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Research on low-carbon design and operational adaptation of urban stadium buildings under the "carbon neutrality" goal

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Abstract. To address the core contradiction of "low-carbon design yet high-carbon operation" in urban stadiums under the "carbon neutrality" goal, this study systematically explores the adaptation logic between low-carbon design and operation of stadiums from a full-life-cycle perspective, drawing on the practice of venues for the 15th National Games in the Guangdong-Hong Kong-Macao Greater Bay Area. The research indicates that the low-carbon transformation of stadiums requires constructing a collaborative system of "low-carbon design gene implantation and operational efficiency conversion": Existing stadiums should adopt a differentiated renovation strategy of "carbon footprint accounting and technology adaptation"; new stadiums need to strengthen the integrated application of bio-based materials, prefabricated technology, and photovoltaic systems; during the operation phase, efficiency optimization should be achieved through intelligent management and control, functional diversification, and resource recycling. Additionally, a two-way feedback mechanism should be established via digital twin technology, full-cycle standards and incentive systems improved, and an innovative revenue model of "energy services + space operation" developed to attain the goal of sustainable urban architecture. This study provides technical pathways for urban stadiums to achieve full-life-cycle carbon emission reduction and offers references for the carbon neutrality transformation in the construction sector.

Keywords: carbon neutrality, urban stadiums, low-carbon design, operational adaptation, full life cycle

1. Introduction

Guided by the global "dual carbon" goal, the construction sector—one of the primary sources of carbon emissions—has made low-carbon transformation an inevitable trend. As a typical representative of large-scale public buildings, urban stadiums are characterized by a long construction cycle, high energy consumption density, diverse usage functions, and significant fluctuations in demand. They boast enormous carbon emission reduction potential throughout their full life cycle while also confronting numerous challenges. The full-life-cycle theory, as a systematic analytical method, emphasizes the holistic consideration of a building's entire life cycle—encompassing planning and design, building material production and construction, operation and maintenance, and demolition and recycling. This theory provides crucial theoretical support for addressing the low-carbon development dilemmas of stadiums and effectively avoids the limitations of emission reduction efforts confined to a single phase [1]. Currently, although domestic and foreign research on the low-carbon development of stadiums has accumulated certain achievements, most studies focus on the application of energy-saving technologies in individual links, lacking the full-process "design-operation" collaborative thinking rooted in the full-life-cycle theory. Consequently, the low-carbon concepts formulated during the design phase struggle to be effectively translated into practice during operation, restricting the full exertion of stadiums' carbon emission reduction efficiency. Against this backdrop, conducting research on the "design-operation" collaborative adaptation system of stadiums under the carbon neutrality framework in the Guangdong-Hong Kong-Macao Greater Bay Area not only enriches the theoretical system of low-carbon building development but also provides practical guidance for the green and low-carbon construction and operation of regional stadiums. It holds profound theoretical and practical significance for promoting carbon emission reduction in the public building sector and advancing the achievement of the "dual carbon" goal [2].

This study adopts a research approach integrating the case study method and comparative analysis method. Firstly, through an extensive literature review, it synthesizes domestic and foreign research on low-carbon design, operation management, and collaborative development of stadiums, clarifying the current research status and core controversies to lay a solid theoretical foundation. Secondly, it selects typical stadiums of different types (newly built and renovated) and scales in the Guangdong-Hong Kong-Macao Greater Bay Area, conducting in-depth investigations into their design schemes, operation models, and practical carbon reduction effects. Finally, through comparative analysis of the differences and commonalities among these cases, it extracts the key elements and core pathways of "design-operation" collaborative adaptation.

The core theoretical underpinnings of this study are the full-life-cycle theory and collaborative governance theory. The full-life-cycle theory emphasizes the systematic management and control of buildings across all stages—from design, construction, and operation to demolition and recycling. In this research, it provides a framework for constructing the "design-operation" collaborative adaptation system, guiding the study to break free from the constraints of traditional segmented research and focus on the connection and linkage between design and operation phases. Meanwhile, collaborative governance theory focuses on the interaction and collaboration among multiple stakeholders (including design units, operators, and government departments), offering a theoretical basis for analyzing the relationships, division of powers and responsibilities, and collaboration mechanisms among subjects in the "design-operation" collaborative process, thereby facilitating the establishment of a multi-participatory collaborative adaptation system [3].

