

Low-Carbon Development for Carbon-Neutral Pathways: Building Designs from Urban to Human Settlement Environment

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1. Introduction

Urban buildings stand as both a core source of carbon emissions and a key carrier of human settlements. Therefore, the low-carbon design and sustainable development of urban buildings have become a core issue, and there is an urgent need to systematically construct carbon neutrality pathways from the perspective of the whole life cycle, including the stages of construction, operation and maintenance, renovation, and demolition. Guided by the goal of achieving carbon neutrality, the urban buildings are undergoing comprehensive transformation and green development. Building design facilitates the synergy between buildings, urban energy networks, regional climate, and ecological cycles to support urban carbon neutrality goals. On the one hand, climate change has imposed higher requirements on the resilience of cities and buildings. The renewal and optimization of existing buildings and their internal infrastructures have promoted the sustainable transformation towards low-carbon development of cities and buildings in the backdrop of climate change. On the other hand, the improvement of the human settlement environment has driven lower energy and resource demands throughout the building life cycle through the enhancement of thermal comfort and the efficient utilization of natural resources. In response to these engineering practice demands, current research has covered innovations in fields, including the sustainable development of architectural heritage, energy-dependent urban planning, and the structure and layout design of distributed energy systems, aiming to address the technical and research bottlenecks in the low-carbon design and development of existing urban buildings. For example, at the urban scale, energy-dependent urban planning has formed carbon-intensive spatial structures, and the adaptive reuse of industrial heritage buildings in particular contributes to the low-carbon renewal of cities. At the building scale, integrated distributed energy systems have demonstrated high-efficiency low-carbon advantages, and a series of innovative applications have been realized for new-generation phase change materials and passive design technologies. From the perspective of the human settlement environment, relevant specifications for the relationship between low-carbon building design and indoor environmental quality are also being gradually improved.

However, there are still significant underexplored areas in previous studies: First, previous studies focus on individual heritage buildings or typical demonstration zones, lacking a multi-scale value assessment model and framework for urban heritage building systems.



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Furthermore, the influence mechanism between the differences in building neighborhood morphology and the changes in residents' low-carbon consumption behaviors remains unclear [1–3]. Second, studies on integrated distributed energy systems are still limited to mechanical superposition, lacking interdisciplinary integration from an architectural perspective (including esthetics, space, and construction) [4,5]. The engineering design method for coupling optimization of new materials and structures has not yet formed a mature application scheme, and traditional methods have defects such as low system coupling efficiency and strong design subjectivity [6,7]. Meanwhile, there is still a lack of long-term empirical research and monitoring cases for various emerging low-carbon building equipment [8]. Finally, indoor environment optimization strategies and low-carbon design methods for buildings targeting different groups and age compositions are not yet clear, and there are deficiencies in the practical application effects of differentiated indoor environment improvements on different age groups (including thermal comfort, electroencephalogram activity, and cognitive performance) [9]. Addressing these technical and research bottlenecks serves as the logical starting point and key cornerstone of this effort. Advancing design practice research alignment for carbon neutrality further guides the building sector's green transformation and holds practical value for sustainable urban development.

This Special Issue focuses on the core theme of “Carbon-Neutral Pathways for Urban Building Design” and includes the latest research achievements in the fields of sustainable development of architectural heritage, energy-dependent urban planning, and distributed energy structure and layout design.

2. Overview of the Published Articles

A total of eight articles have been published, covering innovative research progress in areas such as the sustainable development of heritage buildings and neighborhood morphology design, the optimization of structures and integrated performance for distributed energy systems, the optimization of wind environment in passive buildings, and the relationship between human settlement environment and low-carbon consumption behavior.

Huang et al. investigated historic buildings, which are a crucial component in reducing building carbon emissions. Based on 318 articles from the Web of Science (WOS) database, they conducted a comprehensive review focusing on the research trends, technical pathways, and evaluation methods of energy-saving retrofit measures. The findings indicate that passive and active energy-saving retrofits remain the primary approaches. However, the continued reliance on a single energy consumption metric as the main evaluation method perpetuates a conflict between the goals of energy conservation and the preservation of historic buildings. This study proposes a three-stage LCA boundary framework, covering the retrofit, operation, and demolition phases, that differs from conventional buildings. On this basis, a three-dimensional multi-objective optimization framework integrating thermal comfort, life cycle carbon emissions, and heritage intervention degree is constructed to overcome the biases of single-indicator evaluations. This framework provides a methodological foundation for quantitatively balancing heritage value protection and improved energy performance.

