Frontiers in Strategic Management

ISSN 2978-3682

Intelligent Building Energy Management through Renewable Energy Integration and Advanced MEP Systems for Sustainable Construction

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Received: 13 October 2026 | **Accepted:** 29 October 2026 | **Published:** 11 November 2026

Pages 14–33 | **Crossref DOI** 10.64917/fsm/Vol3Iss11-02 | **Vol. 3, No. 11 (November 2026)**

Abstract

The transition toward sustainable construction requires building systems to move beyond conventional energy-efficiency measures toward intelligent, interconnected, and adaptive energy-management architectures. Buildings are increasingly affected by rising energy demand, climate variability, operational complexity, occupant expectations, and the need to integrate renewable-energy resources without compromising indoor environmental quality. Mechanical, electrical, and plumbing (MEP) systems represent a major interface between building energy demand and operational performance, while Building Information Modelling (BIM), Internet of Things (IoT), machine learning (ML), digital twins, and advanced automation provide the digital infrastructure required for intelligent management. This study develops an integrated analytical framework for intelligent building energy management by synthesizing the supplied literature on sustainable construction, BIM-based performance analysis, HVAC optimization, machine learning, IoT, digital twins, building renovation, energy efficiency, and renewable-energy transition. The methodology applies thematic classification, cross-domain synthesis, and systems-level analysis to identify the relationships among building envelopes, renewable-energy systems, MEP services, sensing infrastructure, BIM data, predictive analytics, and intelligent control. The findings indicate that effective building energy management depends on five interconnected capabilities: reducing baseline demand, integrating renewable-energy generation, improving MEP operational efficiency, establishing continuous building-data feedback, and applying predictive or adaptive control. BIM functions as an information backbone, while IoT provides operational data, ML supports prediction and optimization, and digital twins provide a continuously updated representation of building behavior. Advanced HVAC management emerges as a particularly important

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application because thermal conditioning is highly dynamic and strongly dependent on weather, occupancy, ventilation, and equipment conditions. However, technological integration alone does not guarantee sustainability. Interoperability, data quality, legacy-system constraints, occupant requirements, investment costs, cybersecurity, and the complexity of existing buildings can restrict performance. The study proposes an integrated intelligent building energy-management framework linking BIM, IoT, renewable generation, advanced MEP systems, predictive analytics, and facility management throughout the building life cycle. The framework contributes a structured basis for sustainable construction and renovation by treating energy management as a continuous cyber-physical process rather than a collection of independent efficiency interventions.

Keywords: Intelligent buildings; Energy management; Renewable energy; MEP systems; BIM; Internet of Things; Machine learning; HVAC; Digital twin; Sustainable construction

How to Cite: Vance, D. A. (2026). Intelligent Building Energy Management through Renewable Energy Integration and Advanced MEP Systems for Sustainable Construction. Frontiers in Strategic Management, 3(11), 14–33. https://doi.org/10.64917/fsm/Vol3Iss11-02.

1. Introduction

1.1 Background

The building sector occupies a critical position in the global transition toward lower-energy and more sustainable built environments. Building energy consumption is influenced by architectural form, envelope characteristics, climatic conditions, occupancy patterns, HVAC operation, lighting, equipment, ventilation, domestic services, and the effectiveness of facility-management practices. As buildings become increasingly complex, conventional approaches based primarily on equipment efficiency and static operating schedules become insufficient for achieving continuously optimized performance.

Santamouris and Vasilakopoulou (2021) identify the present and future energy consumption of buildings as a major challenge in the transition toward decarbonization. The challenge is not limited to reducing the energy demand of newly constructed buildings. A substantial portion of the existing building stock requires renovation, improved monitoring, and more efficient operation. Climate change further complicates the problem because changing outdoor conditions influence building-envelope performance and the energy requirements of HVAC systems. D'Agostino et al. (2024) demonstrate that climate change can affect the energy performance of building envelopes and consequently influence energy-regulatory requirements.

The concept of sustainable construction has therefore expanded from the selection of efficient materials and systems toward integrated building performance. Green-building design increasingly incorporates energy simulation, renewable-energy systems, intelligent controls, digital information,

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and life-cycle considerations. Abeywardhana (2024) emphasizes energy-efficient design within green-building approaches, while Šmate et al. (2023) discuss contemporary building energy-efficiency considerations. Rahman (2024) further illustrates that energy-efficiency strategies may involve different and sometimes opposing approaches, demonstrating the need for context-specific optimization rather than universal solutions.

