Real-time Monitoring and Energy Efficiency Optimization in Smart Buildings: A Survey

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Abstract

This survey investigates the critical role of real-time monitoring and energy efficiency optimization in smart buildings, emphasizing the integration of edge computing and IoT technologies to enhance operational efficiency and sustainability. The study explores innovative control strategies that balance thermal comfort and energy efficiency, highlighting the potential of smart building technologies to significantly improve energy management and sustainability. Key findings reveal the importance of real-time monitoring in maintaining building system integrity, facilitating precise analysis, and enhancing grid resilience through advanced techniques like FLISR combined with edge computing. The survey also addresses the challenges of deploying cost-effective IoT solutions in small to medium-sized buildings to promote energy-saving behaviors. Through a structured examination of technologies such as edge computing, IoT integration, and smart building frameworks, the survey provides a comprehensive overview of the benefits and challenges of implementing these technologies. It concludes with a discussion on future directions, emphasizing the transformative potential of integrating advanced technologies to achieve sustainable urban infrastructures. The findings underscore the necessity of innovative solutions to overcome integration and scalability challenges, ensuring the robust development of smart building systems.

1 Introduction

1.1 Objectives of the Survey

This survey investigates the pivotal role of real-time monitoring and energy efficiency optimization in smart buildings, emphasizing operational efficiency and sustainability. The integration of edge computing and IoT technologies is crucial for effective energy management in urban infrastructures, which face significant energy demands and increasing complexity in IoT applications. Real-time monitoring is vital for maintaining the integrity and performance of building systems, enabling precise analysis and informed decision-making, as demonstrated in various industrial contexts [1]. The survey explores innovative control strategies that balance thermal comfort with energy efficiency, addressing the dual objectives of energy-efficient building management and occupant comfort [2]. Additionally, it underscores the significance of real-time monitoring in enhancing grid resilience and mitigating service disruptions through advanced techniques like Fault Location, Isolation, and Service Restoration (FLISR), in conjunction with edge computing [3]. By examining these elements, the survey highlights the potential of smart building technologies to significantly improve energy efficiency and sustainability, contributing to operational efficiency in distributed edge environments and smart grid systems. It also addresses challenges related to deploying real-time monitoring systems in small to medium-sized office buildings, advocating for cost-effective IoT solutions to encourage energy-saving behaviors. This comprehensive overview aims to provide insights into the integration of advanced technologies for enhanced energy demand management in smart building contexts, particularly within modern urban and industrial frameworks.

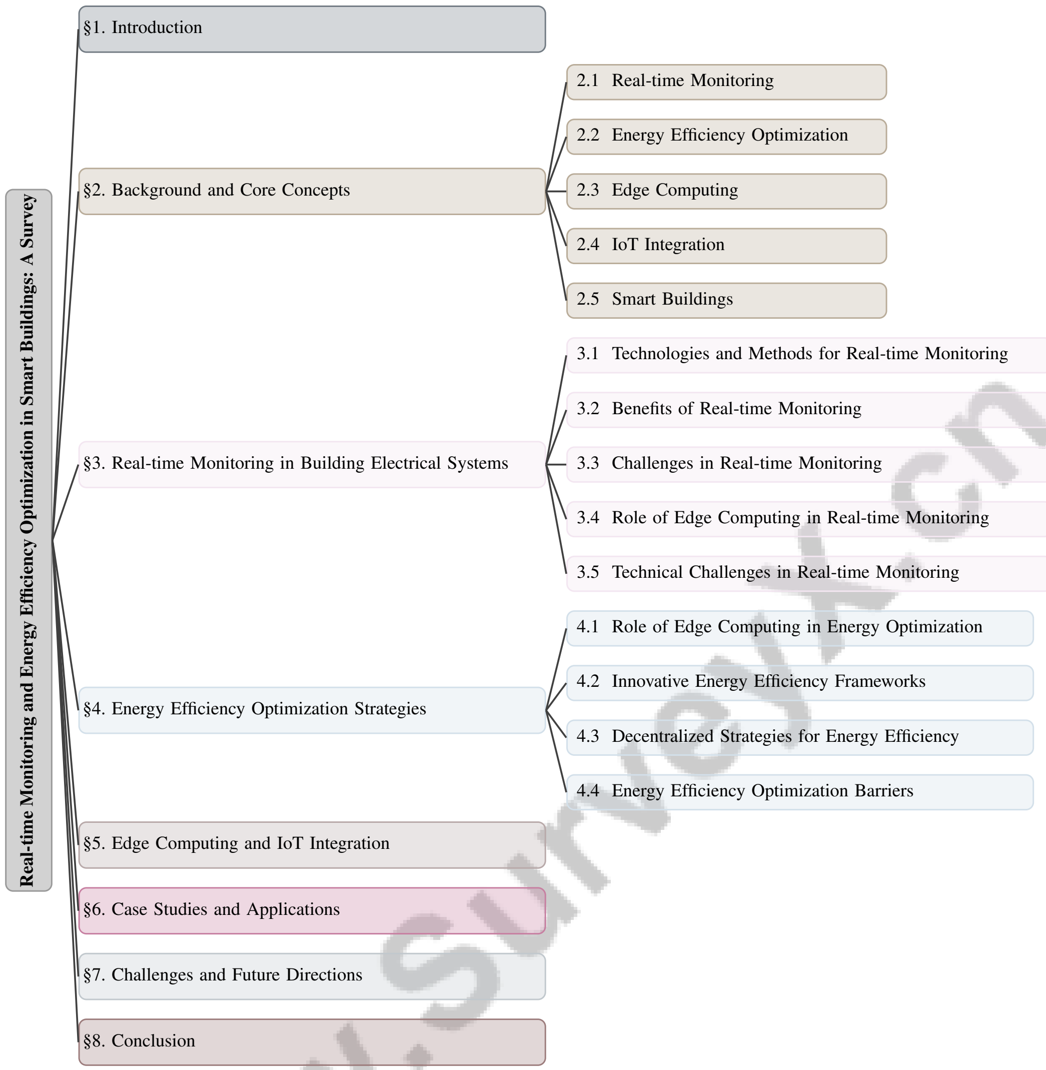

Figure 1: chapter structure

1.2 Structure of the Survey

This survey is structured to deliver a thorough examination of real-time monitoring and energy efficiency optimization in smart buildings. It begins with an introduction that highlights the critical integration of edge computing and IoT technologies in contemporary building electrical systems, establishing the groundwork for subsequent analysis [4]. The objectives are then outlined, emphasizing the need for real-time monitoring and energy efficiency to enhance operational efficiency and sustainability in smart buildings.

The second section provides a background and core concepts overview, detailing key technologies and methodologies, including edge computing, IoT integration, and smart building frameworks [5]. This foundation aids in understanding how these components interconnect to enhance building performance and sustainability [6].

