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Carbon Footprint Analysis of Buildings Based on LCA Theory Under Carbon Neutrality Goals: Taking the 3rd China International Solar Decathlon Competition as an Example

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Abstract: This paper focuses on the design of residential buildings oriented to the efficient use of solar energy, and selects the entries HUI HOUSE of Hefei University of Technology and Lille I University of France in the 3rd China International Solar Decathlon China Competition, based on the theory of the life cycle assessment (LCA) of buildings, and analyzes the carbon footprint from four aspects: building materials production and transportation stage, building construction stage, building operation stage, and building demolition stage. Through the calculation of the carbon footprint of buildings, the socio-economic benefits of HUI HOUSE in carbon reduction were analyzed; the result of the calculation was that HUI HOUSE achieved carbon neutrality in the ninth year, and continued carbon reduction after that, contributing a cumulative total of 947.54 tons of carbon negative in the life cycle of buildings.

Keywords: Zero-energy buildings; Carbon emissions from buildings; Carbon neutrality in buildings; Solar Decathlon

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1. Introduction

Since the 70s of the 20th century, the problem of global warming has been gradually highlighted. According to relevant statistics, as of 2017, the global average temperature has increased by 0.8 compared to the industrial age. Studies have shown that rising global temperatures can lead to rising sea levels, shrinking snowpack, and uneven global rainfall. The Paris Agreement proposes that the global average temperature increase should be limited to 2°C this century and strives to limit the temperature increase to 1.5°C above pre-industrial levels [1-6].

A Solar Decathlon (SD) competition was initiated and sponsored by the US Department of Energy, with universities around the world as the participating units of the solar building technology competition, the competition involves solar energy, energy conservation and building design, and is a forward-looking competition to maximize the use of renewable resources. This paper uses the life cycle assessment (LCA) model to analyze the carbon footprint of the project from four aspects: building materials production and transportation, building construction stage, building operation stage, and building demolition stage according to the 3rd China International Solar Decathlon Competition HUI HOUSE [7,8].

2. Introduction to carbon footprint calculation models

2.1. Building life cycle and carbon footprint theory

The concept of carbon footprint originates from the "ecological footprint," which refers to the total amount of gases emitted in human production and consumption activities related to climate change, which can be expressed in carbon dioxide equivalent (CO_2e) [9].

LCA-based building carbon footprint refers to the entire life cycle of the building, taking into account the entire input-output chain, in which the system boundary is determined by the CO_2 emitted through material and energy consumption. The building carbon footprint can be divided into 4 stages: building materials preparation, construction, building operation, and building demolition.

2.1.1. Production and transportation stages of building materials

The carbon emissions in the production and transportation stage of building materials shall be the sum of the carbon emissions of the production stage of building materials and the carbon emissions of the transportation stage of building materials, and shall be calculated according to the following formula:

$$\boldsymbol{C}jc = \boldsymbol{C}sc + \boldsymbol{C}ys$$

where $\boldsymbol{C}jc$ is the carbon emissions from the production and transportation of building materials (tCO_2e), $\boldsymbol{C}sc$ is the carbon emissions (tCO_2e) from the production stage of building materials, and $\boldsymbol{C}ys$ is the carbon emissions from the transportation phase of building materials (tCO_2e).

2.1.2. Building construction phase

To simplify the calculation of the construction phase of the building, this paper focuses on calculating the number of mechanical equipment shifts used in the construction stage, and uses this data to calculate carbon emission. The calculation formula is as follows:

$$\boldsymbol{C}jz = \sum_{\boldsymbol{i}=\boldsymbol{1}}^{\boldsymbol{n}} \boldsymbol{Q}_{\boldsymbol{jz},\boldsymbol{i}} \times \boldsymbol{K}_{\boldsymbol{jz},\boldsymbol{i}}$$

$$\boldsymbol{K}_{\boldsymbol{jz},\boldsymbol{i}} = \sum_{\boldsymbol{i}=\boldsymbol{1}}^{\boldsymbol{n}} \boldsymbol{T}_{\boldsymbol{i},\boldsymbol{j}} \times \boldsymbol{F}_{\boldsymbol{i},\boldsymbol{j}} \times \boldsymbol{Rz}$$

