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Application Of Ai-Based Systems In Smart Sports Facilities: Enhancing Sustainability And Energy Efficiency In Urban Environments

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Abstract
As global energy consumption in the building sector continues to rise, sports facilities have become critical focal points in the urgent pursuit of sustainable urban transformation. This study presents a comprehensive review of the application of artificial intelligence (AI) in smart sports facilities, focusing on its role in enhancing energy efficiency and promoting urban sustainability. Amid accelerated urbanization and increasing climate pressures, sports venues integrating AI, IoT, and automation technologies have emerged as key sites for energy management, spatial optimization, and behavioral guidance. Drawing on literature from 2015 to 2025, this paper identifies four major domains of AI application: energy monitoring and scheduling, autonomous environmental control, user interaction and behavioral nudging, and contextual adaptability with sustainability integration. It further analyzes measurable energy-saving outcomes, contributions to carbon reduction, and alignment with international green building certification systems such as LEED, BREEAM, and WELL. While AI technologies offer transformative potential, their implementation still faces challenges related to data infrastructure, cost-effectiveness, human-machine interaction, and ethical governance. The study highlights the importance of interdisciplinary collaboration, localized adaptation, and institutional frameworks to ensure effective deployment and social acceptance. It concludes with future directions, including the development of performance-based AI sustainability indicators, regional energy data platforms, cross-sector collaboration models, and inclusive user engagement mechanisms, positioning AI as a critical enabler of resilient, low-carbon, and people-centered urban sports infrastructure.

Keywords: *Sustainable Urban Development; Sustainable Information Technology; Sustainability-Oriented Behavioral Nudging; Energy Optimization Strategies; Intelligent Building Systems*

1. INTRODUCTION

Amid accelerating global urbanization, escalating energy consumption and environmental degradation have emerged as critical challenges for contemporary urban governance. Striking a balance between improving quality of life and economic efficiency while achieving resource optimization and environmental sustainability has become a pressing priority. Urbanization and infrastructure development must proceed in tandem with energy reduction and sustainable transformation to realize the principle of "coexistence between economic benefit and sustainability" (Guang et al., 2025; Wu et al., 2025). According to the Global Status Report for Buildings and Construction 2024/2025, the building and construction sector accounted for 34% of global final energy use and 37% of CO_2 emissions in 2021, with a significant portion attributable to public sports facilities—underscoring their influential role in energy governance (United Nations Environment Programme & Global Alliance for Buildings and Construction, 2025). In the post-pandemic era, the convergence of health promotion and spatial intelligence has positioned sports facilities as pivotal nodes for advancing healthy cities and sustainable communities (Jevtic et al., 2022; Santa et al., 2021). Within this context, Smart Sports Facilities have emerged, integrating artificial intelligence (AI), the Internet of Things (IoT), and building automation technologies to enhance energy efficiency and intelligent facility management, thereby exerting a profound impact on urban sustainability governance (Qian et al., 2024; Bibri et al., 2024). However, existing literature on AI applications in smart sports facilities largely remains confined to isolated technical systems, lacking integrative studies across domains and technologies. In response, this paper proposes a comprehensive review of the current applications of AI in smart sports facilities, focusing on their contributions and challenges in enhancing energy efficiency and promoting sustainable development. Based on literature published between 2015 and 2025, this study employed a multi-keyword retrieval strategy—such as "artificial intelligence" AND "smart sports facilities," "AI systems" AND "urban sustainability" AND "energy efficiency," "smart sports infrastructure" AND "green buildings" AND "AI," "IoT" AND "AI" AND "sports facility management," and "AI-driven" AND "energy optimization" AND "urban environment." This approach facilitates the collection of representative interdisciplinary research and captures emerging trends in AI-driven sustainability governance.

By analyzing and categorizing cross-domain literature, this paper aims to clarify the characteristics, use cases, benefit mechanisms, and potential limitations of AI technologies in this field. It ultimately proposes future research directions and practical strategies, offering a conceptual foundation and actionable framework for the transition of smart sports facilities toward environmental sustainability and digital governance.

