total amount of building energy consumption. ② The energy consumption in the production and transportation of building materials is quantified as the carbon dioxide emissions per ton of building materials. ③ The energy consumption during the use phase is quantified as the carbon dioxide emissions per ton of building materials.

(4) Comprehensive evaluation model. Using the weighted average method, the quantitative values of each indicator are comprehensively calculated to obtain the carbon emissions of the entire life cycle of residential buildings. The calculation formula is carbon emissions= Σ (Quantitative value of indicators * weight).

(5) Weight determination. Conduct weight analysis based on actual situations and expert opinions. ① The weight of energy consumption in architectural design and construction process is 0.2 In terms of energy consumption in the production and transportation of building materials, the weight is 0.3 In terms of energy consumption during the usage phase, the weight is 0.4. ④ In terms of decoration style and building type, the weight is 0.1.

Model D:

Assuming there are n samples and p indicators, it can form a sample matrix x:

$$X=\begin{bmatrix}X_{11} & \cdots & X_{1p}\\ \vdots & \ddots & \vdots\\ X_{n1} & \cdots & X_{np}\end{bmatrix}=(X_1,X_2,\cdots,X_p) \tag{1}$$

Assuming we want to find a new set of variables: z_1,z_2 , … , z_m(m ≤ p) z_1,z_2,…,z_m(m ≤ p), and they meet:

$$\begin{cases} z_1=l_{11}x_1+l_{12}x_2+\cdots+l_{1p}x_p\\ z_2=l_{21}x_1+l_{22}x_2+\cdots+l_{2p}x_p\\ \cdots\\ z_m=l_{m1}x_1+l_{m2}x_2+\cdots+l_{mp}x_p\end{cases} \tag{2}$$

Firstly, carry out standardization processing.

Calculate the mean by column: $\bar{x}_j=\frac{1}{n}\sum_{i=1}^{n}x_{ij}$.

Standard deviation: $S_j=\sqrt{\frac{\sum_{i=1}^{n}(x_{ij}-\bar{x}_j)^2}{n-1}}$.

Standardized data: $X_{ij}=\frac{x_{ij}-\bar{x}_j}{S_j}$.

The original sample matrix has undergone standardized changes:

$$X=\begin{bmatrix}X_{11} & \cdots & X_{1p}\\ \vdots & \ddots & \vdots\\ X_{n1} & \cdots & X_{np}\end{bmatrix}=(X_1,X_2,\cdots,X_p) \tag{3}$$

Covariance matrix of standardized sample difference:

$$R=\begin{bmatrix}r_{11} & \cdots & r_{1p}\\ \vdots & \ddots & \vdots\\ r_{p1} & \cdots & r_{pp}\end{bmatrix} \tag{4}$$

Calculate the eigenvalues and eigenvectors of R:

$\lambda_1\geq\lambda_2\geq\cdots\lambda_p\geq 0$,(R is a semi Positive-definite matrix, and $tr(R)=\sum_{k=1}^{p}\lambda_k=p$).

Feature vector: $a_1=\begin{bmatrix}a_{11}\\ a_{21}\\ \vdots\\ a_{p1}\end{bmatrix}$, $a_2=\begin{bmatrix}a_{12}\\ a_{22}\\ \vdots\\ a_{p2}\end{bmatrix}$, ⋯, $a_p=\begin{bmatrix}a_{1p}\\ a_{2p}\\ \vdots\\ a_{pp}\end{bmatrix}$.

Calculate the principal component contribution rate and cumulative contribution rate:

contribution rate $=\frac{\lambda_i}{\sum_{k=1}^{p}\lambda_k}$,

cumulative contribution rate $=\frac{\sum_{k=1}^{i}\lambda_k}{\sum_{k=1}^{p}\lambda_k}$,(i=1,2,…,p).

4. Solution of the Model

Question 1: First, we need to calculate the Heat transfer coefficient U value of the building. According to the parameters of brick concrete structure and reinforced concrete flat roof, the Heat transfer coefficient of wall and roof can be calculated respectively:

Heat transfer coefficient of wall: U_{wall}=$\frac{0.3}{0.04}$=7.5W/(m^2k).

Heat transfer coefficient of roof: U_{roof}=$\frac{0.3}{0.04}$=7.5W/(m^2k).

According to the area of doors and windows, ground area and Heat transfer coefficient, the heat transfer of doors, windows and ground can be calculated.

Heat transfer of doors and windows: Q_{win}=5×2.9×(26-(-1))×1.16=474.8W.

Ground heat transfer: Q_{floor} =4×3×(26-(-1))×1.16=992.16W.

According to Density of air, indoor and outdoor temperature difference and Heat transfer coefficient, the heat transfer of indoor air to the outside can be calculated.

The heat transfer capacity of indoor air to the outside world is:

Q_{air}=4×3×(26-(-1)×1.16/(1/(7.5+1.16)+1/(7.5+1.16)) =386.67W.

According to the heating Coefficient of performance COP and the cooling Coefficient of performance EER of the air conditioner, the electricity consumption per hour of the air conditioner can be calculated.

The amount of electricity consumed by the air conditioner per hour during heating:

P_{heat}=Q_{air}/COP=110.48W.

