

Study on the Coupling Mechanism and Environmental Benefit Comprehensive Evaluation of Building-Landscape-Energy Systems in Zero-Carbon Campuses

Jialei Nie¹

(1 Jiangsu Ocean University, School of Civil and Port Engineering, Architectural Science, Jiangsu, Lianyungang, 222005, China)

Abstract: Against the backdrop of China's "dual carbon" strategy and high-quality development of higher education, zero-carbon campuses have become a key research focus in green and low-carbon campus construction. Most Chinese universities currently suffer from independent design, separate operation, and poor coordination among building, landscape, and energy systems, which limits carbon reduction and environmental improvement. This paper takes zero-carbon campuses as the research object, explores the coupling mechanism of building-landscape-energy systems, and establishes a comprehensive evaluation system covering carbon reduction, microclimate regulation, thermal comfort, energy efficiency, and ecological quality. Using numerical simulation and case analysis, it identifies how multi-system synergy improves campus environmental performance. Results show that integrated optimization of building energy conservation, ecological landscape design, and clean energy systems can effectively reduce operational energy use and carbon emissions, enhance outdoor thermal environment and comfort, and boost overall campus sustainability. Finally, collaborative optimization strategies for planning, technology, and operation are proposed to support low-carbon campus renovation and the implementation of China's dual carbon goals.

Keywords: Zero-carbon Campus; Building-Landscape-Energy System; Coupling Mechanism; Environmental Benefit; Green Building

Date of receipt: March 5, 2026

<https://orcid.org/0009-0009-8620-6045>

DOI:

Author Profile: Nie Jialei (born 2004), female, from Lianyungang, Jiangsu Province, holds a bachelor's degree. Her research focuses on green buildings, zero-carbon campuses, building energy efficiency, building-landscape-energy system coupling, and building environment and sustainable development.

Corresponding author: Nie Jialei, 1905028100@qq.com

Introduction

Against the global push to achieve carbon peaking and carbon neutrality goals, China's "Dual Carbon" strategy has been deeply integrated into multiple sectors

including urban and rural development, energy transition, and ecological conservation. As compact urban complexes integrating architecture, transportation, energy systems, and ecological landscapes, campuses serve not only as major contributors to energy consumption and carbon emissions but also as pivotal demonstration sites for green, low-carbon practices and energy-saving technologies. With the continuous expansion of higher education institutions, challenges such as rising building energy consumption, diminished ecological functions, and inefficient energy systems have become increasingly prominent ^[1]. Achieving coordinated low-carbon, ecological, and efficient campus development has thus emerged as a critical research focus in green building and campus planning. While recent studies on green buildings, energy efficiency, and low-carbon campuses have advanced, most efforts remain focused on optimizing individual systems—such as building envelope efficiency, photovoltaic applications, or landscape greening—often overlooking the intrinsic connections and synergies among architectural, landscape, and energy systems. In practice, these systems are typically designed separately, managed independently, and operated in isolation, lacking effective coupling mechanisms or integrated optimization pathways. This results in limited overall carbon reduction potential, suboptimal

environmental benefits, and inefficient resource utilization. Therefore, from a systems coupling perspective, exploring the synergistic mechanisms among building-, landscape-, and energy systems and conducting comprehensive environmental benefit assessments hold significant theoretical and practical value for advancing high-quality zero-carbon campus development. In this context, establishing an integrated building-landscape-energy system for zero-carbon campuses is essential. Currently, research on multi-system coupling mechanisms, collaborative optimization models, and quantitative environmental benefit evaluations remains relatively limited, particularly systematic studies at the campus scale. Building on this, this paper focuses on zero-carbon campuses as the research subject, examines the coupling relationships and operational mechanisms of the building-landscape-energy system, develops a multidimensional comprehensive environmental benefit evaluation framework, and reveals systematic optimization patterns through theoretical analysis and simulation studies. It proposes integrated optimization strategies applicable at the campus level ^[2]. The findings provide a scientific foundation for planning low-carbon campuses in higher education institutions, promoting green buildings, enhancing energy system efficiency, and improving ecological environments.