2. Function-Oriented Applications of AI in Smart Sports Facilities

The practical foundation of smart sports facilities lies in the integration of artificial intelligence (AI) technologies with building environmental management systems, tailored to diverse spatial demands and governance objectives. AI is no longer confined to isolated equipment upgrades; instead, it has evolved into a critical enabler for digital governance and sustainable development in sports infrastructure. To systematically present the governance functions and contextual deployments of AI in such venues, this study categorizes its applications into four strategic domains: (1) energy monitoring and scheduling, (2) spatial flexibility and autonomous control, (3) user interaction and behavioral guidance, and (4) contextual adaptability and sustainability-oriented implementation strategies.

2.1 Energy Monitoring and Scheduling

A sustainable governance framework for sports facilities begins with the development of intelligent energy information networks capable of identifying energy sources and forecasting consumption trends. These data-layer systems, driven by AI and IoT technologies, collect real-time environmental parameters—such as temperature and humidity (Lin et al., 2025), lighting intensity (De Paz et al., 2016), occupancy density (Li et al., 2016), and air quality (Saini et al., 2020)—via heterogeneous sensors, and integrate them into cloud-based platforms (Arnesano et al., 2016; Li, 2024; Liu & Wang, 2022), creating a high-resolution, environment-aware data infrastructure. Through machine learning and historical data comparison, these systems can identify energy hotspots and high-consumption activities, forming the basis for load balancing and strategic energy scheduling (Mostafa et al., 2022). In practice, Germany's Commerzbank Arena deployed an IoT-based predictive control system in 2014, linking real-time climate data to turf heating requirements. After implementing a nighttime predictive heating strategy in 2015, the arena reduced winter energy consumption by 85%, saving over 1 GWh of electricity and cutting nearly 200 tons of carbon emissions (Schmidt et al., 2018). The EU SPORTe2 project further established smart energy platforms in multifunctional venues across Italy and Spain, incorporating CO_2 levels, illumination, occupancy, and equipment usage to build a three-tier architecture—on-site sensing, facility management, and cloud-based optimization—achieving cross-site data integration and energy dispatch. In a medium-sized Italian sports facility, this system utilized behavioral prediction models to automatically adjust HVAC and lighting, resulting in a 23% reduction in energy costs (European Commission, 2024).

2.2 Spatial Flexibility and Autonomous Control

As climate variability, functional diversification, and fluctuating occupancy loads challenge facility operations, static energy-efficient design alone is no longer sufficient. The critical determinant of resilience and operational efficiency lies in the ability of facilities to achieve real-time perception and proactive adjustment at the control level. AI-based control systems integrate real-time sensor data with predictive model outputs to create closed-loop logic for subsystems such as shading, ventilation, HVAC, and lighting, enabling autonomous spatial responses to environmental fluctuations (Cotrufo et al., 2020; Sanjeevi et al., 2025).

Neethirajan (2024) highlights that AI controllers, when combined with real-time feedback, enable dynamic adaptive regulation in shading and ventilation systems—signaling a shift from passive energy conservation to proactive governance. Hanafi et al. (2024) further observe that AI has become the decision-making hub for multiple energy subsystems, coordinating inter-device responses through intelligent logic. For instance, during the Tokyo 2020 Olympics, GE Digital deployed a centralized AI energy management platform across 36 venues, automatically adjusting lighting and air conditioning in response to crowd density, microclimates, and event rhythms—ensuring both comfort and efficiency (Tokyo Metropolitan Government, 2021).

2.3 User Interaction and Behavioral Guidance

As AI applications in smart venues mature, the role of users has shifted from passive equipment operators to active co-participants in energy governance. Especially within bottom-up systems, users can set energy-saving goals, engage with interactive interfaces, and receive real-time feedback—actively shaping energy use and behavioral patterns (Pasini et al., 2017). In this context, AI serves not only as a technical controller but also as a behavioral intermediary and cultural conduit for sustainability.

Smart venues often incorporate voice assistants, spatial prompts, personalized scheduling suggestions, and feedback mechanisms to foster user engagement and guide energy-optimizing behaviors (He et al., 2022). AI-powered virtual assistants and chatbots can provide real-time navigation and queue information, prompting users to adjust their actions accordingly (Dorey, 2024). Crowd management systems can predict congestion zones and offer alternative routes, effectively nudging behavior, enhancing spatial efficiency, and supporting energy performance.