2. Technical pathways for low-carbon stadium design

2.1. Differentiated low-carbon renovation pathway for existing stadiums

Carbon emissions during the construction phase account for 17%-50% of the total life-cycle emissions of stadiums, while the renovation of existing stadiums can reduce emissions in this phase by over 60%, making it a priority for low-carbon design. The renovation practice of the Guangzhou Tianhe Sports Center has verified the feasibility of this pathway: As a veteran venue that has hosted three National Games, it achieved near-zero carbon transformation through three core technologies—replacing external windows with heat-insulating aluminum alloy frames paired with low-emissivity insulating glass, reducing air conditioning load by 23%; installing photovoltaic systems on the roof of parking sheds, covering 15% of the venue's annual electricity demand; and demolishing enclosed glass curtain walls to transform them into elevated ventilation platforms, combined with fan-assisted natural ventilation systems, lowering the average indoor temperature by 4℃ in summer. Figure 1 shows the stand design model of the Guangzhou Tianhe Sports Center. This "microrenovation + high adaptation" model avoids carbon emissions from building material production and land development associated with new stadium construction, and its renovation concept should be integrated into the renewal plan of urban stadiums [4].

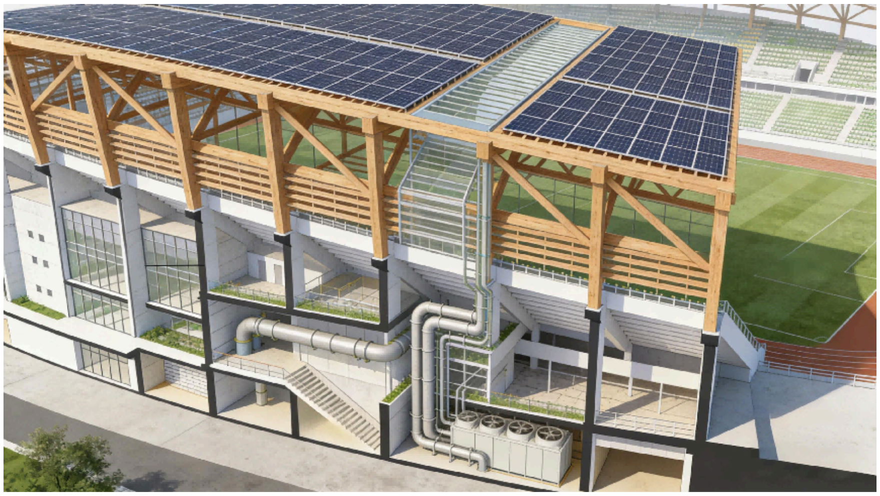

Figure 1. Stand design model of Guangzhou Tianhe Sports Center

2.2. Integrated low-carbon design pathway for new stadiums

New stadiums need to break away from the traditional design thinking of "form first" and construct a technical system centered on low-carbon performance. As China's largest-span wood-structured sports building, the core of the low-carbon design of the Guangming International Equestrian Center lies in material selection and structural innovation: Imported spruce glulam was adopted as the main structural material, reducing production carbon emissions by 60% compared with steel structures; prefabricated technology, involving factory production and on-site assembly of components, reduced construction-phase carbon emissions by 45% and shortened the construction period to 1/3 of that of traditional processes (Figure 2). This practice proves that the combination of bio-based materials and prefabricated technology can reduce the carbon fixation cost of stadiums from the source.