The amount of electricity consumed by the air conditioner per hour during refrigeration:

P_{cool}=Q_{air}/EER=143.19W.

Therefore, during the time period between 18 and 26 degrees Celsius when air conditioning is required to adjust the temperature, the carbon emissions generated per hour are as follows:

Carbon emissions generated per hour during heating: P_{heat}×0.28kg/kWh=30.9g/h.

Carbon emissions generated per hour during refrigeration: P_{cool}×0.28kg/kWh=40.1g/h.

Multiplying the hourly carbon emissions by the total hours during that time period can calculate the annual carbon emissions of the building through air conditioning temperature regulation. The formula is as follows:

Annual carbon emissions =((P_{heat}×0.28)×n_{heat}+(P_{cool}×0.28)x×n_{cool})x×24×365.

Among them, n_{heat} and n_{cool} represents the total number of hours during which heating and cooling are required. According to the conditions given in the question, the time periods for heating are January and February, and the time periods for cooling are July and August.

n_{heat}=(31+28)×24=1416, n_{cool}=(31+31)×24=1488.

Substitute the data into the formula to calculate:

Annual carbon emissions =((30.9×0.28)×1416+(40.1×0.28)×1488)×24×365=1333.56kg.

Therefore, the annual carbon emissions of the building through temperature regulation through air conditioning are approximately 1333.56 kilograms.

Question 2: Secondly, the results of the three-year comprehensive evaluation are shown in the table below.

Table 3. Weighted results of four evaluation indicators

Year	Energy consumption during architectural design and construction process (100 million tce)	Energy consumption in the production and transportation of building materials (100 million tons)	Energy consumption during the usage phase (100 million tons)	Energy consumption of decoration style and building type (100 million tons)	Weighted results
2018	0.47	27.2	21.1	6.8	17.343
2019	0.9	27.7	21.3	7.7	17.780
2020	0.9	28.2	21.6	5.3	17.810

Question 3: The effectiveness of the principal component analysis contribution rate result model.

Table 4. Principal Component Analysis Contribution Rate Results

Eigenvalue	Contribution rate	Accumulated contribution rate
13.090790	0.201397	0.201397
9.171669	0.141103	0.342499
6.477168	0.099649	0.442148
5.065004	0.077923	0.520071
4.413407	0.067899	0.587970
3.247621	0.049963	0.637933
2.789701	0.042918	0.680852
1.988155	0.030587	0.711439
1.981280	0.030481	0.741920
1.646757	0.025335	0.767255
1.449439	0.022299	0.789554

Question 4: Predict the carbon emissions throughout the construction process in Jiangsu Province in 2023.

Weighted results can be used to predict the carbon emissions throughout the construction process in Jiangsu Province in 2023. Assuming that the energy consumption values of the four evaluation indicators remain unchanged for the next three years, the predicted carbon emissions for 2023 are:

2023 Forecast=17.810/(0.47+27.2+21.1+×(0.9+28.2+21.6+5.3)=17.86.

This is a simple estimation based on current evaluation indicators and energy consumption values, and the actual situation may change due to various factors.

Question 5: Policy recommendations for building carbon reduction in Jiangsu Province

(1) Promoting efficient and energy-saving buildings: As one of the industries with the highest energy consumption, energy conservation and emission reduction in the construction industry are very important. Therefore, the government should increase the promotion of efficient and energy-saving building technologies, and encourage and guide enterprises and individuals to adopt efficient and energy-saving buildings through policy measures.

(2) Strengthening standards for building materials and equipment: Building materials and equipment also have a significant impact on energy consumption. The government can promote the use of green and environmentally friendly building materials and equipment by setting stricter standards for building materials and equipment.

(3) Support the application of clean energy: Clean energy is one of the important means for the construction industry to achieve carbon reduction. The government can promote the application of clean energy technologies such as solar energy and ground source heat pumps in the construction industry by increasing support.

(4) Establish a Carbon emission trading market: the Carbon emission trading market can effectively stimulate the enthusiasm of enterprises to reduce emissions. The government can promote the emission reduction work of the construction industry by establishing a Carbon emission trading market, and encourage enterprises to achieve carbon emission reduction through the market mechanism.

(5) Strengthen supervision and law enforcement: The government should strengthen supervision and law enforcement of the construction industry, strictly implement energy-saving and emission reduction standards, seriously investigate and punish violations, and punish violations to maintain the ecological environment of the construction industry.

5. Conclusions

Based on the above table, it is not difficult to draw the following conclusion:

(1) It can be seen that the weighted result in 2019 was the highest, reaching 1.778 billion tons, slightly higher than the 1.7343 billion tons in 2018. In terms of specific evaluation indicators, the energy consumption in the production and transportation of building materials has remained relatively stable for three years, while the energy consumption in the use stage has slightly increased. In addition, the energy consumption of decoration styles and building types was relatively high in 2018, but decreased in the following two years.

(2) The contribution rates of the first two principal components have exceeded 34%, and the contribution rates of the first four principal components have exceeded 52%. Therefore, if only the first four principal components are selected for analysis, most of the information can be retained while ignoring other unexplained information.

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