1 Current Research Status Domestically and Internationally

In the field of green, low-carbon, and sustainable campus development, international research began earlier and has primarily focused on building energy efficiency, clean energy applications, and the synergistic optimization of ecological environments. Developed countries such as those in Europe and North America have conducted extensive practical explorations in areas including campus building energy consumption management, renewable energy system integration, and landscape ecological regulation, establishing well-established technical approaches and management models. In systematic coupling research, foreign scholars have progressively shifted from isolated building energy efficiency studies to multidimensional integrated analyses encompassing buildings, energy systems, and ecosystems, emphasizing the dynamic interrelationships between energy supply, building loads, and landscape regulation, and proposing a building-energy-ecology collaborative design philosophy. However, systematic research addressing the intrinsic coupling mechanisms, collaborative operational frameworks, and quantitative evaluation of comprehensive environmental benefits among buildings, landscapes, and energy systems at the campus scale remains relatively limited.

Driven by the “Dual Carbon” strategy,

research in domestic zero-carbon campuses, green buildings, and building energy efficiency has advanced rapidly. The focus primarily encompasses low-carbon campus planning, building energy retrofiting, utilization of clean energy sources such as photovoltaics, landscape ecological optimization, and environmental quality enhancement. In systematic interdisciplinary studies, Chinese scholars have begun examining the interactions among buildings and energy systems, buildings and landscapes, and energy and ecosystems. However, most research remains confined to combined analyses of two systems, with relatively few studies conducting integrated coupling analyses across the building-landscape-energy tri-system framework. Current evaluation methodologies predominantly emphasize single indicators such as energy consumption or carbon emissions, lacking a multi-objective comprehensive assessment framework that integrates carbon reduction, thermal comfort, microclimate, ecological environment, and energy efficiency. This limitation hinders the full reflection of the comprehensive environmental benefits derived from coordinated campus system operations^[3].

2 Composition and Coupling Mechanism of Zero-Carbon Campus Architecture-Landscape-Energy System

The three major systems—architecture,

landscape, and energy—interact, constrain, and support each other within campus spaces, forming a coupled system with complex interrelationships. Their intrinsic coupling mechanisms manifest primarily at three levels: material exchange, energy transfer, and functional synergy. From the perspective of energy transfer, the landscape system modulates the external thermal environment through shading, cooling, and ventilation, reducing the building's air conditioning and heating loads; the energy system provides power support for intelligent building and landscape facilities while achieving carbon reduction through renewable energy utilization. In terms of functional synergy, the architectural system establishes spatial foundations, the landscape system delivers ecological regulation services, and the energy system ensures power supply—these three components complement each other through rational spatial planning, technological integration, and operational coordination. Regarding system performance, optimizing any single system has inherent limitations; however, multi-system coupling enables synergistic effects of “low-energy buildings—energy-efficient landscapes—highly clean energy,” significantly enhancing overall environmental benefits and low-carbon performance. The relationship among these systems is not merely additive but rather integrates spatial, load, operational, and benefit coupling to form

a unified operational mechanism. Only through multidimensional synergy can the comprehensive potential of zero-carbon campuses be fully realized in carbon reduction, thermal comfort, microclimate improvement, and ecological enhancement^[4].

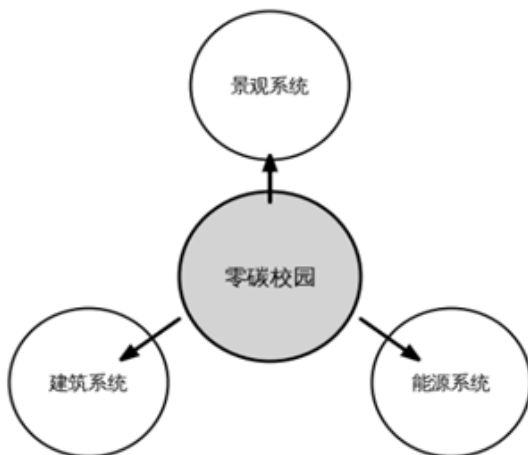
3 Construction of an Indicator System for Evaluating the Environmental Benefits of Zero-Carbon Campuses