The envelope structure is a highlight of low-carbon design for new stadiums, mainly optimizing thermal performance to reduce energy demand and lay the foundation for energy conservation during the operation phase. The Macao Tap Seac Multisport Pavilion reduced daytime lighting energy consumption by 70% through natural lighting design of glass and aluminum exterior walls; the Shenzhen Joy Theater adopted high-performance thermal insulation materials and adjustable sunshade systems, with building carbon emission intensity nearly 50% lower than that of reference buildings, exceeding the requirements of Shenzhen's near-zero carbon pilot project. Notably, the roof design of large-span stadiums has become an important carrier for the integration of low-carbon technologies—the Climbing Venue of the Guangzhou University Town Sports Center deployed photovoltaic modules on the roof, combined with a high-efficiency multi-connected system, achieving a 53% energy saving rate and 46% carbon reduction rate of the building itself, making it China's first zero-carbon renovated sports venue. This integrated design of "photovoltaics + envelope" not only meets the lighting needs of large-span structures but also lays the foundation for energy self-sufficiency during the operation phase [5].

Figure 2. Guangming International Equestrian Center

2.3. Low-carbon energy system pathway for stadiums

The large-scale application of renewable energy in stadiums needs to break the misunderstanding of "technology accumulation" and construct an energy system of "load matching—energy storage regulation—power grid interaction." The Shenzhen Longhua Culture and Sports Center built a distributed photovoltaic system with a supporting energy storage power station system, featuring a charging and discharging duration of 2 hours (Figure 3).

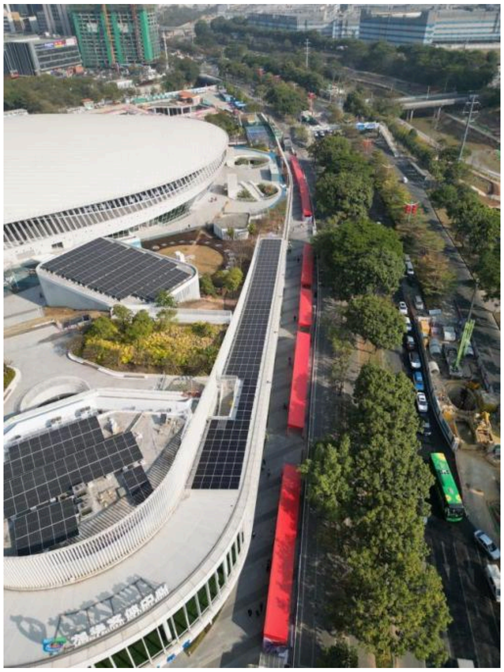

Figure 3. Shenzhen Longhua Culture and Sports Center with photovoltaic panels installed

The coordination between passive energy technology and active renewable energy is the core pathway to improve energy system efficiency, with its inherent logic of "first reducing demand, then optimizing supply." Passive technology reduces energy consumption by utilizing natural conditions, reducing the load pressure on active technology, and forming an adaptive relationship of "demand-side reduction—supply-side efficiency." The main venue of the Hong Kong Kai Tak Sports Park is connected to a regional cooling system for air conditioning, saving 30% more energy than traditional central air conditioning. These indicate that the coordination between active renewable energy technology and passive energy-saving technology can form a "supply-demand matching" low-carbon energy system, providing flexible space for energy management during the stadium operation phase.

The implementation of the aforementioned technical pathways essentially involves implanting "low-carbon genes" into stadiums during the design phase. However, without matching operational mechanisms, these technical potentials are difficult to translate into actual carbon reduction efficiency. Therefore, how to achieve the transformation from "technology implementation" to "efficiency optimization" through intelligent, diversified, and recycling-oriented operational methods has become a key link in forming a closed loop for full-life-cycle low-carbon development.