Subsequent sections delve into specific themes: real-time monitoring in building electrical systems, energy efficiency optimization strategies, and the integration of edge computing and IoT. Each section highlights the benefits and challenges of implementing these technologies, supported by relevant case studies and applications [7]. The survey concludes with a discussion on challenges and future directions in the field, identifying potential solutions and emerging trends that could further advance smart building systems. This structured approach aims to provide a holistic understanding of the

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current landscape and future possibilities in smart building technologies.The following sections are organized as shown in Figure 1.

2 Background and Core Concepts

2.1 Real-time Monitoring

Real-time monitoring is crucial in smart buildings, enabling data-driven decision-making and system visualization to enhance energy efficiency and operational performance. IoT integration enhances this process through continuous data collection and predictive analytics, particularly benefiting small and medium-sized offices by overcoming traditional limitations [8, 9]. In smart grids, it addresses the inadequacy of centralized State Estimation methods for complex, decentralized power grids [8]. Furthermore, real-time monitoring supports multi-layered manufacturing architectures by integrating real-time data into virtual environments, facilitating human-in-the-loop interactions and reducing asynchrony errors. Its applications extend to photovoltaic systems' Maximum Power Point Tracking (MPPT) and IoT-enabled smart car parking systems, which provide immediate updates on availability and environmental conditions, thereby ensuring operational efficiency and sustainability [8].

2.2 Energy Efficiency Optimization

Optimizing energy efficiency in smart buildings involves strategies and technologies that reduce energy use while maintaining performance and comfort. Model Predictive Control (MPC) is pivotal in managing thermal regulation, energy storage, and renewable sources, predicting future demands for dynamic operation adjustments [10]. AI-driven methods, including deep learning and linear optimization, enhance energy management by adapting to urban environments' changing conditions [11]. In wireless networks, optimizing total and minimum energy efficiency addresses necessary trade-offs for sustainable energy use [12]. IoT facilitates non-intrusive load monitoring (NILM) and real-time analytics, informing interventions to reduce waste [13]. In Industrial IoT (IIoT) networks, managing transmission thresholds improves efficiency by minimizing unnecessary data transmissions [14]. Edge computing frameworks like GreenScale incorporate carbon emissions into scheduling, enhancing energy efficiency [15]. UAV-assisted systems optimize energy for data collection in remote areas [16], while clustering schemes like Chicken Swarm Optimization (CSO) improve IoMT systems' data transmission efficiency [17]. Methods like OptTopo optimize set-points based on physical topology, enhancing industrial systems' energy efficiency [18]. Addressing sector-specific inefficiencies, such as ports, is crucial due to their high operational costs and emissions [19]. These comprehensive approaches, combining advanced controls, AI, renewable strategies, and IoT analytics, ensure a balance between comfort and energy use, addressing challenges in thermal comfort, air quality, and overall energy management [20, 21, 7].

2.3 Edge Computing

Edge computing significantly advances smart building systems by decentralizing data management, shifting tasks from centralized servers to localized nodes. This approach reduces latency and enhances real-time analytics, crucial for optimizing building operations. Traditional cloud-centric architectures face high latency and privacy issues, particularly in IoT environments [22]. Edge computing overcomes these challenges by utilizing end devices' computational resources, offering benefits such as low bandwidth use, responsiveness, scalability, and privacy [23]. The rise of IoT necessitates processing data closer to its generation, driving edge computing's development [24]. In smart buildings, it enables cooperative data processing across nodes, enhancing efficiency and reducing delays, vital for real-time systems [25]. Edge computing is expected to surpass cloud computing due to reduced latency and higher throughput [1]. Supporting a layered architecture, it enhances IoT connectivity and scalability [26]. Efficient resource management in fog and edge environments is crucial, with methods optimizing bandwidth allocation and offloading decisions to minimize delays [27]. These advancements highlight edge computing's role in supporting intelligent infrastructures, optimizing resources, and meeting IoT applications' quality of service requirements, with potential enrichment through integration with quantum computing.

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2.4 IoT Integration

IoT integration in smart buildings transforms traditional management into data-driven frameworks that enhance efficiency and sustainability. IoT devices, including sensors and smart meters, collect detailed data on energy use, occupancy, and environmental conditions, enabling real-time performance optimization [8]. A primary challenge is high latency in data transmission to cloud centers, impeding real-time decisions and increasing energy consumption and emissions [19]. Edge computing mitigates these issues by processing data closer to its source, reducing reliance on centralized systems and enhancing responsiveness. Mobile Edge Computing (MEC) technologies further enable real-time processing and low-latency communication. The convergence of IoT with AI fosters sophisticated analytics and decision-making at the network edge, addressing latency and bandwidth constraints through local processing [8]. Integrating IoT with edge intelligence and blockchain enhances security and efficiency in IIoT environments, providing decentralized and tamper-resistant systems. This integration is crucial for maintaining data integrity and security, ensuring reliable real-time monitoring and protection against threats. As IoT evolves, its role in smart buildings will grow, driving innovations in energy management, security, and operational efficiency [19].

2.5 Smart Buildings

Smart buildings integrate advanced technologies to enhance energy efficiency, comfort, and operational effectiveness. Leveraging IoT and edge computing, they facilitate real-time data collection and processing, dynamically adjusting to conditions and needs to optimize energy use and indoor climate control [28]. The evolution from mechanical to electronic and smart meters illustrates technological advancements in smart building operations, enhancing monitoring and precision [29]. Efficient resource management in fog and edge environments is crucial for processing data closer to users, reducing latency and enhancing decision-making [23]. Multi-technology communication platforms support comprehensive data collection and analysis, forming a robust framework for operations. Digital twins exemplify these technologies' potential to meet diverse IoE application requirements, providing virtual asset representations for enhanced monitoring and predictive maintenance [30]. Smart buildings contribute to resilient energy grids capable of withstanding climate-related disruptions, optimizing resource allocation for uninterrupted service [31]. UAV-assisted systems enhance efficiency by streamlining data transmission from terrestrial tags [32]. In specific applications, such as neonatal incubators, smart technologies control and monitor environments, enhancing safety and outcomes. This adaptability underscores smart building technologies' significance across domains [32]. Smart buildings embody a convergence of technologies that enhance efficiency and monitoring. Integrating IoT, edge computing, and digital twins, they improve efficiency, comfort, and sustainability, facilitating real-time processing and analytics at the edge, reducing latency and congestion, and enabling advanced applications like energy management and predictive maintenance. These advancements transform urban infrastructures into smarter, more responsive environments that meet evolving needs [33, 34, 35, 36].