where $\boldsymbol{Q}_{\boldsymbol{jz},\boldsymbol{i}}$ is the *i*th project quantity in the sub-project; $\boldsymbol{K}_{\boldsymbol{jz},\boldsymbol{i}}$ is the energy consumption coefficient of the *i*th project in the sub-project; $\boldsymbol{T}_{\boldsymbol{i},\boldsymbol{j}}$ is the *i*th project unit engineering quantity and the *j*th type of construction machinery shift consumption; $\boldsymbol{F}_{\boldsymbol{i},\boldsymbol{j}}$ is the energy consumption of the *J* construction machinery unit shift of the *i*th project, the selection value is referred to the following table; $\boldsymbol{Rz}$ is the carbon emission coefficient of energy consumed by the *j*th type of construction machinery per shift.

2.1.3. Building operation phase

The calculation of carbon emissions in the operation stage of the building should include the carbon emissions during the operation of air conditioning equipment, domestic water, lighting equipment, and building carbon sink system in the operation stage. The lighting system is determined according to the needs of the builder and is powered by battery. The water system is mainly used for domestic and firefighting, which is tap water. Greenhouse gas emissions from refrigerant use in the heating, ventilation, and air conditioning (HVAC) systems are calculated as follows:

$$Cr = mr \cdot GWPr/1000$$

where Cr is the carbon emissions produced by refrigerants (tCO2); r is the type of refrigerant; mr is the refrigerant charge of the equipment (kg/unit); $GWPr$ is the global warming potential of the refrigerant r.

2.1.4. Building demolition phase

The carbon emissions of the building demolition stage are the carbon emissions generated by the use of various energy consumed by the machinery and equipment used in mechanical demolition, but because there is no data related to the energy consumption of the building demolition stage, the empirical formula method is selected to estimate the carbon emissions of demolition per unit building area. The formula is sourced from the "Guangdong Provincial Department of Housing and Urban-Rural Development Carbon Emission Calculation Guidelines," which is as follows:

$$\boldsymbol{Y} = 0.06\boldsymbol{X} + 2.01$$

where $\boldsymbol{Y}$ is carbon emissions per unit area ($kgCO_2/m^2$); $\boldsymbol{X}$ is the number of above-ground layers; It is calculated that $\boldsymbol{Y} = 2.13\ kgCO_2/m^2$.

3. Project overview

3.1. Natural conditions of the site

The venue is located in Desheng Village, Zhangbei County, Zhangjiakou City, Desheng Village is 12 kilometers away from Zhangbei County Government, surrounded by large-scale hotels, homestays, inns, catering facilities and other complete facilities, convenient transportation. The overall land use shall be limited to conditional construction areas, and the site shall not occupy basic farmland. The layout of the building's surroundings is shown in **Figure 1**.

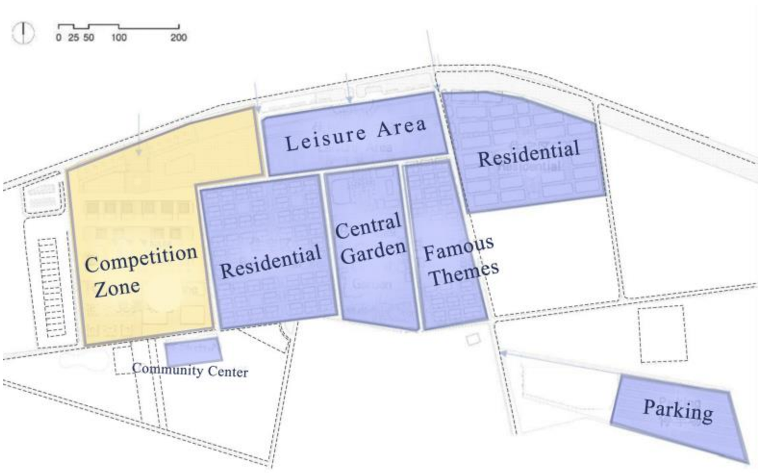

Figure 1. Facilities around the project site

3.2. Main meteorological elements

The project is located in Zhangjiakou City, Hebei Province. Zhangjiakou is located in the cold A zone and has a temperate continental monsoon climate. The four seasons are distinct, with dry and windy springs, hot and short precipitation in summer, sunny autumns with moderate temperatures, and cold and long winters. The annual average temperature is 9 °C, the annual average maximum temperature is 15 °C, and the annual average minimum temperature is 3 °C. The rain and heat are the same season, and the growing season is cool. High temperature, high humidity, and few hot weather. The annual precipitation is 330–400 mm.