3. Operational adaptation mechanisms for efficiency optimization

3.1. Intelligent control systems for dynamic load matching

Intelligent management and control systems are the core hub connecting low-carbon design and operational efficiency, whose core value lies in realizing dynamic matching between "technical potential and actual load" through data-driven approaches. From the perspective of adaptation mechanism, the technical efficiency of low-carbon design (such as photovoltaic power generation efficiency and air conditioning energy-saving potential) can only be released through precise regulation, while traditional manual operation and maintenance struggle to cope with real-time fluctuations in stadium load. The energy and carbon management platform of the Guangzhou Tianhe Sports Center constructed a closed loop of "data collection—algorithm analysis—precision control": By deploying IoT sensors to collect real-time data on electricity consumption, water use, and carbon emissions, it established a correlation model between energy consumption and load of each system; AI algorithms dynamically adjusted the operating parameters of air conditioning and lighting based on historical data and real-time scenarios (such as event type, number of spectators, and outdoor temperature), ultimately reducing overall energy consumption by 18%. This practice reveals the core function of intelligent systems: breaking the data barrier between design and operation—the low-carbon parameters during the design phase (such as photovoltaic installed capacity and air conditioning energy efficiency ratio) need to be verified through operational data, while load fluctuations during operation provide feedback for design optimization. The "digital twin" operation hub of the Shenzhen Bao'an Sports Center (Figure 4) went a step further, integrating data such as photovoltaic power generation, energy storage status, and stadium load for visual display, and optimizing energy scheduling strategies in advance by simulating energy demand under different event scenarios, improving operation and maintenance efficiency by 35%. These prove that the core value of intelligent management and control systems lies in breaking the data barrier between design and operation and realizing dynamic matching between low-carbon technologies and actual loads [6].

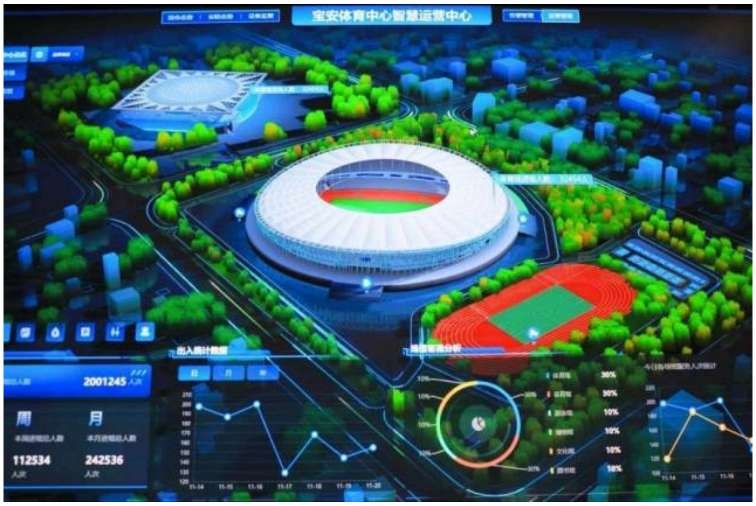

Figure 4. Intelligent operation and maintenance system of Shenzhen Bao'an Sports Center

3.2. Functional diversification for enhanced space utilization

Functional diversification is a key pathway to solve the "high-carbon paradox" of stadiums—the huge contrast between full-load operation during events and idleness after events leads to a surge in carbon emissions per unit use efficiency. Functional diversification reduces the carbon emission intensity per unit function by improving space utilization. Its inherent logic is that the carbon emissions of stadiums are relatively fixed, and the carbon cost per unit time and unit function can be amortized by increasing the frequency of use and types of functions. The "shared operation" model of the 15th National Games addressed this problem: The Shenzhen Longhua Culture and Sports Center undertook competitive functions during events and transformed into a civic space integrating sports activities and cultural performances after events, ensuring a 100% post-event utilization rate of permanent venues; the Guangzhou Olympic Sports Center transformed the second-floor evacuation corridor into an intelligent track, converting idle space into national sports resources. Functional diversification is not a simple spatial superposition but a win-win situation of carbon emission reduction and social benefits through flexible reservation in the design phase and scenario conversion in the operation phase [7].

The scientific paradigm of functional diversification operation needs to establish a triple adaptation mechanism of "event demand—daily operation—emergency support," whose core is to achieve low-carbon operation under different scenarios through the coordination of design flexibility and operation management. The practice of the Macao Tap Seac Multisport Pavilion is quite informative: During the design phase, an adjustable stand system was adopted, which can quickly complete the layout of 5,000 seats during events and shrink to a 3,000-seat multi-functional hall in daily use, while reserving emergency shelter functional space; during operation, through scenario-based settings of intelligent lighting and air conditioning systems, the energy consumption fluctuation under different functional modes is controlled within 15%. This "one venue for multiple purposes" operation model increased the annual usage days of the stadium from 120 days of traditional venues to more than 300 days, reducing carbon emissions per unit function by 40%.