Liu et al. investigated the sustainable value assessment of industrial heritage along the Guanzhong Section of the Longhai Railway from a linear cultural heritage perspective, contributing to low-carbon pathways for urban building renewal. By developing a two-level evaluation framework integrating individual-building and factory-unit scales, as well as applying AHP-based weighting and field-based scoring, the research systematically analyzed fourteen representative textile industrial heritage units. The results reveal a clear spatial value gradient and hierarchical node structure along the railway corridor,

highlighting the dominant contribution of production-related buildings such as workshops and warehouses. Importantly, the study translates value assessment outcomes into differentiated low-carbon renewal strategies, emphasizing adaptive reuse, life cycle extension, and minimal intervention as effective approaches to reducing embodied carbon and supporting sustainable transformation of existing building stock. This work provides a transferable methodological framework and practical insights for integrating heritage conservation with carbon-neutral urban development.

Liu et al. examined the mechanisms through which the built environment influences low-carbon consumption behavior in energy-based cities, using a GIS–SEM integrated framework with 825 survey samples from Ordos, China. By incorporating 5D built-environment indicators and testing chained mediation effects, the study found that density, land-use mix, and street connectivity exert both direct and indirect (perception–psychology) influences on low-carbon behavior, while accessibility factors (distance to transit and shopping) operate primarily through full mediation pathways. Psychological factors show the strongest direct effect ($\beta = 0.545$), confirming their dominant role in behavioral transformation. The results highlight that urban spatial form alone is insufficient; instead, effective carbon-neutral pathways require coordinated optimization of physical environment, perceived convenience, and behavioral readiness. This study provides actionable insights for integrating urban design and behavioral governance to promote low-carbon lifestyles and support sustainable urban building development.

By analyzing 82 peer-reviewed articles published between 2001 and 2025, Li et al. investigated the scalability of building-integrated photovoltaics (BIPVs) from a multidisciplinary perspective. The results show that research focuses predominantly on electrical (91.5%) and thermal (86.6%) performance, with East Asia and Europe (especially China, Japan, and Germany) being the most active regions. User-centered dimensions such as visual comfort (23.2%), indoor thermal comfort (9.8%), and air purification (7.3%) remain underexplored. Simulation-based methods dominate (80.5%), while empirical validation is limited (36.6%). A notable lack of architectural perspectives was identified, with energy engineering (11.2%) and architecture (10.0%) as the top disciplines but with weak cross-disciplinary integration. Co-occurrence analysis shows strong coupling among thermal, electrical, and optical performance, indicating integrated system research. The review also reveals significant gaps in long-term monitoring, standardization, and economic alignment, with payback periods varying by region (e.g., 6–9 years in East Asia, 8–10 years in Brazil). This study highlights the evidence-to-deployment translation bottleneck and calls for stronger interdisciplinary collaboration, empirical validation, and product-level design strategies to enhance BIPV scalability.

Apart from the coupling among thermal, electrical, and optical performance, phase change materials and their structures are also core factors influencing the feasibility of distributed energy systems. Wang et al. evaluated the thermal performance enhancement and structural optimization of finned shell-and-tube heat storage units coupled with air-source heat pump (ASHP) systems, aiming to improve clean heating efficiency in cold regions. Through combined experiments and validated numerical simulations (error < 5%), the results reveal that natural convection dominates the phase change heat transfer process, while the addition of expanded graphite significantly enhances thermal conductivity. A key finding is the identification of an optimal finning coefficient range (4.16–5.68), which balances conductive enhancement and convective suppression, leading to a 47–59% reduction in PCM melting time. Furthermore, a predictive model for melting time was developed in the study, enabling rapid system design. The results demonstrate that optimized thermal storage units can effectively mitigate supply–demand mismatch and improve ASHP opera-

tional flexibility, providing a practical pathway for reducing fossil fuel dependence and advancing carbon-neutral building energy systems.