3.3. Building parameters

Team HUI, a team from Hefei University of Technology, representing Anhui Province in the decathlon competition, tried to integrate the architectural style of the Hui-style into the design of solar architecture. The traditional Hui-style architecture reflects a harmonious, orderly, and elegant architectural image, and the beautiful landscape where the architectural image and the mountains and rivers intersect each other, showing a unique regional style. The design is based on traditional Hui-style houses, blending modern construction systems and solar energy technology, and strives to explore the possibilities of new Hui-style houses. Due to the extensive integration of green energy-saving technology and building design, HUI HOUSE won the Silver Award for Energy Performance and the Sustainability Award in the Decathlon. The analysis of the architectural design concept is shown in **Figure 2**.

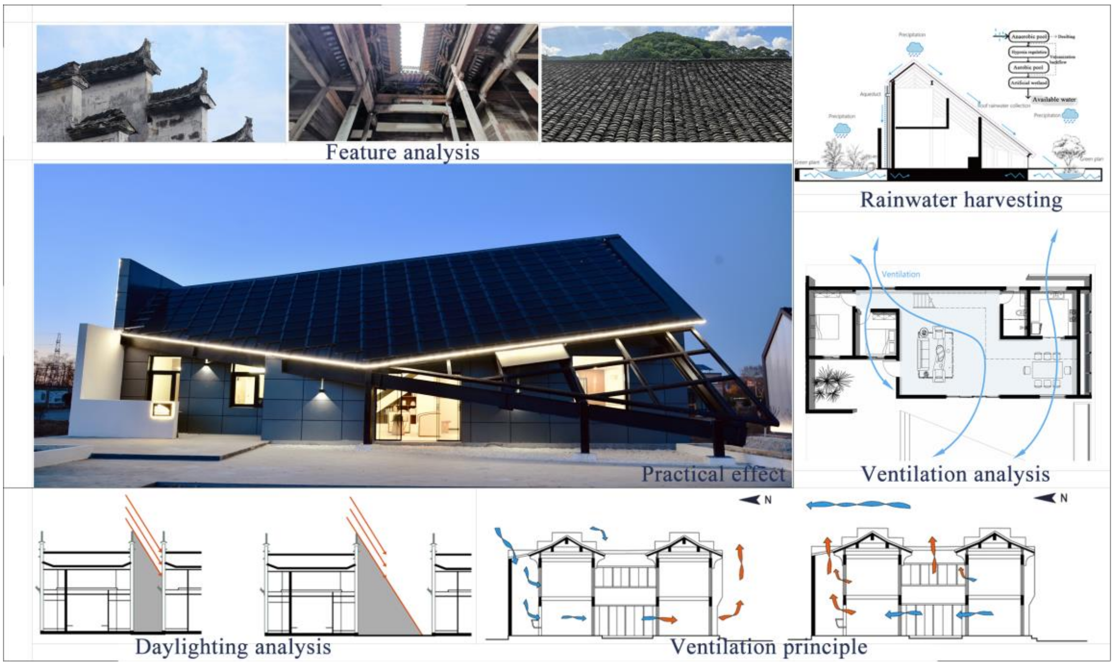

Figure 2. Architectural design concept

4. Analysis of accounting results

4.1. Calculation instructions

This report takes GB/T 51366-2019 and JGJ/T 449-2018 as reference to calculate the carbon emissions of the whole life cycle of building materials (production, transportation, and recycling), construction, operation, and demolition, and considers the optimization calculation of carbon saving, carbon reduction, and carbon neutrality control measures such as renewable energy and green vegetation (carbon sink) [10,11].

4.2. Calculation results of carbon emissions during the production and transportation of building materials

Carbon emissions of building material production stage is the carbon emitted by the building materials required during its production stage, and the calculation results are shown in **Table 1**.