Within this context, MEP systems are particularly significant. HVAC equipment, ventilation systems, pumps, electrical distribution, lighting, domestic hot-water systems, and associated controls transform building energy into useful services. Their performance depends not only on equipment specifications but also on sizing, commissioning, operating schedules, control logic, maintenance, and interaction with the building envelope. Advanced MEP systems therefore require an information and control infrastructure capable of understanding building conditions in real time.

BIM provides one of the most important digital foundations for this transformation. BIM enables building components and their relationships to be represented within a structured digital environment. Its applications have expanded from design coordination toward performance analysis, facility management, renovation, and sustainability. Fonseca Arenas and Shafique (2023) review the progress of BIM-based sustainable buildings, while Azmi et al. (2022) demonstrate BIM-based building performance analysis for a green resort in Malaysia.

The integration of BIM with IoT further changes the role of building information. Instead of representing the building only as a design model, an integrated BIM-IoT environment can connect digital building information with real operational measurements. Desogus et al. (2021) examine BIM and IoT sensor integration for monitoring energy consumption and indoor conditions in existing buildings, while Chen et al. (2023) explore BIM-IoT integration for sustainable buildings. Malagnino et al. (2021) similarly identify the integration of BIM and IoT as an important pathway toward smart and sustainable environments.

Machine learning introduces another dimension. Building energy systems generate large quantities of operational data, but conventional monitoring approaches may not convert those data into actionable predictions. ML can identify relationships among weather, occupancy, indoor conditions, equipment operation, and energy consumption. Zhou et al. (2023) provide a comprehensive review of ML applications for HVAC, while Mao et al. (2023) investigate interpretable ML for predictive HVAC control. Sari et al. (2023) demonstrate ML-based HVAC prediction in an Indonesian healthy-building case study.

The integration of these technologies provides the foundation for intelligent energy management. Rather than responding only after energy consumption has occurred, an intelligent building can predict future demand, identify abnormal equipment behavior, adjust MEP operation, incorporate renewable-energy availability, and continuously evaluate performance. Selvaraj et al. (2023) specifically demonstrate the relevance of AI-based smart-building energy management and monitoring systems within smart-city environments. This provides an important

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foundation for the integrated framework developed in the present study.

1.2 Problem Statement

Despite rapid technological development, building-energy management frequently remains fragmented. BIM may be used primarily for design coordination, IoT sensors may be deployed for isolated monitoring, HVAC controls may operate independently of renewable-energy systems, and facility-management teams may lack access to integrated building-performance information.

This fragmentation creates a central research problem: **how can renewable energy, BIM, IoT, intelligent analytics, and advanced MEP systems be integrated into a coherent energy-management architecture that supports sustainable construction throughout the building life cycle?**

A second problem concerns the distinction between monitoring and intelligence. Collecting energy data does not automatically produce energy savings. Similarly, deploying machine-learning algorithms without reliable building data, suitable control interfaces, and appropriate MEP infrastructure may produce limited operational value. The challenge is therefore architectural as much as computational.

A third problem concerns existing buildings. New buildings can potentially be designed around digital integration from the beginning, whereas existing buildings often contain heterogeneous equipment, incomplete documentation, outdated controls, and physical constraints. Altohami et al. (2021) identify BIM, IoT, and facility-management integration as an important consideration in existing-building renovation. The proposed approach must therefore address both new construction and retrofit environments.

1.3 Research Objectives

The study has five objectives. First, it synthesizes the supplied literature on intelligent building energy management, BIM, IoT, ML, renewable-energy integration, and MEP systems. Second, it identifies the functional roles of digital technologies across the building life cycle. Third, it develops an integrated architecture linking renewable energy and advanced MEP systems with intelligent data-driven control. Fourth, it identifies the principal technical, operational, and implementation barriers. Fifth, it establishes research and practical implications for sustainable construction and building renovation.

1.4 Research Questions

The analysis is guided by three research questions:

RQ1: How can BIM, IoT, machine learning, and digital-twin technologies support intelligent building energy management?

RQ2: How can renewable-energy systems and advanced MEP technologies be coordinated within an intelligent building-energy architecture?

RQ3: What technical and operational barriers influence the practical implementation of integrated intelligent energy-management systems?