3 Real-time Monitoring in Building Electrical Systems

Real-time monitoring is crucial for enhancing operational efficiency and sustainability in building electrical systems. It provides immediate access to data on energy consumption and system performance, enabling stakeholders to make informed decisions. This section explores the technologies and methods that facilitate effective real-time monitoring practices, essential for optimizing building energy management and operational strategies. Table 1 presents a detailed categorization of the technologies, benefits, challenges, and the role of edge computing in real-time monitoring of building electrical systems, providing insights into the methods and features crucial for optimizing energy management and operational strategies. Additionally, Table 4 provides a comparative analysis of different methods utilized for real-time monitoring in building electrical systems, focusing on their technological integration, data processing capabilities, and system optimization strategies. As illustrated in **??**, the hierarchical structure of real-time monitoring in building electrical systems encompasses key technologies, benefits, challenges, and the role of edge computing. The technologies and methods section emphasizes IoT integration, smart meters, AI-driven methodologies, and digital twins. Benefits focus on operational efficiency and cost-effectiveness, while challenges address data constraints and technical issues. Furthermore, the role of edge computing is detailed in terms of

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Category	Feature	Method
Technologies and Methods for Real-time Monitoring	Advanced Communication	5G-PMU[37]
Benefits of Real-time Monitoring	Immediate Data Handling	SRMMSDG[38], AREO[27], IoT-CO2[8], EEMEC[1]
Challenges in Real-time Monitoring	Energy Optimization	ECS-ILT[39], MAIOT-SWM[40], RVDM[41], WTSS[42], DSGF[11], INDDE[43]
Role of Edge Computing in Real-time Monitoring	Collaborative Processing	SEC[44], 5G-AWCW[45], ISSTO[22], LTDRA[25], iFogSim[24]
	Real-Time Optimization	DRL-MEC[46], TOPNA[30]
Technical Challenges in Real-time Monitoring	Resource Management	DRAA[47], DADO[48]

Table 1: This table provides a comprehensive overview of the technologies, benefits, challenges, and the role of edge computing in real-time monitoring systems for building electrical systems. It categorizes various methods and features, highlighting advanced communication through 5G-PMUs, immediate data handling benefits, energy optimization challenges, and the integration of edge computing for collaborative processing and real-time optimization. The table serves as a reference for understanding the multifaceted aspects of enhancing operational efficiency and sustainability in smart building environments.

latency reduction and resource management, underscoring its significance in the overall monitoring framework.

3.1 Technologies and Methods for Real-time Monitoring

Method Name	Technological Integration	Data Processing	System Optimization
5G-PMU[37]	5G Technology	Machine Learning	-
SRMMSDG[38]	Cellular Network Integration	Real-time Data	Optimal Scheduling Policies
EEMEC[1]	Sagin-supported Mec	Alternating Optimization Algorithm	Joint Optimization Approach

Table 2: Comparison of technological integration, data processing, and system optimization across various methods for real-time monitoring in electrical systems. The table highlights the role of 5G technology, cellular network integration, and Sagin-supported MEC in enhancing monitoring capabilities through advanced data processing techniques and optimization strategies.

Real-time monitoring optimizes energy consumption and operational efficiency in building electrical systems through IoT integration, enabling continuous data collection and analysis for precise energy usage control. As illustrated in Figure 2, key technologies and methods for real-time monitoring are categorized into IoT integration, AI-driven methodologies, and Mobile Edge Computing (MEC) systems. Advancements in smart meters enhance measurement accuracy and remote monitoring, providing critical insights into energy consumption patterns [29]. Edge computing frameworks further improve real-time monitoring by reducing latency and enhancing system responsiveness, particularly in smart grids [3]. For instance, 5G-enabled Phasor Measurement Units (PMUs) stream data over 5G networks, using generalized dynamic linear models (GDLM) for real-time anomaly detection [37].

AI-driven methodologies, such as the Artificial Intelligence-based Sensor Data Analytics Framework (AISDAF), continuously monitor and analyze power quality to detect faults in Single Wire Earth Return (SWER) networks [38]. The Optimal Transmission Scheduling Policy (OTSP) minimizes the long-term average Age of Information (AoI), ensuring timely data updates critical for reliable monitoring systems [2]. Digital twins enhance real-time monitoring and resource allocation in smart grids by providing virtual representations of physical systems for continuous optimization [49]. Mobile Edge Computing (MEC) systems support real-time monitoring by dynamically allocating tasks and resources based on real-time energy levels and communication conditions [1].

Table 2 presents a comparative analysis of different methods utilized for real-time monitoring in building electrical systems, focusing on their technological integration, data processing capabilities, and system optimization strategies.

3.2 Benefits of Real-time Monitoring

Real-time monitoring in smart buildings enhances operational efficiency, energy management, and occupant well-being. It provides immediate feedback and predictive insights, encouraging users to optimize energy settings, such as dynamically adjusting air conditioning systems for improved efficiency [8]. High-accuracy, low-latency data processing is essential for managing large data

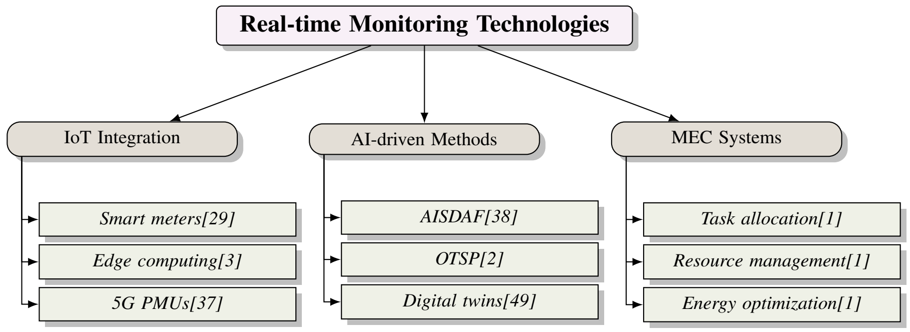

Figure 2: This figure illustrates the key technologies and methods for real-time monitoring in building electrical systems, categorized into IoT integration, AI-driven methods, and MEC systems.

volumes in dynamic environments [38]. Real-time monitoring improves energy management by minimizing AoI while adhering to power constraints, making it ideal for energy-constrained Industrial Internet of Things (IIoT) applications [1]. Edge computing integration reduces energy consumption, achieving savings of up to 55

Additionally, real-time monitoring enhances safety and maintenance protocols. In SWER networks, real-time systems provide high detection accuracy and reduced latency, ensuring prompt fault detection and reliability [38]. The use of active Reconfigurable Intelligent Surfaces (RIS) in Integrated Sensing and Communication (ISAC) systems improves energy efficiency, validating their effectiveness in enhancing performance and reliability [27]. Real-time monitoring supports applications like environmental monitoring, alerting for high CO2 levels and optimizing indoor conditions for health and productivity [8]. Cost-effective edge computing solutions offer low-cost, easy-to-deploy systems that promote device interoperability without vendor lock-in, enhancing the adaptability and scalability of smart building technologies [23].