3.3. Full-chain resource recycling for low-carbon operations

Resource recycling during the operation phase is an important supplementary pathway for the low-carbonization of stadiums, whose core lies in establishing a full-chain recycling system of "energy—water resources—waste." The Hong Kong Kai Tak Sports Park constructed a closed-loop resource management system: The roof photovoltaic system meets 10% of the power demand; the rainwater collection system treats and uses water for lawn irrigation; kitchen waste is converted into compost through a decomposition system for park greening, realizing internal resource circulation.

The effective operation of the resource recycling system relies on the collaborative adaptation of design and operation. The Guangming International Equestrian Center reserved rainwater collection pipelines and garbage sorting space during the design phase, and realized precise matching between rainwater storage capacity and irrigation demand through IoT technology during operation, making the utilization rate of non-traditional water sources reach 30%; the Climbing Venue of the Guangzhou University Town Sports Center processed construction waste generated from renovation into recycled aggregates for site pavement, reducing double carbon emissions from waste transportation and new material procurement. These indicate that resource recycling is not an additional measure during the operation phase but the result of joint actions of space reservation in the design phase and process design in the operation phase [8].

Although the adaptation mechanisms in the operation phase can effectively unlock the technical potential of the design side, their sustainability still faces challenges in the absence of institutional guarantees and market incentives. To truly realize in-depth "design-operation" collaboration, it is imperative to construct a full-cycle adaptation system that integrates technical feedback, standard guidance, and revenue innovation.

4. Collaborative adaptation system for full life-cycle integration

4.1. Technology adaptation through two-way design-operation feedback

Construct a technology collaboration platform centered on digital twins to achieve data intercommunication between design and operation. During the design phase, access historical load data of operators and optimize technical schemes by simulating energy demand under different scenarios—based on sports population data of surrounding communities, the Shenzhen Guangming International Equestrian Center flexibly designed competition venues and civic activity spaces, reducing post-event operation energy consumption by 30% [9]. During the operation phase, establish a technical efficiency evaluation system and regularly feed back actual carbon emission data to the design team to provide a basis for subsequent stadium renovation. The Guangzhou Tianhe Sports Center releases quarterly carbon footprint reports, and optimizes and adjusts the tilt angle and cleaning cycle of modules in response to fluctuations in photovoltaic system efficiency, increasing power generation efficiency by 12%.

Promote the technical pathway of "modular design + scenario-based operation." Modular design can realize rapid spatial conversion of stadiums—for example, the Hong Kong Coliseum adopts a movable stand system, controlling energy consumption fluctuations within 10% under different scenarios such as basketball games and concerts; scenario-based operation presets energy consumption parameters for different functional modes through intelligent systems to achieve precise adaptation of technology application. This technical pathway not only ensures the functional needs of events but also reduces daily operation costs, forming a virtuous cycle between design and operation [10, 11].

4.2. Institutional adaptation with full-cycle standards and stakeholder participation

Establish a low-carbon standard system covering the entire cycle of design, construction, and operation. During the design phase, incorporate carbon emission standards for the operation phase into design specifications, referring to the "Guidelines for the Construction of Near-Zero Carbon Emission Zone Pilots in Shenzhen" and clarifying the mandatory indicator that the stadium's operational carbon emission intensity should be lower than $54kgCO_2/(m^2 \cdot a)$; during the operation phase, implement a "carbon footprint certification

+ annual audit" system, linking certification results to stadium operation subsidies. The "pre-event calculation—mid-event accounting—post-event recalculation" mechanism of the 15th National Games can be transformed into a regular system to ensure the continuous compliance of the low-carbon performance of stadiums [12].