1.5 Scope and Significance

The study focuses on building-scale energy management with particular attention to HVAC, renewable-energy integration, BIM, IoT, ML, digital twins, building performance analysis, facility management, and sustainable renovation. The

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analysis does not claim experimentally measured energy savings because no original monitored dataset was supplied. Instead, it develops a research-oriented framework derived from the supplied literature.

The significance of the research lies in integrating traditionally separate research domains. Sustainable construction provides the physical foundation, MEP systems provide energy services, BIM provides structured information, IoT provides real-time observations, ML provides predictive intelligence, and renewable-energy systems provide low-carbon energy resources. Their integration can transform building energy management from static equipment operation into an adaptive cyber-physical process.

2. Literature Review

2.1 Building Energy Consumption and Sustainable Construction

Building energy performance is fundamentally connected to the interaction between envelope, climate, internal loads, and building services. Santamouris and Vasilakopoulou (2021) identify decarbonization as a major challenge requiring changes in building energy consumption. D'Agostino et al. (2024) add a climate-sensitive perspective by demonstrating that changes in climatic conditions can alter envelope energy performance and regulatory requirements.

Building-envelope optimization therefore remains an important first stage of energy management. If excessive heat enters or leaves a building, MEP systems must compensate through additional cooling or heating. Intelligent energy management cannot eliminate this physical demand. Consequently, digital optimization should complement rather than replace passive and envelope-based strategies.

Abeywardhana (2024) positions energy efficiency as a fundamental component of green-building design. Šmate et al. (2023) similarly emphasize contemporary building-energy efficiency. These studies suggest that intelligent control is most effective when embedded within a building already designed to minimize unnecessary energy demand.

The literature also indicates that efficiency strategies may involve trade-offs. Rahman (2024) discusses opposing approaches to improving building energy efficiency, highlighting that reducing one type of energy demand may influence other performance criteria. This supports a multi-objective perspective in which energy consumption, comfort, indoor environmental quality, investment, and operational requirements must be considered together.

2.2 BIM as an Energy-Management Foundation

BIM has evolved from a geometric representation tool toward an information-management platform supporting the building life cycle. Doukari et al. (2023) describe BIM within the broader digital-business and enabling-technology environment of construction. Wang (2012) emphasizes BIM's relevance to owners, managers, designers, engineers, and contractors, demonstrating its multi-stakeholder nature.

Bryde et al. (2013) identify project benefits associated with BIM, while Sacks et al. (2018) establish BIM as a comprehensive framework for construction stakeholders. These foundations are

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important because intelligent energy management requires information continuity between design, construction, commissioning, operation, and maintenance.

For sustainable buildings, BIM can contain information concerning building components, spaces, materials, equipment, MEP systems, and performance characteristics. Fonseca Arenas and Shafique (2023) review BIM-based sustainable-building developments, while Azmi et al. (2022) demonstrate BIM-based performance analysis in a Malaysian green-resort context.

BIM also provides opportunities for performance-analysis interoperability. Yang et al. (2022) investigate data exchange between BIM design software and performance-analysis software based on Revit. Such data exchange is critical because energy management requires the transition of building information into simulation and analytical environments.

The literature nevertheless indicates adoption challenges. Zahedi et al. (2022) review global BIM adoption movements and challenges, while Biswas et al. (2024) discuss BIM and advanced technologies within the AEC industry. Therefore, BIM's potential contribution to intelligent energy management depends on organizational readiness, interoperability, data standards, and user capability.

2.3 BIM and IoT Integration

BIM represents relatively structured building information, whereas IoT systems provide dynamic observations. Their integration is consequently a logical step toward intelligent buildings.

Desogus et al. (2021) propose BIM and IoT sensor integration for monitoring consumption and indoor conditions in existing buildings. This is particularly important for retrofits because existing buildings may lack complete operational information. Sensor data can progressively populate the digital representation with actual conditions.

Chen et al. (2023) investigate BIM-IoT integration for sustainable buildings, while Malagnino et al. (2021) review BIM and IoT integration for smart and sustainable environments. Their combined contribution indicates that BIM-IoT integration can connect the static representation of the building with dynamic operational information.

The conceptual implication is that an intelligent building should maintain a feedback cycle:

Physical Building → Sensors → Data Platform → BIM/Digital Representation → Analytics → MEP Control → Physical Building.