3.3 Challenges in Real-time Monitoring

Real-time monitoring systems in buildings face challenges related to data transmission, energy consumption, and technical limitations. Large data volumes from sensor nodes are often unfeasible in Wireless Sensor Networks (WSNs) due to energy constraints [43]. High energy consumption associated with traditional sensing systems leads to rapid battery depletion [42]. Sensitivity and accuracy issues in traditional monitoring methods, such as the Hough transform, can result in missed detections or excessive false positives, especially in complex environments [41]. Environmental factors, such as camera placement and occlusions, can significantly affect localization performance, resulting in errors in real-time monitoring [39].

Technical issues, including internet connectivity problems and sensor inaccuracies, pose substantial challenges to effective real-time monitoring implementation [40]. These issues can disrupt data collection and analysis, undermining system reliability. Existing energy distribution systems often struggle to manage demand effectively while ensuring timely energy delivery, presenting a barrier in smart city contexts [11]. This challenge is compounded by the need for accurate quantification of energy consumption and carbon emissions, particularly in Federated Learning processes, where both centralized and decentralized frameworks face difficulties in tracking and optimizing energy use [31].

Addressing these challenges requires enhancing data management through advanced technologies like mobile edge and fog computing, improving energy efficiency with smart meters and real-time analytics, and ensuring the accuracy and reliability of real-time monitoring systems through the integration of artificial intelligence and IoT devices [50, 33, 35, 29].

3.4 Role of Edge Computing in Real-time Monitoring

Edge computing enhances real-time monitoring by reducing latency and improving data processing efficiency. Processing data closer to its source minimizes the distance data must travel, reducing latency and bandwidth usage, crucial for applications requiring immediate response [45]. This decentralized approach is essential for efficient data management, enabling devices to self-organize

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Method Name	Latency Reduction	Decentralized Data Processing	Resource Allocation
5G-AWCW[45]	Reduced Latency	Edge Computing Integration	Dynamically Allocating Resources
ISSTO[22]	Reduce Latency	Localized Processing	Resource Management
SEC[44]	Minimize Delays	Edge Computing	Dynamic Offloading
DRL-MEC[46]	Processing Data Closer	Decentralized Approaches	Allocate Computational Resources
TOPNA[30]	Minimizes Average Delay	-	Optimize Task Delay
LTDRA[25]	Reduce Latency	Collaborative Computing	Resource Allocation
iFogSim[24]	End-to-end Latency	Fog Computing Environments	Resource Management Strategies

Table 3: Comparison of Various Edge Computing Methods for Latency Reduction and Resource Management in Real-time Monitoring Systems. This table presents a detailed analysis of different methodologies, highlighting their approaches to latency reduction, decentralized data processing, and resource allocation within edge computing environments.

and optimize performance in dynamic environments [22]. The integration of 5G technology with edge computing facilitates faster data processing and reduced latency, supporting real-time monitoring in power systems [45]. The proximity of edge computing significantly enhances real-time monitoring capabilities in building electrical systems by reducing communication delays [44]. The DRL-MEC method dynamically determines offloading decisions and computational frequency allocations, enhancing data processing and reducing latency [46]. Table 3 provides a comprehensive comparison of various edge computing methods, illustrating their effectiveness in enhancing real-time monitoring through latency reduction, decentralized data processing, and optimized resource allocation.

The combination of Mobile Edge Computing (MEC) and network slicing enables localized processing and delivery of IoT services, minimizing the need for data to travel to distant cloud servers and thus reducing latency [22]. An online proactive network association decision model that incorporates semi-Markov task states and independent identically distributed random events optimizes task delay and energy consumption, illustrating the role of edge computing in real-time monitoring [30]. The Long-Term Dynamic Resource Allocation (LTDRA) method adaptively allocates resources while minimizing energy consumption and ensuring high tracking accuracy through collaborative computing, highlighting edge computing's effectiveness in real-time monitoring scenarios [25]. The iFogSim tool models interactions between Fog devices and IoT applications, enabling detailed analysis of resource allocation and management strategies that support efficient real-time monitoring [24].

3.5 Technical Challenges in Real-time Monitoring

Real-time monitoring systems in smart buildings encounter technical challenges affecting efficiency and reliability. Optimizing resource usage while maintaining high throughput and low latency is a significant challenge. The Dynamic Resource Allocation Algorithm (DRAA) addresses this by optimizing resource usage in real-time, ensuring efficient data processing and transmission [47]. However, the dynamic nature of resource allocation complicates managing computational tasks, especially in large-scale deployments where resource constraints can lead to bottlenecks and reduced system performance.

Another challenge is the computational intensity of optimization models used in real-time monitoring systems. The Mixed Integer Linear Programming (MILP) formulation of the Distributed Architecture for Data Offloading (DADO) requires substantial computational resources and is applicable only to infrastructures with fewer than 300 nodes due to memory constraints [48]. This limitation poses a barrier to scaling real-time monitoring systems in large smart building environments, where node counts often exceed this threshold.

Integrating diverse IoT devices and sensors into a cohesive monitoring system presents interoperability challenges, particularly in managing vast amounts of heterogeneous data, ensuring seamless communication across platforms, and enabling timely decision-making through technologies like edge computing and artificial intelligence. These challenges are intensified by the complexities of processing data from various sources, essential for creating intelligent, responsive systems across applications from healthcare to transportation [50, 36]. Variations in device protocols and data formats can lead to inconsistencies and inaccuracies in data collection and analysis, undermining the effectiveness of real-time monitoring. Ensuring reliable data transmission in environments with fluctuating network conditions remains a persistent issue, potentially resulting in data loss or delays that compromise monitoring outputs' timeliness and accuracy.

Addressing these technical challenges requires developing scalable and adaptive solutions that efficiently manage resource allocation, computational demands, and device interoperability in real-time monitoring systems. As smart building technologies advance, overcoming inherent challenges—such as data processing complexities, communication limitations, and the need for timely decision-making—will be essential for improving real-time monitoring systems' performance and reliability. These systems leverage innovations in smart meter technology and the integration of artificial intelligence with IoT to enable efficient power management, accurate data analysis, and enhanced operational efficiency in smart environments [50, 29].

Feature	IoT Integration	AI-driven Methodologies	Mobile Edge Computing (MEC)
Technological Integration	Sensor Networks	AI Frameworks	Edge Devices
Data Processing Capabilities	Continuous Data Collection	Fault Detection	Reduced Latency
System Optimization Strategies	Energy Usage Control	Power Quality Analysis	Dynamic Resource Allocation

Table 4: This table presents a comparative analysis of various methods employed for real-time monitoring in building electrical systems. It focuses on three key aspects: technological integration, data processing capabilities, and system optimization strategies. The table highlights the roles of IoT integration, AI-driven methodologies, and Mobile Edge Computing (MEC) in enhancing real-time monitoring efficiency and effectiveness.