3.1 Framework Construction of the Evaluation Indicator System

This paper adopts comprehensive environmental benefit evaluation as its overarching objective. It establishes a criterion layer based on four dimensions: carbon reduction benefits, thermal environment and microclimate, energy utilization efficiency, and ecological environment quality. On this foundation, representative quantitative indicators are selected to form an indicator layer, resulting in a well-structured and comprehensive evaluation system (see Table 1). This system effectively reflects the interactions and synergistic contributions among the building, landscape, and energy systems during their coupled operation, highlighting the zero-carbon campus's overall value in low-carbon performance, energy efficiency, ecological sustainability, and occupant comfort. The coupling relationship among the building, landscape, and energy systems is detailed in Figure 1.

Table 1 Comprehensive Evaluation Index System for Environmental Benefits of Zero-Carbon Campus

<i>Target Layer</i>	<i>Policy Level</i>	<i>Indicator Level</i>
Comprehensive Evaluation of Environmental Benefits	Carbon reduction benefits	Annual carbon emissions, carbon reduction rate
	Thermal Environment and Microclimate	Thermal Comfort Index, Cooling Intensity
	Energy utilization efficiency	Building energy consumption intensity; proportion of clean energy compare
	Ecological and Environmental Quality	Green space ratio; Degree of air quality improvement



耦合协同运行 → 环境效益提升

Figure 1 Schematic diagram of the coupling relationship between building, landscape, and energy systems

3.2 Analysis of the Connotation of Evaluation Indicators

The carbon reduction benefit indicators primarily measure the effectiveness of carbon emission reductions achieved

through systematic optimization on campuses, serving as the core manifestation of low-carbon campus development under the dual carbon goals. Thermal environment and microclimate indicators focus on the comfort of building peripheral spaces, reflecting how landscape ecological regulation and architectural layout enhance outdoor thermal conditions. Energy efficiency indicators demonstrate the level of clean energy utilization and energy consumption management effectiveness on campuses, directly reflecting building energy conservation and energy system optimization. Ecological environment quality indicators assess improvements in campus ecological services through metrics such as green space configuration and air quality. These four categories of indicators complement and integrate organically, collectively forming a zero-carbon campus framework.

4 Empirical Cases and Simulation Analysis

4.1 Overview of the Study Area and Data Sources and Processing

This chapter employs a zero-carbon campus demonstration zone at a domestic university as its empirical case study. The area integrates green buildings, ecological landscapes, and distributed energy systems, exhibiting typical characteristics of coupled operation among building, landscape, and energy systems. Covering a total area of

approximately $3.2 \times 10^4 \text{ m}^2$, the study site includes teaching buildings, ecological green spaces, photovoltaic systems, natural ventilation corridors, and rain gardens, serving as a key demonstration area for the campus' s low-carbon transition. Data for this study primarily derive from on-site measurements, campus energy consumption statistics, meteorological monitoring records, and landscape greening parameters, spanning a full calendar year to ensure annual representativeness. All data underwent outlier removal and consistency checks, meeting the precision requirements for empirical research.

4.2 System Coupling Environmental Benefit Simulation and Calculation

Based on the comprehensive index evaluation model, the carbon reduction benefits, thermal environment and microclimate, energy utilization efficiency, and ecological environment quality of the zero-carbon campus demonstration zone were subjected to itemized accounting and integrated analysis. The results show that under a multi-system coupled operation mode, the study area achieved an annual carbon reduction of 128.6 tCO₂, with the carbon reduction rate increasing to 23.7%, a 18.2% decrease in building comprehensive energy consumption intensity, an average regional cooling intensity of 1.4 °C , and a green space ratio maintained at 38.6%. After weighting and calculation, the

region' s comprehensive environmental benefit evaluation index reached 0.82. According to the evaluation criteria in Table 3, the environmental benefit level of the study area is rated as “good” and close to “excellent,” indicating that the building-landscape-energy system coupled operation model significantly enhances overall campus environmental benefits. However, there remains room for improvement in energy structure optimization and refined microclimate regulation ^[5].