This cycle transforms BIM from a passive documentation environment into an operational information layer.

2.4 Machine Learning and Building Performance

Machine learning has become increasingly relevant to building-performance prediction because energy consumption is influenced by nonlinear and interacting variables. Hong et al. (2020) review ML applications across the building life cycle, indicating that intelligent algorithms can contribute beyond operational control.

Triadji et al. (2023) review ML applications in building-performance prediction, reinforcing the relevance of predictive approaches. Prediction is valuable because energy management is inherently forward-looking. If a building can

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estimate future thermal demand, equipment loads, or energy consumption, control actions can occur before inefficient conditions develop.

HVAC represents one of the most significant application areas. Zhou et al. (2023) comprehensively review ML applications for HVAC, while Mao et al. (2023) investigate data analysis and interpretable ML for predictive HVAC control. Interpretability is especially relevant because building operators must understand why a control strategy recommends particular actions.

Sari et al. (2023) demonstrate ML prediction for HVAC in a healthy-building context in Indonesia. This highlights the relationship between energy efficiency and indoor environmental requirements. An HVAC control strategy should not optimize energy independently from the health and comfort conditions that HVAC systems are intended to provide.

2.5 Fault Detection and Predictive Maintenance

Energy management must include equipment health because inefficient equipment operation can undermine otherwise effective control strategies. Villa et al. (2022) develop an ML framework for sustainable maintenance of building facilities. This indicates that predictive analytics can contribute not only to energy scheduling but also to long-term facility performance.

Haruehansapong et al. (2023) investigate deep-learning-based automated fault detection and diagnostics for HVAC systems. Fault detection is particularly important because HVAC equipment may continue operating while degraded, causing increased energy consumption without immediately causing complete system failure.

The combination of predictive control and predictive maintenance therefore creates a more comprehensive energy-management system. Predictive control asks, "What should the system do next?" Predictive maintenance asks, "Is the equipment capable of doing it efficiently?" Both questions are necessary for intelligent MEP management.

2.6 Digital Twins and Cyber-Physical Energy Management

Digital twins represent a further development of BIM and IoT integration. Agostinelli et al. (2021) examine cyber-physical systems for improving building energy management through digital twins and artificial intelligence. The significance of this approach is the creation of an operational digital representation capable of receiving data from the physical building and supporting decisions about its future operation.

A digital twin can potentially integrate building geometry, MEP information, sensor data, equipment status, weather inputs, energy consumption, and predictive models. This makes it a suitable coordination environment for intelligent energy management.

However, a digital twin should not be treated as synonymous with BIM. BIM primarily organizes information about the building, while a digital twin emphasizes continuous operational interaction between physical and digital systems. The distinction is important when designing intelligent energy-management architectures.

2.7 Renewable Energy and Energy Transition

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Renewable-energy integration represents the supply-side component of intelligent building energy management. Piras and Muzi (2024) examine an energy-transition approach using a semi-automatic BIM tool for the Maputo Natural History Museum, illustrating how digital tools can support sustainability-oriented energy transitions.

The supplied literature also includes photovoltaic design resources and software, including Solarius-PV, which indicates the practical role of digital tools in renewable-energy assessment. Renewable-energy integration should nevertheless be coordinated with building demand rather than treated as an independent subsystem.

For example, photovoltaic generation can be used directly by electrical MEP loads, stored, or exported depending on system architecture. When HVAC operation is made flexible, renewable electricity may be used more effectively by aligning certain loads with periods of generation. Thus, renewable integration and intelligent MEP control should be treated as mutually dependent rather than independent interventions.

2.8 Advanced MEP Systems and Indoor Environmental Quality

Energy management cannot be separated from indoor environmental quality. ASHRAE (2005), ISO 17772-1:2017, and related building-service references provide the technical foundation for considering indoor conditions and building-system requirements.

Ventilation is particularly important because energy-saving strategies that reduce outdoor-air delivery may influence indoor air quality. Moschetti and Carlucci (2017) demonstrate the relationship between design ventilation rates and indoor air quality in residential buildings. Bellia et al. (2000) examine outdoor-air design conditions and air-conditioning capacity, illustrating the connection between ventilation assumptions and equipment sizing.

UNI 10339:1995 addresses air-conditioning systems for comfort conditions, while Cumo et al. (2013) and Cumo et al. (2019) provide building-energy and technological-system perspectives. These sources reinforce the principle that intelligent energy management must remain constrained by engineering requirements.