4 Energy Efficiency Optimization Strategies

Enhancing energy efficiency in smart building systems requires a nuanced understanding of optimization strategies, particularly focusing on the role of edge computing. This section explores how edge computing decentralizes data processing, thereby improving operational efficiency and energy management.

4.1 Role of Edge Computing in Energy Optimization

Edge computing is crucial for energy optimization in building systems by decentralizing data processing and reducing dependency on centralized cloud infrastructures. This enhances communication and operational efficiency by facilitating real-time data processing near the data source, thereby minimizing latency and energy costs [45, 51]. Opportunistic Edge Computing (OEC) exemplifies scalability and cost-effectiveness, providing low-latency access to computing resources.

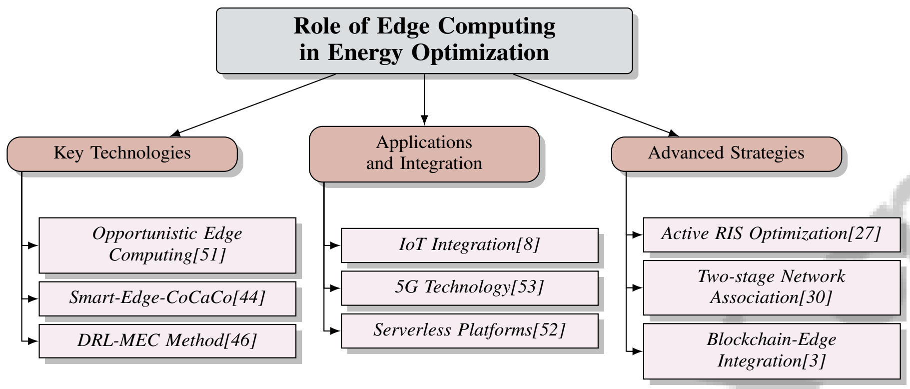
Figure 3 illustrates the role of edge computing in energy optimization, categorizing key technologies, applications, and advanced strategies. It highlights the integration of Opportunistic Edge Computing, Smart-Edge-CoCaCo, and DRL-MEC as primary technologies, while showcasing IoT, 5G, and serverless platforms as crucial applications. Advanced strategies such as Active RIS Optimization, Two-stage Network Association, and Blockchain-Edge Integration further enhance energy efficiency.

Integration with IoT technologies is vital for applications requiring timely interventions, such as environmental monitoring systems that respond to unsafe CO2 levels, enhancing health and safety [8]. Algorithms like Smart-Edge-CoCaCo optimize task offloading between local devices, edge clouds, and remote clouds, thereby enhancing energy efficiency [44]. The DRL-MEC method further demonstrates how edge computing minimizes energy consumption while maximizing task completion before deadlines [46].

Advanced strategies, such as Active RIS-aided Energy Efficiency Optimization (AREO), improve uplink transmission quality, reducing latency and enhancing performance for delay-sensitive applications critical to energy management [27]. Deploying serverless platforms on edge devices, particularly with ARM architecture, shows improved energy efficiency compared to traditional cloud services, underscoring the viability of edge environments for energy optimization [52].

Moreover, edge computing optimizes energy flows in industrial systems by decomposing complex systems into subsystems for tailored models and efficient resource management [3]. Integration with 5G technology enhances real-time data processing and reduces latency, essential for resource orchestration in non-terrestrial networks, similar to energy optimization strategies in smart buildings [53]. The Two-stage Online Proactive Network Association (TOPNA) exemplifies edge computing's benefits by adaptively optimizing network associations in real-time, significantly reducing task delay and energy consumption [30].

Edge computing significantly contributes to energy optimization in building systems by decentralizing data processing, enhancing real-time analytics, and enabling efficient resource management. The integration of advanced AI frameworks and model predictive control strategies further enhances energy optimization in smart buildings, promoting energy efficiency while balancing occupant comfort, air quality, and overall energy consumption, crucial given the projected rise in building energy demands by over 40% in the next two decades [52, 20, 10, 7, 54].



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4.2 Innovative Energy Efficiency Frameworks

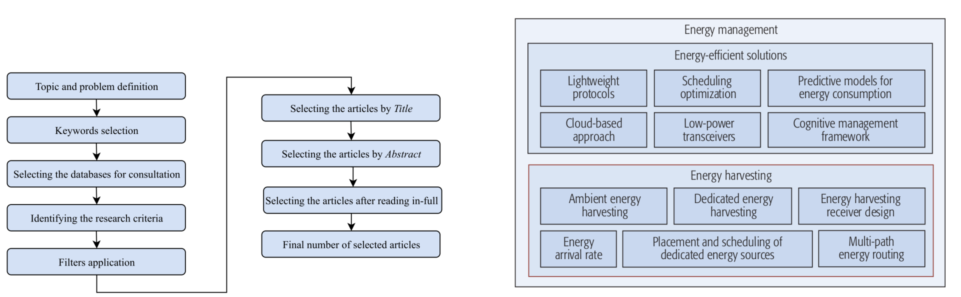
Innovative energy efficiency frameworks are vital for advancing sustainability and operational efficacy in smart buildings. These frameworks integrate cutting-edge technologies to optimize energy consumption and enhance building performance. A notable approach categorizes research into energy-efficient solutions and energy harvesting operations, highlighting the interconnected nature of smart city technologies [21]. This categorization aids in developing integrated solutions leveraging advancements in IoT, edge computing, and renewable energy.

In smart buildings, energy efficiency frameworks often use predictive analytics and machine learning algorithms to dynamically optimize energy usage, enabling real-time adjustments to systems like HVAC based on occupancy patterns and environmental conditions. Leveraging data-driven insights and AI, these frameworks minimize energy waste while enhancing occupant comfort, balancing energy efficiency and well-being [11, 20, 55].

Beyond individual buildings, these frameworks extend to urban environments, including container terminals and ports, where energy efficiency is crucial for reducing costs and environmental impact. Reviews emphasize implementing energy-efficient practices in ports, achieving significant savings through logistics and infrastructure optimization [19]. These frameworks often integrate renewable energy sources and advanced monitoring systems to manage energy efficiently across supply chains.

Innovative energy efficiency frameworks in smart buildings and urban infrastructures are essential for sustainable development goals. By integrating technologies such as Fog computing and data-driven frameworks, and promoting cross-sector collaboration, these approaches enhance the development of resilient, energy-efficient urban environments. Fog computing facilitates real-time data processing at the network's edge, reducing resource wastage, while data-driven frameworks optimize energy management through techniques like deep learning and linear optimization, addressing complexities from autonomous vehicles and rising energy demands. Together, these frameworks create sustainable infrastructure supporting modern smart cities' diverse needs [11, 33].