At Ohio State University, an AI-based collective intelligence system paired with real-time video analytics helped spectators make informed decisions via a mobile app and visual dashboards—reducing queue times and redistributing crowd flows by 25%. This not only improved energy efficiency but also strengthened user trust and engagement with AI-based services (Wong, 2024). These cases demonstrate that AI-enabled systems not only support smart facility operations but also construct a participatory, human-centered model of energy governance fundamental to sustainability implementation.

2.4 Contextual Adaptability and Sustainability-Oriented Implementation

Despite the promising capabilities of AI in perception, control, and interaction (Hanafi et al., 2024), its practical effectiveness depends on responsiveness to local spatial structures, usage behaviors, and socio-cultural dynamics. Deploying AI based solely on standardized logic without considering local needs and institutional contexts risks creating operational gaps, user friction, or governance failures. Therefore, AI implementation must emphasize contextual adaptability (Lee, 2024), involving system design and integration strategies tailored to site-specific features—ranging from architectural configuration and operational protocols to behavior-oriented interventions—to realize sustainable outcomes and community-aligned governance.

Taiwan has demonstrated responsive strategies in promoting smart sports and health-oriented spaces. For instance, Taichung Central Park installed a DALI-compliant smart lighting system that adjusts illumination based on time, foot traffic, and usage patterns—balancing energy saving, light pollution control, and nighttime safety. In Kenting National Park, smart lighting along trails responds to real-time occupancy, achieving both ecological sensitivity and energy efficiency. Yunlin County's "Smart Health Trail," jointly developed by local government and universities, integrates Bluetooth sensors, an AI app, and interactive displays to deliver personalized exercise recommendations and health feedback. A point-based reward system encourages long-term participation and strengthens community engagement and behavioral self-regulation.

These cases reflect not only the localization of technical systems but also the dynamic negotiation between people and environments during smart infrastructure implementation. Through the integration of crowd sensing, real-time interaction, and adaptive control, AI systems can concurrently support energy management and public health goals. Importantly, such systems must also uphold data ethics, transparency, and institutional linkages—ensuring that AI serves not merely as a technological tool but as a key intermediary for sustainable governance and community collaboration.

3. Contributions of AI to Sustainability and Energy Efficiency

3.1 Transforming Energy Efficiency and Management Models in Sports Facilities

The integration of artificial intelligence (AI) into smart sports facilities signifies not only a digital transformation of operational logic but also delivers measurable impacts in energy conservation, carbon reduction, and sustainable practice. A growing body of empirical research (Ali et al., 2024) highlights the critical role of AI systems in reducing energy consumption, lowering carbon emissions, and enhancing energy scheduling efficiency. Farzaneh et al. (2021) report that AI applications in Building Management Systems (BMS) and Demand Response Programs (DRP) achieve an average of 26% energy savings, with particularly strong performance in ventilation and preheating controls. These systems leverage real-time sensing and predictive control to optimize building operations, suppress peak loads, and reduce unnecessary energy waste—thereby minimizing carbon footprints and operational costs while positioning AI as a core technology in urban energy transition strategies.

More fundamentally, AI not only improves energy efficiency but redefines the management paradigm of energy use in sports venues. Traditional facility management often relies on static schedules and manual oversight, which tend to respond poorly to rapidly shifting user behaviors and climatic variability, resulting in inefficient energy coordination. In contrast, AI systems—driven by deep learning and streaming sensor data—possess real-time learning and predictive capabilities. They can autonomously optimize HVAC, lighting, and ventilation parameters based on current occupancy, temperature, humidity, and activity schedules, enabling second-level adjustments and micro-level energy optimization (De Lemos & Grześ, 2019). Furthermore, AI models evolve with long-term operational data, continually refining their strategies and creating feedback loops that co-adapt with spatial usage patterns. This marks a paradigm shift from static to dynamic, resilient, and adaptive facility management.

From an applied perspective, Qian et al. (2024) demonstrate through simulation that small- to mid-sized sports facilities can reduce cooling loads by up to 30% by integrating AI systems with passive energy-saving designs, such as natural ventilation, shading strategies, and optimal building orientation. Similarly, Yakak et al. (2024) applied Rao algorithms to optimize rooftop solar panel layouts, achieving annual electricity savings of 18–27% and shortening payback periods—underscoring the value of AI in supporting renewable energy deployment decisions. Overall, the adoption of AI in sports facilities not only enhances energy performance but also advances predictive, dynamic, and stable energy strategies, positioning AI as a vital driving force for the future of intelligent and sustainable architecture.