Construct an incentive system of "government guidance + market drive + public participation." At the government level, increase subsidies during the operation phase and provide annual operation subsidies to stadiums that meet near-zero carbon standards; at the market level, promote the inclusion of stadium carbon emissions in the regional carbon trading market, encouraging enterprises to participate in stadium low-carbon renovation through carbon asset donations; at the public level, promote a "carbon points" system, guiding citizens to participate in low-carbon actions through mini-programs such as "Zero-Carbon National Games," forming a good atmosphere of joint governance by the whole people.

4.3. Market adaptation through energy service and space operation models

Promote the composite revenue model of "energy services + space operation." In terms of energy services, introduce professional institutions to invest in and operate photovoltaic and energy storage systems through energy performance contracting, with stadiums paying service fees using saved energy costs to reduce initial investment pressure. In terms of space operation, learn from the experience of the Shenzhen Longhua Culture and Sports Center, converting idle stadium space into commercial, cultural and other functional areas, and using diversified revenues to subsidize low-carbon operations [13].

Tap the economic value of carbon assets and green power transactions. Stadium operators should establish a carbon footprint accounting system, converting carbon emission reductions from energy-saving renovations into tradable carbon assets; at the same time, realize the market-oriented sales of surplus photovoltaic power through green power trading platforms. The Hong Kong Kai Tak Sports Park adopted a combination of green power procurement and carbon offsetting, not only ensuring the carbon neutrality goal of events but also enhancing the social value of the stadium through carbon credit accumulation [14].

Through the three-dimensional collaboration of technical adaptation, institutional guarantees, and market drivers, urban stadiums are expected to break free from the traditional "construction-focused and operation-neglected" model and move toward a new paradigm of full-life-cycle carbon neutrality.

5. Conclusion and outlook

The low-carbon transformation of urban stadiums under the "carbon neutrality" goal is essentially a systematic collaboration between low-carbon genes in the design phase and adaptive capabilities in the operation phase. Practices from the 15th National Games in the Guangdong-Hong Kong-Macao Greater Bay Area have proven that through pathways such as prioritizing the renovation of existing stadiums, integrating technologies for new stadiums, precise regulation by intelligent systems, and functional diversification operation, stadiums can achieve a carbon emission reduction of over 40% throughout their life cycle. Currently, the core problem to be solved is the adaptation bottleneck between design and operation, which requires constructing a collaborative system from three dimensions: technology, system, and market—breaking data barriers with digital twin technology, ensuring low-carbon efficiency with full-cycle standards, and activating market dynamics with composite revenue models.

The innovations of this study are mainly reflected in three aspects: Firstly, it proposes the conceptual framework of a "low-carbon gene - operational adaptation" collaborative system, breaking through the limitation of the separation between design and operation in traditional research. It constructs a full-chain adaptation logic from technology implantation at the design stage to efficiency conversion at the operation stage, providing a systematic analytical framework for the low-carbon transformation of stadiums. Secondly, it achieves breakthroughs at the technical and practical levels: it clarifies the integrated application pathways of bio-based materials, prefabricated technology, and photovoltaic systems, and verifies the empirical effects of the "load matching - energy storage regulation - power grid interaction" energy system and the intelligent operation and maintenance closed loop. This delivers replicable technical schemes for different types of stadiums (newly built and renovated). Thirdly, it offers new directions for policy formulation and industry development: it promotes the establishment of full-cycle low-carbon standards covering design, construction, and operation, and innovates a market-oriented incentive model of "energy services + space operation + carbon asset trading." It thus provides a reference paradigm with both theoretical and practical value for the carbon neutrality transformation in the construction sector [15].

Future research can focus on two directions: First, research on the scenario-based adaptation of low-carbon technologies, formulating differentiated technical schemes for stadiums of different scales and functions; second, the refined development of carbon accounting systems, realizing real-time tracking and precise accounting of carbon emission data combined with IoT technology. With the advancement of the "dual carbon" goal, urban stadiums will no longer be merely carriers for competitions and fitness but also nodes for urban energy circulation, spaces for low-carbon life, and symbols of ecological civilization, providing solid support for the carbon neutrality transformation in the construction sector.

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