To more intuitively demonstrate the achievements of the zero-carbon campus initiative, a comparative analysis was conducted between the key metrics of the coupled system and those of the traditional standalone system, with the specific differences shown in Figure 2.

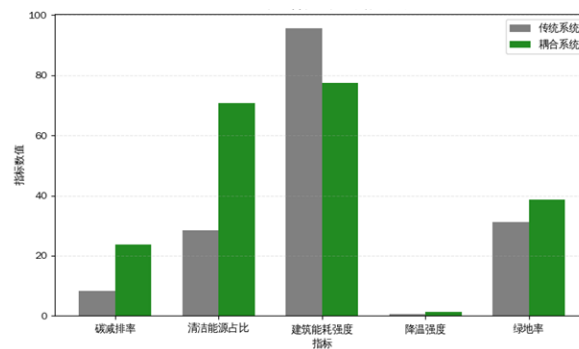


Figure 2 Comparison of environmental benefit indicators between the zero-carbon campus coupling system and the traditional system

The comparative results demonstrate that, in key indicators such as carbon reduction rate, clean energy share, and cooling intensity, the coupled system achieves improvements exceeding 15% compared to the traditional system.

Specifically, the clean energy share increases by 42.3%, while improvements in thermal comfort index and air quality are attributed to the synergistic optimization of ecological landscapes and building wind environments. This indicates that system coupling delivers synergistic benefits of low carbon emissions, energy efficiency, enhanced comfort, and ecological sustainability^[6].

5 Conclusion and Prospects

This study focuses on zero-carbon campuses and establishes an environmental benefit evaluation index system comprising four dimensions: carbon reduction benefits, thermal environment and microclimate, energy utilization efficiency, and ecological environment quality. Empirical results demonstrate that the coupled operation of the building-landscape-energy system significantly enhances overall campus environmental benefits. Future research could further integrate economic and social benefit dimensions into the existing evaluation framework to improve comprehensiveness. Additionally, by incorporating smart monitoring and dynamic simulation technologies, real-time optimization of system operations can be achieved, enabling broader application of the evaluation methodology to low-carbon development scenarios such as residential communities and industrial parks.

References :

- [1] Tan Yong. Research on Energy-saving Models for University Building Data under the “Dual Carbon” Context [D]. Jilin Jianzhu University, 2023. DOI: 10.27714/d.cnki.gjljs. 2023.000129.
- [2] Wang Zhendong. The Logroño Urban Complex in Spain: Synergistic Coexistence of City, Architecture, Landscape, and Energy [J]. *Urban Architecture*, 2013, (07):102–108. DOI: 10.19892/j.cnki.csjz. 2013.07.009.
- [3] Zhong Shuli, Huo Lei. Research on the Smart Building Industry and Green Building Development under the “Dual Carbon” Context: A Case Study of the Green Campus Construction at X University’ s New Campus [J]. *Stone Materials*, 2025, (10):134–136. DOI: 10.14030/j.cnki.scaa. 2025.0567.
- [4] Zhu Xinli. Research on Comprehensive Energy Utilization Technologies in Green Construction [J]. *Sichuan Building Materials*, 2026,52(02):58-60.
- [5] Wang Hai. Research on Policy Support for the Synergistic Development of New Energy Applications in Construction Engineering and Green Buildings [C] // China Land Economics Society. Proceedings of the 2026 Smart City Construction and Innovation Development Symposium. China Electric Power Construction Group Hebei Engineering Co., Ltd.; 2025:273–276. DOI: 10.26914/c.cnkihy.2025.100004.
- [6] Meng Xiaojiang. Application of Green Building Construction Technologies under Low-Carbon Conditions [J]. *Bulk Cement*, 2025, (06):16-18.