3.2 International Standards and Certification Mechanisms

AI technologies are rapidly being integrated into global regulatory frameworks for building energy efficiency and sustainable development, serving as key evaluation criteria in internationally recognized certification systems such as LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Method), and the WELL Building Standard. AI demonstrates distinct advantages in rating categories such as "Energy & Atmosphere" and "Operations Optimization," enabling real-time energy monitoring, dynamic load control, and intelligent equipment management. These capabilities not only boost buildings' energy performance ratings but also align with policy mandates for net-zero emissions and climate-resilient smart cities (Shen & Pan, 2023). As international green building standards place increasing emphasis on verifiable performance during the operational phase, AI's real-time monitoring and predictive control capabilities are emerging as critical tools for transitioning from static design-based evaluations to performance-based assessments. For instance, Energizer Park in St. Louis, Missouri—the home stadium of the St. Louis CITY SC professional soccer team—implemented an AI-powered energy management system during its design and operational phases. This system, integrated with real-time occupancy sensors and user behavior analytics, enabled automated load balancing of lighting and HVAC systems. According to its annual energy report, the facility exceeded the energy efficiency benchmarks required for LEED Gold certification and received local government awards and policy incentives for outstanding carbon management performance (Matchday, 2025). This case not only validates the practical energy-saving effectiveness of AI systems but also illustrates their role as intermediaries linking certification systems, public-sector incentives, and intelligent operations.

In sum, AI applications in smart sports facilities are no longer confined to technical system upgrades but are increasingly positioned as core infrastructures supporting energy transition, carbon neutrality, and institutional integration. Their real-time energy-saving capabilities, alignment with international standards, and dynamic control functions suggest that AI will become a pivotal module in future sustainability assessment frameworks. Promoting interoperability across facilities, developing high-comparability performance metrics, and implementing institutionalized technical subsidies and market-based incentives will be critical in scaling the sustainable transformation of smart venues.

4. Challenges and Limitations

Despite the promising potential of artificial intelligence (AI) in the context of smart sports facilities, its actual deployment and broader diffusion remain hindered by a range of interrelated challenges. These can be categorized into four main dimensions: technological infrastructure, economic feasibility, operational culture, and governance frameworks. First, deficiencies in data quality and sensor infrastructure form a fundamental barrier to system performance. Most facilities lack sensing infrastructure embedded from the design stage, resulting in fragmented data sources, insufficient coverage, or sampling bias. These issues constrain the predictive accuracy and generalizability of AI models and may even lead to overfitting (Vasicek, 2019). Moreover, inconsistent communication protocols and data formats across different manufacturers further complicate data integration and model deployment, thereby limiting scalability and cross-facility implementation.

Second, economic and maintenance feasibility present significant obstacles for small- to medium-sized sports facilities. AI systems typically require substantial investment in advanced sensors, edge computing devices, and integrated platforms (Coiera, 2019). Such capital-intensive demands impose burdens on publicly funded or regionally managed facilities with limited budgets. Additionally, AI systems are not “deploy-and-forget” solutions; their sustained performance depends on continuous data updates, model recalibration, and hardware upgrades—resulting in a high total cost of ownership (TCO). Without robust cost–benefit assessment models, it is difficult to secure long-term commitment from decision-makers.

Third, operational and cultural gaps may diminish the effectiveness of these technologies (Hammerschmidt et al., 2025). Facility staff unfamiliar with digital platforms may distrust system predictions and autonomous controls, preferring manual interventions to maintain a sense of control—thereby undermining system efficiency. Furthermore, the lack of explainability in AI decision-making processes can erode user trust and acceptance, leading to human–machine interaction mismatches.

Fourth, concerns over data governance and ethical risks are growing (Zhang et al., 2021). Real-time crowd monitoring, facial recognition, and environmental tracking systems in smart venues frequently involve sensitive personal data. Without robust mechanisms for anonymization, secure storage, and transparent use, these technologies risk serious privacy violations and misuse. While regulations such as the EU’s GDPR emphasize principles like data minimization, informed consent, and system transparency, the implementation of such safeguards in multifunctional, high-traffic environments remains insufficient.