Moreover, Song et al. focused on optimizing microchannel heat sinks with concave compound triangular prism structures to address thermal management challenges in high-power electronic devices, where heat flux typically ranges from 100 to 1000 W/cm². Through numerical simulations, the effects of three groove cross-sectional shapes (arc-shaped, rectangular, trapezoidal) and varying groove depths (e.g., 0.2–0.8 mm) on the thermal and flow performance of microchannels were systematically analyzed. The results indicate that under the Performance Evaluation Criterion (PEC), the arc-shaped groove configuration achieves optimal PEC values of 1.32 and 1.28, representing improvements of 4.3% and 0.7% over rectangular and trapezoidal configurations, respectively. This configuration enhances heat transfer efficiency while effectively controlling flow resistance. Structural optimization led to an overall thermo-hydraulic performance improvement of approximately 15–25%, offering an efficient and energy-saving thermal management solution for high-power chips and other high-energy-consumption devices, with a potential reduction in specific cooling energy consumption of about 10–20%. By optimizing microstructural design at the cross-scale level, this work advances energy efficiency from the source, providing quantifiable and verifiable technical support for carbon neutrality pathways in the building sector—particularly for high-energy-consumption systems such as data centers and power electronics. The study offers actionable data and forward-looking insights to support sustainable urban renewal and the green transformation of the building industry.

Passive building design is an important cornerstone for achieving carbon-neutral pathways. Passive design not only reduces the carbon emissions throughout the building life cycle, but also improves the human settlement environment by reducing latent load. For example, an active wind-guiding design strategy for offshore building morphology can address the extreme wind environments and high maintenance costs faced by such buildings throughout their entire life cycle. The geometric optimization such as “curved pitched roofs” can reduce the surface pressure difference across all wind directions by more than 60%. This not only significantly reduces the implicit carbon emissions during the construction phase (due to the reduced anchoring and support materials resulting from lower structural loads), but also greatly enhances the climate adaptability and energy regulation potential during the operation phase. By reducing structural vibration and mechanical losses, the building’s life cycle is extended. This provides crucial technical support and empirical evidence for achieving low-carbon synergy between offshore buildings and regional ecological cycles, and for exploring urban carbon-neutral design paradigms in the deep blue space.

Ren et al. used dynamic building energy simulation to investigate the climate-dependent performance of natural ventilation in Japanese residential buildings under continuous 24 h mechanical ventilation across different climate zones. The results show that the effectiveness of natural ventilation is closely related to climatic conditions and depends on the balance between sensible load reduction and latent load increase. Natural ventilation during the transition seasons usually cannot reduce annual HVAC loads; in contrast, summer night ventilation can achieve the most significant load reduction in transitional climate zones, while adaptive ventilation with humidity control can reduce latent loads and bring moderate energy-saving effects in some regions. This study reveals the climate dependence of hybrid ventilation strategies and provides a useful reference for climate-responsive design, operation optimization, and performance improvement of residential buildings under different environmental conditions.

Finally, Li et al. investigated the effects of solar radiation thermal effects on thermal comfort, electroencephalogram (EEG) activity, and cognitive performance in elderly and

young adults under three radiation intensities (0 W, 500 W, and 1000 W). The results show that age has a relatively small effect on subjective thermal responses, but a significant impact on mental state and cognitive performance. Under high IR (1000 W), the elderly exhibited improved cognitive levels in attention (CPT: +1.53%), reaction ability (DLT: +0.78%), and visual search (VST: +2.04%), whereas young people showed declines of −2.78%, −1.21%, and −3.82%, respectively. EEG analysis revealed that frontal lobe logarithmic power in both groups was 4.55–6.79% higher than other brain regions. High radiation suppressed EEG activity in young people but triggered compensatory activation in the elderly, reducing age-related neural differences. Correlation analysis identified the right frontal electrodes (F4, F8) and occipital O1 as potential candidate electrodes for evaluating cognitive performance. This study provides objective physiological evidence for understanding how solar radiation's thermal effect directly influences human thermal comfort and cognition, with implications for designing indoor thermal environments in elderly care buildings.

3. Conclusions and Outlook

This Special Issue presents significant advances in carbon-neutral pathways for urban building design across multiple scales. Key findings include: (1) a multi-scale value assessment framework for industrial heritage enabling differentiated low-carbon renewal strategies; (2) evidence that urban form influences low-carbon behavior through direct and perception–psychology pathways, with psychological factors playing the strongest role; (3) identification of BIPV scalability gaps, particularly in user-centered dimensions and empirical validation; (4) an optimal finning coefficient range for thermal storage units, reducing melting time by 47–59%; (5) arc-shaped groove microchannel designs achieving superior thermal–hydraulic performance; (6) active wind-guiding geometries reducing offshore building wind pressure differentials by over 60%; (7) climate-dependent natural ventilation performance under continuous mechanical ventilation; (8) age-differentiated cognitive responses to infrared radiation, with elderly showing compensatory neural activation. Future research should prioritize interdisciplinary integration, long-term monitoring, empirical validation, and personalized design strategies for diverse user groups to accelerate carbon-neutral transitions in the built environment.

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