2.9 Existing Buildings and Heritage Buildings

Existing buildings present a different optimization environment from new construction. Their energy performance may be constrained by outdated equipment, incomplete documentation, limited space, and architectural characteristics.

Altohami et al. (2021) identify BIM-IoT-facility-management integration as relevant to renovation. Mulero-Palencia et al. (2021) investigate ML for deep-renovation projects using as-built BIM models, indicating that digital information can support renovation decisions.

Heritage buildings create additional constraints. Annibaldi et al. (2020) examine integrated sustainable and profitable energy-efficiency approaches for heritage buildings, while Curto et al. (2023) investigate energy efficiency in historic architecture in Palermo. These studies indicate that sustainability interventions must account for architectural preservation and economic feasibility.

Piras and Muzi (2024) provide another example of digital support for energy transition in a museum context. Together, these studies indicate that

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intelligent energy management should support both new construction and carefully planned retrofit programs.

2.10 Hospitality and Commercial Buildings

Hospitality buildings provide a particularly relevant application because hotels and resorts combine high occupancy variability with substantial HVAC, lighting, hot-water, kitchen, and facility-management requirements. Bardukova (2023) examines trends and strategies in hospitality, while Azmi et al. (2022) provide a BIM-based performance-analysis example for a green resort in Malaysia.

Singh et al. (2024) specifically investigate interventions for energy-efficient systems in hotel buildings. Such buildings can benefit from intelligent occupancy-based controls, predictive HVAC management, renewable-energy integration, and centralized monitoring.

The hospitality sector therefore provides a practical environment for testing the integrated framework because energy services must remain responsive to changing occupancy while maintaining comfort and service quality.

2.11 Research Gap

The supplied literature is rich but distributed across multiple research domains. BIM studies emphasize information management and performance analysis; IoT studies emphasize sensing; ML research emphasizes prediction and control; HVAC research emphasizes thermal systems; and sustainability studies emphasize energy efficiency and decarbonization.

The research gap is the absence of a unified analytical structure that explicitly positions these technologies around **renewable-energy integration and advanced MEP operation**. The present study addresses this gap by proposing an integrated energy-management framework in which BIM, IoT, ML, digital twins, renewable energy, and MEP systems are treated as interconnected components.

3. Methodology

3.1 Research Design

The research adopts a structured analytical synthesis methodology. The 51 supplied references were classified into thematic domains: sustainable building design, climate and building envelopes, BIM, IoT, machine learning, HVAC, digital twins, renewable-energy transition, MEP systems, facility management, renovation, and indoor environmental quality.

The objective of classification was not to rank the references but to identify complementary technological functions. The analysis then examined how information, energy, and control flow between these functions.

3.2 Conceptual Framework

The proposed framework contains seven interconnected layers:

Layer 1 – Building and Envelope: physical building characteristics, orientation, envelope performance, glazing, thermal properties, and internal loads.

Layer 2 – Renewable-Energy Layer: photovoltaic and other renewable-energy technologies supplying low-carbon energy.

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Layer 3 – MEP Layer: HVAC, ventilation, electrical systems, pumps, domestic hot-water systems, and associated equipment.

Layer 4 – Sensing and IoT Layer: sensors measuring temperature, humidity, occupancy, air quality, equipment status, and energy consumption.

Layer 5 – BIM Information Layer: structured information describing spaces, equipment, MEP assets, geometry, and performance characteristics.

Layer 6 – Analytics and Intelligence Layer: ML, predictive models, fault detection, optimization, and recommendation systems.

Layer 7 – Control and Facility-Management Layer: operational decisions, maintenance, scheduling, commissioning, and continuous improvement.

These layers operate as a feedback system rather than a linear hierarchy.

3.3 Data Acquisition

The IoT layer collects operational information from the physical building. Relevant data categories include:

- indoor temperature and humidity;
- outdoor environmental conditions;
- occupancy;
- energy consumption;
- HVAC operating conditions;
- equipment status;
- ventilation conditions;
- renewable-energy generation;
- indoor air-quality indicators; and
- maintenance and fault information.

Desogus et al. (2021) support the use of BIM-IoT integration for consumption and indoor-condition monitoring, while Chen et al. (2023) establish the broader relationship between BIM and IoT for sustainable buildings.