Finally, an overarching governance framework is still lacking. At present, the implementation of AI in smart venues is predominantly led by private technology providers, with limited leadership or systemic support from public authorities. This results in closed systems, lack of data transparency, and technological lock-in. The absence of mature governance mechanisms—such as interdepartmental coordination and clearly defined responsibilities—

further impedes sustainable integration (Arun et al., 2025). Moving forward, there is an urgent need to strike a balance between operational efficiency and public value by establishing an integrated governance system encompassing legal regulations, technical standards, and institutional structures. Such a framework is essential to ensure the long-term viability and public trust in AI systems within smart sports infrastructure.

5. Future Trends and Research Directions

In light of the aforementioned limitations, the future development of AI technologies in sports facilities should move beyond isolated technical breakthroughs toward structural transformation. This transition requires strategic planning, interdisciplinary integration, and institutional co-construction to establish a resilient and scalable framework for sustainable operations.

5.1 Structural Integration of AI with Green Building Modules

Future smart venue design should emphasize the structural integration of AI technologies with energy-efficient architectural elements—such as natural lighting, ventilation pathways, and thermal insulation systems—while embedding AI-based control modules for real-time operational optimization. Integrating Building Information Modeling (BIM) with simulation platforms to create lifecycle-based energy models (LCC) can enhance energy efficiency from the design to the operational stages and support advanced green certifications such as LEED and WELL.

5.2 Development of Regional Smart Energy Collaboration Platforms

Rather than focusing solely on individual facilities, development should progress toward regional AI energy platforms that interlink energy consumption, activity schedules, and maintenance data across sports venues of varying scales. Such a data-sharing and strategy-alignment framework enables cluster-based coordination, enhances overall energy scheduling efficiency and risk management, and provides a governance foundation for city-level smart sports infrastructure.

5.3 Advancement of User-Centered Interactive Energy-Saving Mechanisms

Interactive systems with strong behavioral guidance and feedback capabilities should be developed to foster active user participation in energy-saving practices. Through AI assistants, carbon footprint feedback, real-time heatmap information, and gamified interfaces, such systems can motivate users to engage proactively. These mechanisms also serve educational and communicative functions, transforming facility operations into participatory arenas for public-facing sustainability practices.

5.4 Co-Creation of Cross-Disciplinary Smart Venue Models

Future research and practice should promote collaborative models among AI engineering, environmental design, sports science, and the social sciences. This includes establishing experimental platforms and modular databases to support the development of multi-objective smart venue models that integrate goals such as energy efficiency, health promotion, safety, and aesthetic experience. Applying System Dynamics modeling can facilitate simulation-based planning and iterative feedback mechanisms, enhancing the precision and adaptability of both policy formulation and technological deployment.

5.5 Institutionalization of Smart Venue Certification and Subsidy Mechanisms

It is recommended to establish dedicated AI sustainability evaluation metrics for smart sports facilities, encompassing data governance, energy performance, user experience, and social impact. These metrics should be used as criteria for public subsidies and upgrade incentives. Through institutional incentives and policy support, public and private sectors can be mobilized to jointly advance the sustainable transformation of smart sports infrastructure.

6. CONCLUSION

The application of artificial intelligence (AI) in smart sports facilities is rapidly evolving from a supportive technology to a central pillar of governance. Through its multi-layered functions—encompassing sensing, prediction, control, and interaction—AI has proven effective in enhancing energy efficiency, managing carbon emissions, and improving user experience, making it a critical node in the broader transition toward urban sustainability. While current research and practice demonstrate substantial energy-saving benefits and strategic potential, widespread implementation still faces key barriers, including fragmented data sources, limited model stability, integration challenges, and difficulties in achieving return on investment particularly in small-scale facilities and diverse community contexts. Moreover, digital divides, privacy concerns, and the absence of unified regulatory frameworks hinder the scalability and institutionalization of AI-based systems. In response, future efforts must focus on developing comprehensive design guidelines that integrate technical standards, sustainability indicators, and robust data governance protocols. Establishing standardized evaluation systems and smart certification mechanisms, while fostering interdisciplinary collaboration and policy support, will be essential. Ultimately, AI should be positioned as a bridge that connects operational practice, civic engagement, and urban governance. Only through the coordinated alignment of technology, institutional frameworks, and cultural contexts can smart sports facilities truly emerge as transformative hubs for sustainable and inclusive urban futures.

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