As shown in Figure 4, innovative frameworks are crucial for enhancing energy use sustainability and effectiveness. The figures provide a comprehensive overview of such frameworks, highlighting key methodologies and solutions. The first figure presents a flowchart guiding researchers in selecting



(a) Flowchart for Selecting Relevant Articles for Research[20]

(b) Energy Management and Energy Harvesting Solutions[21]

Figure 4: Examples of Innovative Energy Efficiency Frameworks

relevant articles for energy efficiency research. This process begins with defining the research topic and problem, followed by meticulous selection of keywords and databases, culminating in applying filters to finalize article selection based on titles and abstracts. This structured approach ensures identifying the most pertinent research, facilitating informed decision-making in energy efficiency strategies. The second figure showcases a diagram of energy management and harvesting solutions, categorizing energy management into innovative strategies, such as lightweight protocols and predictive models, while detailing energy harvesting techniques, including ambient and dedicated energy harvesting. Together, these figures underscore the importance of a systematic and innovative approach to optimizing energy efficiency, providing a robust framework for advancing research and practical applications in this critical field [20, 21].

4.3 Decentralized Strategies for Energy Efficiency

Decentralized strategies enhance sustainability and operational effectiveness in smart buildings by distributing data processing and energy management tasks across multiple nodes, reducing reliance on centralized systems. Satellite IoT exemplifies a decentralized approach, offering seamless global coverage and reliability, crucial in disaster scenarios for rapid deployment [56].

Microgrids represent a significant decentralized strategy, enabling buildings to operate autonomously from the main power grid, facilitating real-time monitoring and management of energy resources. This approach supports integrating renewable energy sources and advanced functionalities like demand-side management and predictive control, reducing energy consumption and improving energy systems' performance [49, 38, 57, 21, 54]. Microgrids can integrate renewable sources like solar panels and wind turbines, enabling localized energy generation and consumption, thus reducing transmission losses and enhancing resilience against grid disruptions. Moreover, microgrids facilitate demand response strategies, adjusting energy consumption based on real-time grid conditions and energy prices, optimizing energy use and reducing costs.

Decentralized strategies also involve distributed energy storage systems, storing excess energy generated during low-demand periods for use during peak times. This approach balances energy supply and demand by leveraging real-time data and advanced monitoring technologies, enhancing grid stability through improved observability and coordination among stakeholders, while simultaneously reducing the necessity for additional power generation capacity by optimizing resource utilization and integrating renewable energy sources [57, 55, 45, 38]. Advanced energy management systems utilizing machine learning algorithms and predictive analytics further optimize the operation of decentralized energy resources, ensuring efficient energy distribution and consumption.

Decentralized strategies significantly enhance the sustainability of smart buildings by improving resilience against energy demand fluctuations, minimizing waste through advanced management techniques, and optimizing resource utilization across various subsystems, including heating, cooling, and lighting. As building energy consumption is projected to rise by over 40

4.4 Energy Efficiency Optimization Barriers

Implementing energy efficiency optimization strategies in smart buildings faces significant barriers due to the complexity and interdependencies of interconnected systems. Existing methods often struggle to address these challenges effectively, complicating the optimization process [18]. A primary obstacle is the dynamic and stochastic nature of wireless systems in building automation, where incomplete network information, such as wireless channel states and available computation resources, complicates energy management [58]. This unpredictability necessitates sophisticated models capable of adapting to fluctuating conditions, yet many current approaches fall short.

Integrating various IoT devices and technologies adds complexity, as these systems must operate seamlessly to achieve optimal energy efficiency. However, current studies often fail to address the intricacies involved in integrating diverse IoT components, leading to inefficiencies and suboptimal performance [21]. The computational limitations of edge devices further exacerbate this challenge, as these devices must manage dynamic configurations and network management tasks often beyond their capabilities [33].

Security and privacy concerns hinder the effective implementation of energy efficiency strategies. Smart meters, for instance, must ensure data security and privacy while integrating with evolving smart grid technologies, posing significant technical challenges [29]. The emergence of new security threats specific to edge computing-assisted IoT environments exacerbates these issues, as edge devices are typically resource-constrained and ill-equipped to handle sophisticated cyber threats [59].

Additionally, traditional approaches to resource allocation in wireless networks are often inappropriate and inefficient, failing to support the dynamic wireless channels required by industrial applications [60]. This inadequacy is compounded by the need for robust communication layer security in IoT networks to prevent unauthorized access and cyber-attacks, prevalent in smart environments [61].

Overcoming these barriers requires innovative solutions that address the complexities of system integration, enhance the computational capabilities of edge devices, and ensure robust security measures. As smart building technologies advance, tackling the challenges associated with energy efficiency optimization strategies is essential, as these challenges significantly impact the effectiveness of various energy consumption optimization techniques. Addressing these issues will be pivotal in maximizing the potential of building energy management systems, designed to enhance energy efficiency in both residential and non-residential structures, especially given that buildings currently account for 30–45

5 Edge Computing and IoT Integration

5.1 Decentralized Data Processing

Decentralized data processing enhances the efficiency, scalability, and responsiveness of smart building systems by distributing computational tasks across cloud, fog, and edge environments. This approach reduces reliance on centralized infrastructures, minimizing latency and improving real-time data processing crucial for IoT applications in smart buildings [46]. Structuring technologies into distinct layers addresses challenges of scalability and modularity [62].

Edge computing plays a pivotal role in decentralized processing by ensuring low-latency responses and improved user experiences, essential for IoT functionality [63]. The integration of digital twins enhances system performance, enabling real-time predictions and optimizations through localized data processing [64].

Incorporating AI techniques within frameworks like the Artificial Intelligence-based Sensor Data Analytics Framework (AISDAF) highlights the benefits of decentralized processing, facilitating rapid fault detection and efficient monitoring [65]. These AI-driven methodologies enhance operational efficiency through real-time data analysis and decision-making [63].

Decentralized data processing optimizes energy management by analyzing data from smart meters and IoT devices, enabling adaptive strategies that enhance efficiency and sustainability [64]. Techniques such as experience replay and clipping improve training stability and overall system performance [46].

Moreover, leveraging edge computing and blockchain technologies enhances system performance by reducing latency, improving privacy, and increasing efficiency. This approach minimizes bandwidth usage and ensures data security through distributed computational tasks, facilitating real-time monitoring and resource optimization while addressing privacy concerns associated with sensitive data transmission, fostering a responsive and sustainable infrastructure for smart cities [3, 66, 67, 33].

As illustrated in Figure 5, the key components of decentralized data processing are highlighted, focusing on efficiency enhancements, energy management, and privacy and security aspects in smart building systems. Advanced frameworks and architectures continue to drive innovations, ensuring smart buildings meet modern urban infrastructure demands.