3.4 BIM-Based Information Integration

BIM provides the semantic context for sensor and equipment data. A sensor measurement has greater operational value when its relationship to a specific space, HVAC zone, air-handling unit, pump, or electrical circuit is known.

The framework therefore assigns each relevant MEP asset a digital identity connected to its physical location, equipment properties, operating conditions, and maintenance history.

Yang et al. (2022) demonstrate the importance of data exchange between BIM design software and performance-analysis software. Such interoperability is a prerequisite for using design information in energy-management applications.

3.5 Machine-Learning Layer

The ML layer performs three principal functions: prediction, optimization, and anomaly detection.

Prediction models estimate future energy demand and equipment behavior. Optimization models determine appropriate operating strategies under energy, comfort, and equipment constraints. Anomaly-detection models identify deviations from expected behavior.

The framework emphasizes interpretable ML where possible because facility managers require actionable explanations rather than unexplained algorithmic outputs. This approach is consistent

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with Mao et al. (2023), who specifically investigate interpretable ML for HVAC predictive control.

3.6 HVAC Management

HVAC is treated as the primary controllable MEP subsystem. A predictive HVAC controller can use weather, occupancy, indoor conditions, equipment state, and historical consumption to determine future operating requirements.

A simplified control objective can be expressed conceptually as:

Minimize Total Energy Cost = HVAC Energy + Auxiliary Energy + Grid Energy − Renewable Utilization

subject to:

Comfort constraints + Indoor-air-quality constraints + Equipment constraints + Operational constraints.

This formulation emphasizes that energy minimization cannot be separated from building-service requirements.

3.7 Renewable-Energy Integration

Renewable-energy generation is incorporated into the energy-management model as a variable supply source. The controller estimates available renewable energy and adjusts flexible MEP loads accordingly.

For example, when photovoltaic generation is high, the system may increase the operation of suitable flexible loads or reduce grid dependence. When renewable generation decreases, the controller can modify operating schedules while maintaining comfort constraints.

The framework therefore treats renewable energy as an input to intelligent control rather than simply an additional energy source.

3.8 Predictive Maintenance

The maintenance component uses operational data to identify degradation before complete equipment failure. Villa et al. (2022) demonstrate the relevance of ML to sustainable facility maintenance, while Haruehansapong et al. (2023) demonstrate automated HVAC fault detection.

In the proposed framework, maintenance predictions influence energy optimization. An HVAC unit showing abnormal performance may be prevented from operating under unnecessarily high loads until inspection or corrective action is completed.

3.9 Digital Twin Integration

The digital twin acts as an operational integration layer connecting BIM information, IoT measurements, ML models, and MEP systems. Agostinelli et al. (2021) establish the relationship among cyber-physical systems, digital twins, AI, and building energy management.

The twin is continuously updated with operational information. It can therefore be used to compare expected and actual performance, test potential control strategies, and support facility-management decisions.

3.10 Performance Evaluation

The proposed framework evaluates performance through five dimensions:

Energy: reduction in unnecessary consumption and improved renewable-energy utilization.

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Environmental: reduction of energy-related environmental impact and support for decarbonization.

Operational: improved HVAC and MEP reliability and maintenance.

Occupant: maintenance of thermal comfort and indoor environmental quality.

Digital: quality, continuity, interoperability, and usefulness of building information.

A system is considered successful only when improvements occur without unacceptable deterioration in another dimension.

4. Results

The analytical synthesis produces six principal findings.

First, **intelligent building energy management is fundamentally an integration problem**. BIM, IoT, ML, renewable energy, and MEP technologies produce limited value when deployed independently. The strongest architecture is one in which each technology performs a distinct function within a continuous feedback cycle. BIM provides contextual information, IoT provides current observations, ML converts data into predictions, and MEP systems execute decisions.

Second, **HVAC represents a critical control opportunity**. The literature demonstrates extensive development of ML applications for HVAC, predictive control, and fault diagnostics. HVAC demand varies with weather, occupancy, ventilation, and equipment condition, making static schedules inherently limited. Predictive management can therefore provide a pathway toward more responsive operation (Zhou et al., 2023; Mao et al., 2023; Sari et al., 2023).

Third, **BIM becomes more valuable when connected to operational data**. Conventional BIM can describe building components, but BIM-IoT integration transforms that information into an operational context. Sensors can identify current conditions while BIM provides spatial and equipment relationships. This finding is supported by Desogus et al. (2021), Chen et al. (2023), and Malagnino et al. (2021).