Table 1. Carbon emissions from the production of building materials

	Types of building materials	Dosage	Unit	Production factor (tCO_2e/unit dosage).	Carbon emissions (tCO_2e)
1	Rebar	5.76	t	2.34	13.48
2	Concrete	60.48	m³	2.95×10^-1	17.84
3	Glass	3.75	t	2.84	10.65
4	Thermal insulation rock wool	3.20	t	1.98	6.34
5	Color steel tiles	2.22	t	2.53	5.62
6	Roof panels	0.62	t	2.03×10^1	12.65
7	Steel	5.76	t	2.35	13.54
8	Exterior wall insulation panels	10.60	m³	2.27×10^-2	0.24
9	PV modules	12420	W	1.41×10^-3	17.5
Total					**97.86**

The carbon emissions during the transportation stage of building materials are calculated by recording the means of transportation used in the construction process, and the calculation results are shown in **Table 2**.

Table 2. Carbon emissions generated during the transportation phase

	Types of building materials	Dosage	Unit	Mode of transportation	Transportation factor [$tCO_2e/(t*km)$]	Transportation distance (km)	Carbon emissions (tCO_2e)
1	Rebar	5.76	t	Medium diesel trucking (8t)	1.79×10^{-4}	1084	1.12
2	Concrete	60.48	m³	Medium diesel trucking (8t)	1.79×10^{-4}		30.51
3	Glass	3.75	t	Medium diesel trucking (8t)	1.79×10^{-4}		0.73
4	Thermal insulation rock wool	3.20	t	Medium diesel trucking (8t)	1.79×10^{-4}		0.62
5	Color steel tiles	2.22	t	Light diesel truck transportation (load 2t)	2.86×10^{-4}		0.69
6	Roof panels	0.62	t	Light gasoline truck transportation (load 2t)	3.34×10^{-4}		0.23
7	Steel	5.76	t	Medium-duty gasoline trucks (8 tons)	1.15×10^{-4}		0.72
8	Exterior wall insulation panels	10.60	m³	Light gasoline truck transportation (load 2t)	3.34×10^{-4}		0.08
9	PV modules	1.3	t	Light diesel truck transportation (load 2t)	2.86×10^{-4}		0.69
Total							**35.39**

4.3. Building construction phase

There are many details involved in the construction stage of this project, such as the list of project cost budget and final accounts, the main mechanical schedule, the actual construction record, and so on. The details of carbon emissions during the construction phase are shown in **Table 3**.

Table 3. Detailed information on carbon emissions during the construction phase

Project name	Construction machinery name	Energy consumption per unit	Energy usage units	Total shift consumption of construction machinery (shift)	Total carbon emissions (tCO_{2e})
New sub-project project	Forklift crane	26.46	kg diesel/shift	1.50	42.31
	Jack-up tower crane	166.29	kg diesel/shift	81.00	
	Crawler type single bucket hydraulic excavator	33.68	kg diesel/shift	2.00	
	Scroll type concrete mixer	34.10	kg diesel/shift	0.38	
	Concrete pump	243.46	kg diesel/shift	0.25	

4.4. Calculation results of carbon emissions during the operation phase of the building

In terms of design, HUI HOUSE used the area of the roof to achieve the integration of energy output, and the solar photovoltaic tiles were closely combined with the roof of the building to form a Building Integrated Photovoltaics (BIPV) system. The carbon emissions during the building operation stage are shown in **Table 4**.

Table 4. Calculation results of carbon emissions during building operation

Type of energy consumption	Annual power consumption (kW·h/a)	Carbon emission factor ($tCO_2e/kW·h$)	Annual carbon emissions (tCO_2e)
Heating system	1350	0.928×10^{-3}	1.25
Lighting and hot water systems	65.7		0.06
renewable energy (Solar)	21450		-19.9
Total	**19415.7**	**--**	**-18.59**

4.5. Calculation results of carbon emissions during the demolition phase

The carbon emissions of the building demolition stage are the carbon emissions generated by the use of various energy consumed by the machinery and equipment used in mechanical demolition, the total carbon emission is $0.3tCO_2e$.

4.6. Comparison of carbon emissions at different stages of the building

The carbon emissions of the whole life cycle of buildings are shown in **Table 5**, the carbon emissions of building materials production and transportation stage are 115.04 tCO_2e, and the carbon emissions of building construction stage and photovoltaic construction and transportation stage are 60.47 tCO_2e. The average annual carbon emissions of photovoltaics in the building operation stage are 19.9 tCO_2e, and the carbon emissions in the building demolition stage are very low and negligible. As can be seen from **Table 5**, buildings have been contributing carbon negative after the ninth year, contributing to the achievement of the carbon neutrality goal.