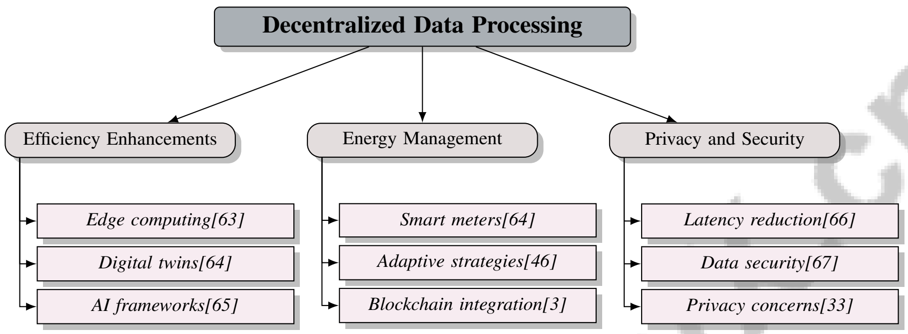


Figure 5: This figure illustrates the key components of decentralized data processing, focusing on efficiency enhancements, energy management, and privacy and security aspects in smart building systems.

5.2 Integration with IoT Devices

Integrating IoT devices into building systems enhances data collection and analysis, optimizes energy management, and improves overall building performance. Devices like sensors, smart meters, and actuators are embedded throughout infrastructures to monitor parameters such as energy consumption, occupancy, and environmental conditions. This real-time data collection enables building management systems to make informed decisions, dynamically adjusting operations to optimize energy usage and occupant comfort [68].

IoT devices support advanced energy optimization strategies by refining predictive models and control algorithms using collected data. These devices provide granular insights into energy consumption patterns, facilitating non-intrusive load monitoring and identifying inefficiencies. Future work suggests that integrating IoT applications can enhance data collection and analysis capabilities, enabling sophisticated energy optimization strategies adaptable to changing conditions and demands [68].

The synergy between IoT devices and edge computing frameworks is critical for reducing latency and improving responsiveness. Localized data processing minimizes the need for data transmission to centralized servers, enhancing real-time decision-making and reducing bandwidth usage. This approach benefits real-time applications, such as environmental monitoring systems that dynamically adjust ventilation and heating based on current indoor conditions, optimizing thermal comfort and energy efficiency. These systems utilize advanced control strategies, including artificial intelligence and model predictive control, to manage indoor climate factors like temperature, humidity, and air quality [20, 69, 10, 70, 71].

5.3 Performance Enhancement Strategies

Performance enhancement strategies in smart buildings leverage edge computing and IoT integration to optimize operations, improve energy efficiency, and enhance occupant comfort. A key strategy involves decentralized data processing frameworks that enable real-time decision-making and reduce latency by processing data closer to its source, thereby enhancing the responsiveness and scalability of building management systems [72].

Integrating IoT devices with edge computing frameworks facilitates seamless data collection and analysis, enabling advanced energy management strategies that adjust systems based on real-time conditions. For instance, a proposed framework allowing terminal devices to offload computation tasks to UAVs exemplifies how edge computing can enhance both computation and communication capabilities, improving overall smart building performance [72].

Deploying AI-driven methodologies within edge computing environments supports predictive analytics and machine learning applications that optimize energy consumption and improve system efficiency. These methodologies leverage artificial intelligence and model predictive control to create intelligent energy management systems that adapt to fluctuations in occupancy and environmental conditions. By integrating factors such as thermal comfort, humidity, air quality, and noise levels, these systems optimize energy consumption while enhancing occupant well-being, contributing to sustainable and efficient building operations [54, 20, 10].

5.4 Security and Privacy Considerations

The integration of edge computing and IoT in smart building systems introduces unique security and privacy challenges that necessitate careful examination and mitigation strategies. As IoT device deployment increases, the potential attack surface for cyber threats expands, raising concerns about data integrity, confidentiality, and unauthorized access. While the decentralized nature of edge computing reduces latency and enhances performance, it also introduces vulnerabilities that must be effectively managed [59].

A primary security challenge in EC-assisted IoT systems is protecting data during processing and transmission across various nodes. The distributed architecture can lead to inconsistencies in security protocols, complicating the maintenance of a uniform security posture across devices and networks. The fragmentation of IoT networks creates significant vulnerabilities that malicious actors may exploit, leading to cyberattacks such as data breaches, denial of service (DoS), and man-in-the-middle (MitM) attacks. As interconnected devices increase, so does the risk of these threats, necessitating robust cybersecurity measures to protect sensitive data and maintain network integrity [73, 74, 75, 76, 51].

To address these security concerns, robust encryption methods and secure communication protocols are vital for safeguarding data integrity and confidentiality. Implementing end-to-end encryption ensures sensitive information remains secure throughout its lifecycle, even during transmission across various nodes in edge computing environments, where data breaches and unauthorized access are prevalent. This approach enhances data security and supports effective access control mechanisms essential for mitigating risks associated with IoT and edge computing architectures [3, 59, 77, 78, 79]. Additionally, blockchain technology can provide a decentralized and tamper-resistant framework for managing data transactions, enhancing security and trustworthiness.

Privacy concerns are equally critical, as IoT devices often collect sensitive information about building occupants and their activities. Ensuring that data collected from various sources, such as IoT devices and smart meters, is thoroughly anonymized and securely stored is essential, as these data streams can reveal sensitive information about personal activities and locations, posing significant privacy risks if mishandled [59, 77, 80, 50, 66]. Privacy-preserving techniques, such as differential privacy and federated learning, can be employed to analyze data while minimizing the risk of exposing personal information.

Moreover, implementing robust access control mechanisms is crucial for preventing unauthorized access to IoT devices and edge computing resources. Role-based access control (RBAC) and multi-factor authentication (MFA) are critical security measures that ensure only authorized users can access sensitive systems and data, particularly in the context of edge computing and IoT, where the proliferation of smart devices and associated data traffic heightens security breach risks. These strategies enhance data confidentiality and integrity while addressing the unique challenges posed by the decentralized nature of edge computing, requiring flexible and scalable access control mechanisms to mitigate potential threats to data security and privacy [78, 59, 77, 74].

As illustrated in Figure 6, the hierarchical structure of security and privacy considerations in edge computing and IoT systems encompasses primary security challenges, mitigation strategies, and privacy concerns, thereby providing a comprehensive overview of the complex interplay between these elements.