Fourth, **renewable-energy integration should be coupled with demand management**. Renewable generation does not automatically reduce total building energy demand. Its value increases when flexible MEP loads can respond to generation availability. Consequently, renewable-energy systems should be included within the intelligent energy-management algorithm rather than managed independently.

Fifth, **digital intelligence should incorporate maintenance and fault detection**. Energy efficiency deteriorates when MEP equipment operates under degraded conditions. ML-based maintenance and HVAC diagnostics can identify abnormal behavior and support corrective action before failures become severe (Villa et al., 2022; Haruehansapong et al., 2023).

Sixth, **implementation feasibility depends on more than technology**. BIM adoption challenges, interoperability, legacy equipment, data quality, occupant requirements, financial limitations, and building-specific constraints can restrict the realization of theoretical benefits. The framework therefore identifies integration readiness as a prerequisite for intelligent energy management.

The resulting architecture can be summarized as:

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Building Envelope → Renewable Generation → MEP Systems → IoT Sensing → BIM/Data Environment → ML/Digital Twin → Intelligent Control → MEP Operation → Continuous Feedback.

The most important finding is therefore systemic: intelligent energy management should be implemented as a **closed-loop cyber-physical building process** rather than as an isolated monitoring or automation project. This interpretation is consistent with AI-based smart-building energy-management research (Selvaraj et al., 2023).

5. Discussion

The findings extend the conventional understanding of sustainable construction by positioning digital intelligence as an operational component of energy efficiency. Traditional green-building approaches often emphasize passive design, efficient equipment, and renewable-energy installation. These remain essential, but the analysis indicates that their performance can be enhanced through continuous monitoring and adaptive control.

The theoretical contribution is the integration of four traditionally distinct perspectives: **physical efficiency, digital representation, predictive intelligence, and operational control**. Building-envelope efficiency reduces the amount of energy required. Renewable energy changes the source of supplied energy. BIM and IoT establish information continuity. ML and digital twins determine how available information can be transformed into operational decisions.

This framework also clarifies why BIM alone should not be regarded as an intelligent energy-management solution. BIM provides structured information but does not necessarily provide real-time operational feedback. IoT addresses this limitation by connecting the physical building to the digital environment. Malagnino et al. (2021) and Desogus et al. (2021) demonstrate the significance of this integration.

Likewise, ML should not be considered a substitute for engineering knowledge. A model can predict energy demand but cannot compensate for poorly designed ventilation, undersized or oversized equipment, inadequate insulation, or unsuitable control architecture. The physical constraints of MEP systems remain fundamental. The ML layer should therefore operate within engineering constraints rather than replace them.

HVAC illustrates this principle clearly. Predictive control can reduce unnecessary operation, but aggressive optimization may conflict with thermal comfort or indoor-air-quality requirements. Sari et al. (2023) and Zhou et al. (2023) demonstrate the potential of ML-based HVAC prediction, while the supplied ventilation and indoor-environment references indicate why performance objectives must remain multidimensional.

The framework also highlights the importance of explainability. Building operators are responsible for equipment performance and occupant conditions. If an algorithm recommends a substantial change in HVAC operation without explaining the underlying factors, operational trust may decline. Mao et al. (2023) therefore provides an important direction by emphasizing interpretable ML.

Renewable-energy integration introduces another trade-off. The amount of renewable generation available depends on building geometry, climate,

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equipment, and site conditions. Renewable generation may also be temporally mismatched with demand. Intelligent energy management can reduce this mismatch by scheduling flexible MEP loads, but it cannot eliminate the physical intermittency of renewable resources.

The building life cycle is another major consideration. During design, BIM and performance analysis can be used to evaluate alternative configurations. During construction, BIM can support coordination. During commissioning, IoT can establish operational baselines. During operation, ML and digital twins can support prediction and optimization. During renovation, as-built BIM can provide a basis for upgrading existing systems. Mulero-Palencia et al. (2021) and Altohami et al. (2021) support the importance of digital approaches in renovation.

Existing and heritage buildings require particularly careful implementation. Annibaldi et al. (2020) and Curto et al. (2023) demonstrate that energy-efficiency interventions in heritage buildings must account for architectural and economic considerations. The proposed framework can therefore be implemented incrementally: first establish digital documentation, then deploy monitoring, subsequently optimize existing MEP systems, and finally introduce renewable generation or deeper retrofit measures where feasible.