Table 5. Carbon emissions throughout the life cycle of buildings

Architectural design years (years)		70
Carbon neutrality time (years)		9
Building construction phase	Building materials production stage (tCO2e).	80.35
	Building materials transportation stage (tCO_2e)	34.69
	Construction phase (tCO_2e)	42.31
	PV module construction and transportation phase (tCO_2e)	18.16
Building operation phase	Heating system (tCO_2e)	1.25
	Lighting and hot water systems (tCO_2e)	0.06
	Number of replacements (times) during the life of the building	2
	Carbon emissions from photovoltaic replacement (tCO_2e)	90.2
	Carbon emissions from photovoltaic power generation (tCO_2e)	-19.9
Building demolition stage (tCO_2e)		0.3
Greening the carbon sink stage (tCO_2e)		-0.035
Carbon emissions throughout the life cycle of buildings (tCO_2e)		-947.54

5. Summary

Based on the HUI HOUSE of the 3rd China International Solar Decathlon Competition, this paper uses the LCA theory to study the HUI HOUSE from four aspects: building materials production and transportation stage, building construction stage, building operation stage, and building demolition stage for the Desheng Village project in Zhangbei County, Zhangjiakou City Full lifecycle carbon footprint analysis. In its operation stage, the building relies on solar power generation, and the battery storage mode can meet the daily needs of the building. On this basis, through the actual monitoring data of the building, the cumulative power generation of the building throughout its whole life cycle is predicted in order to estimate the contribution of the building in terms of social and economic benefits. According to the experimental results, it is clear that the building has made great contributions to energy conservation and emission reduction, and acts as a great reference for the design and construction of zero-energy houses, which is significant for the development of new directions of housing in the future.

Disclosure statement

The authors declare no conflict of interest.

References

[1] Płoszaj-Mazurek M, Ryńska E, Grochulska-Salak M, 2020, Methods to Optimize Carbon Footprint of Buildings in Regenerative Architectural Design with the Use of Machine Learning, Convolutional

Neural Network, and Parametric Design. Energies, 13(20): 5289. https://doi.org/10.3390/en13205289

[2] Liu C, Zhang H, Luo B, Li L, 2022, A Quantitative Recovery Process of Rare Earth in Bastnaesite Leachate for Energy Saving and Emission Reduction. Minerals Engineering, 190: 107920.

[3] Jin H, Yang J, Chen Y, 2022, Energy Saving and Emission Reduction Fiscal Policy and Corporate Green Technology Innovation. Frontiers in Psychology, 13: 1056038. https://www.doi.org/10.3389/fpsyg.2022.1056038

[4] Sahoo N, Kumar A, Samsher S, 2022, Review on Energy Conservation and Emission Reduction Approaches for Cement Industry. Environmental Development, 44: 100767. https://doi.org/10.1016/j.envdev.2022.100767

[5] Wang S, Luo Y, Liu Z, et al., 2022, Analysis on Energy Conservation and Emission Reduction Efficiency and Influencing Factors for Ports Around Bohai in China Under the Low Carbon Target. Sustainability, 14(22): 14765.

[6] Bai Y, Gao Y, Li D, et al., 2022, Coordinated Distribution or Client Introduce? Analysis of Energy Conservation and Emission Reduction in Canadian Logistics Enterprises. Sustainability, 14(24): 16979.

[7] Shi F, Jin W, 2018, Research on the Design Concept and Type of Building Thermal Buffer Space: A Case Study of the International Solar Decathlon Competition. Southern Architecture, 2018(2): 60–66.

[8] Sun Y, 2018, Competition, Construction and Education: A Review of the 2018 China International Solar Decathlon Competition. Architectural Journal, 2018(12): 77-79.

[9] Seyedabadi MR, Eicker U, Karimi S, 2021, Plant Selection for Green Roofs and Their Impact on Carbon Sequestration and the Building Carbon Footprint. Environmental Challenges, 4: 100119. https://doi.org/10.1016/j.envc.2021.100119

[10] Ministry of Housing and Urban-Rural Development of the People's Republic of China and State Administration for Market Regulation, 2019, Standard for Building Carbon Emission Calculation, viewed November 12, 2022.

[11] Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2018, Standard for Green Performance Calculation of Civil Buildings, JGJ/T 449-2018, viewed November 12, 2022.