Cybersecurity and data governance represent additional limitations of the proposed architecture. Greater connectivity increases the number of interfaces through which building information flows. Although the supplied references do not provide sufficient evidence for a detailed cybersecurity model, the architecture logically requires controlled data access, reliable communication, and secure integration.

The findings also have practical relevance to hospitality. Hotels and resorts exhibit dynamic occupancy, substantial HVAC demand, and extensive MEP services. Bardukova (2023), Azmi et al. (2022), and Singh et al. (2024) collectively indicate the relevance of sustainability and energy-management interventions in this context. Intelligent control could potentially coordinate guest-room conditioning, common-area HVAC, lighting, hot-water demand, and renewable-energy availability.

The principal limitation of the present research is that it is an analytical synthesis rather than a field experiment. No original sensor dataset, building simulation, energy baseline, or measured retrofit result was provided. Accordingly, the framework should be interpreted as a research model rather than evidence of a specific percentage reduction in energy consumption.

Future validation should compare conventional control with integrated BIM-IoT-ML control under identical operating conditions. Additional studies should investigate renewable-energy sizing, occupant response, lifecycle cost, interoperability, cybersecurity, and long-term maintenance. These areas would enable the proposed framework to move from conceptual integration toward quantitatively validated building-performance outcomes.

6. Conclusion

The transition toward sustainable construction requires a shift from isolated energy-efficiency technologies toward intelligent building systems capable of continuously responding to changing

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environmental, operational, and energy conditions. This study developed an analytical framework for intelligent building energy management through the integration of renewable energy, BIM, IoT, machine learning, digital twins, and advanced MEP systems.

The analysis demonstrates that BIM can serve as the information foundation for building-performance management, while IoT provides the operational data required to understand current conditions. Machine learning transforms these data into predictions, recommendations, and anomaly detection. Digital twins provide an environment in which digital building information and physical building behavior can be continuously connected. Advanced MEP systems then execute control decisions within engineering and occupant constraints.

HVAC emerges as one of the most significant applications because its energy consumption is dynamic and closely related to weather, occupancy, ventilation, and equipment condition. Predictive HVAC control can therefore become an important component of intelligent energy management. However, energy optimization must remain compatible with indoor environmental quality and occupant requirements.

Renewable-energy integration further strengthens the framework by introducing low-carbon energy sources into the building system. The study emphasizes that renewable generation should not be treated as an isolated installation. Its effectiveness increases when coordinated with flexible MEP loads, predictive demand management, and continuous monitoring.

The research also establishes the importance of life-cycle integration. Intelligent energy management should begin during design, continue through construction and commissioning, and remain active throughout operation, maintenance, and renovation. BIM-based performance analysis can support design decisions; IoT can support commissioning and monitoring; ML can support operational optimization; digital twins can support facility management; and as-built BIM can support renovation.

The practical contribution is therefore a seven-layer intelligent building architecture comprising the building envelope, renewable-energy layer, MEP layer, IoT sensing layer, BIM information layer, analytics layer, and facility-management/control layer. The architecture provides a structured basis for connecting physical building performance with digital intelligence.

Nevertheless, the proposed framework does not imply that digitalization automatically produces energy savings. Data quality, interoperability, legacy-system constraints, implementation cost, occupant acceptance, maintenance capability, and organizational readiness can significantly influence outcomes. The most effective intelligent building is therefore not necessarily the building with the greatest number of sensors or most sophisticated algorithms, but the building in which digital technologies are appropriately matched to physical systems and operational objectives.

The study contributes to the research field by positioning intelligent energy management as a **closed-loop cyber-physical process** that integrates energy generation, MEP services, information, prediction, and control. This perspective provides a foundation for future empirical research involving monitored buildings, digital twins,

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renewable-energy optimization, predictive HVAC control, and BIM-enabled facility management.

Future research should quantify the proposed framework through longitudinal case studies and building simulations. Particular attention should be given to renewable-energy utilization, HVAC energy reduction, occupant comfort, fault detection, lifecycle cost, retrofit feasibility, and interoperability among BIM, IoT, ML, and building-management platforms. Such validation would strengthen the evidence base for deploying intelligent building energy management as a core component of sustainable construction.

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