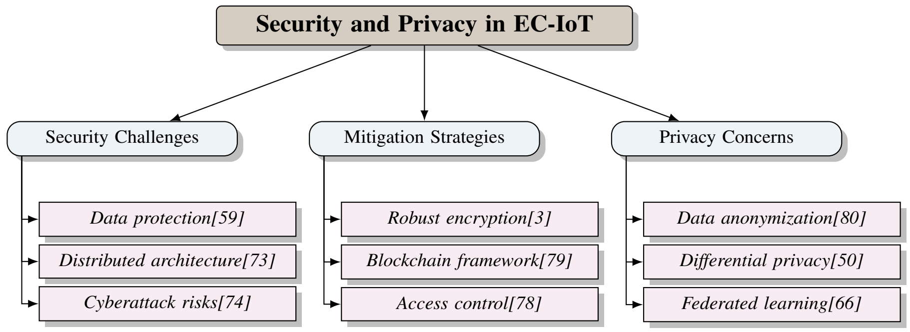


Figure 6: This figure illustrates the hierarchical structure of security and privacy considerations in edge computing and IoT systems, including primary security challenges, mitigation strategies, and privacy concerns.

6 Case Studies and Applications

6.1 Case Studies and Real-World Applications

Smart building technologies have proven their effectiveness in enhancing operational efficiency, energy management, and occupant comfort through various case studies. The SAFEMYRIDES system highlights this integration, achieving a 90.1

Edge computing's effectiveness in monitoring indoor environmental quality is emphasized through various studies, underscoring its advantages for real-time management [81]. An intelligent agricultural greenhouse control system further validates its real-world applicability by improving crop yields and resource utilization [82]. At Lofstad Castle, an edge-based parametric digital twin method was applied for indoor climate management, optimizing building operations and demonstrating the benefits of integrating digital twin technologies with edge computing [63]. Additionally, a RIS-assisted edge computing system improved uplink transmission rates and reduced maximum delay in task offloading, enhancing communication efficiency in smart building systems [83].

Advancements in 5G-enabled adaptive computing workflows have also revolutionized power grid management, offering real-time monitoring and decision-making capabilities, illustrating the transformative impact of advanced communication technologies in smart building systems [45]. Collectively, these case studies highlight the diverse applications and benefits of smart building technologies, reinforcing their role in achieving sustainable and efficient building operations.

6.2 Proof-of-Concept Implementations in Cultural Heritage Buildings

Preserving cultural heritage buildings involves unique challenges, particularly in integrating modern smart technologies while maintaining historical integrity. A proof-of-concept implementation in Bled, Slovenia, utilized sensors connected to Raspberry Pi devices to monitor environmental parameters, exemplifying decentralized architectures that enhance building management systems without compromising architectural authenticity [67]. This implementation used a blockchain-based decentralized self-balancing architecture to enhance data integrity and security, crucial for sensitive environments like cultural heritage sites. By leveraging edge computing, the system optimized resource usage and addressed challenges associated with traditional centralized systems, such as privacy and performance [3, 84, 85, 67]. The integration of blockchain technology ensured secure data logging and auditing, facilitating real-time processing and effective resource management tailored to the unique needs of IoT devices in these critical settings. This approach managed data locally, reducing latency while enhancing real-time monitoring capabilities, thus optimizing energy usage and maintaining optimal environmental conditions essential for preserving historical artifacts.

These implementations demonstrate the feasibility of integrating advanced technologies into cultural heritage buildings, offering a balanced approach that respects historical significance while enhancing operational efficiency and sustainability. The success of this proof-of-concept underscores the potential for broader applications of smart building technologies in preserving cultural legacies at similar sites. By leveraging advancements in artificial intelligence and IoT, innovative solutions can enhance the management and conservation of these sites, ensuring they remain accessible and relevant in the digital age. This approach facilitates real-time data collection and analysis through edge and fog computing, promoting sustainable practices vital for the future of smart cities and enriching the cultural experience for visitors and communities alike [50, 33, 35].

6.3 Scalability and Integration Issues

Deploying smart building solutions often encounters scalability and integration challenges that hinder widespread adoption and operational effectiveness. A primary scalability issue is managing the vast amounts of data generated by numerous IoT devices and sensors. As the number of connected devices increases, the demand for computational resources and data storage escalates, necessitating robust architectures to handle this data influx [51]. Integration challenges arise from the heterogeneity of devices and systems within smart buildings, which often operate on different protocols and standards, leading to interoperability issues. The lack of standardized communication protocols complicates integration efforts, requiring custom solutions to bridge gaps between disparate systems [59].

Additionally, the dynamic nature of smart building environments, characterized by fluctuating occupancy patterns and varying conditions, necessitates adaptable systems that can respond to real-time changes. Traditional centralized architectures are often inadequate due to inherent latency and bandwidth limitations. Integrating edge computing can mitigate these challenges by enabling localized data processing, reducing reliance on centralized cloud infrastructures, and enhancing system scalability and responsiveness [63]. Security and privacy concerns also critically impact the integration of smart building technologies. The decentralized nature of edge computing introduces vulnerabilities that must be addressed to protect sensitive data. Implementing robust security measures, such as encryption and access control, is essential for safeguarding data integrity and maintaining user trust [59].

7 Challenges and Future Directions

7.1 Future Directions and Emerging Trends

The evolution of smart building technologies is increasingly driven by trends that enhance efficiency, adaptability, and sustainability. A key research focus is the enhancement of edge computing through 5G integration, which significantly boosts IoT and smart grid performance [1]. Mobile Edge Computing (MEC) is also being developed to address IoT security and privacy issues by advancing MEC architectures and integration technologies [22]. In artificial intelligence, optimizing models for smart city applications using unsupervised learning to meet latency requirements is promising [9], along with innovations in video coding and AI frameworks for proactive decision-making [30]. Energy management research is expected to focus on reducing computational loads through sophisticated optimization and parallelization techniques [27].

Decentralized approaches like Federated Learning and flexible coordination for heterogeneous edge devices are anticipated to improve the adaptability and scalability of smart building systems [31]. Enhancing task scheduling algorithms for dynamic environments and integrating machine learning for optimization are crucial for advancing smart building technologies [26]. Future studies should emphasize resource management, user participation incentives, and addressing reliability and fault tolerance in opportunistic environments [23].

Furthermore, integrating AI and IoT in smart metering is critical for device interoperability and data security standards [8]. Investigating task partitioning in dynamic offloading scenarios will enhance efficiency by distributing tasks across multiple edge servers [22]. Refining the Long-Term Dynamic Resource Allocation (LTDRA) algorithm for adaptability to changing network conditions and exploring hierarchical structures in other IoT domains are important research areas [25]. Enhancing iFogSim simulation capabilities to reflect real-world dynamics and developing resource management strategies for complex IoT scenarios are also pivotal [24].

These future research directions highlight the transformative potential of smart building technologies, underscoring the need for ongoing innovation and interdisciplinary collaboration. Such efforts are essential for addressing the complexities of modern urban infrastructures and leveraging advancements in AIoT, mobile edge computing, and fog computing. These technologies collectively enhance data processing efficiency, improve user experiences, and support sustainable smart city development, meeting the evolving demands of urban living [50, 33, 35].

7.2 Security and Privacy Concerns

The integration of edge computing and IoT in smart building systems presents significant security and privacy challenges that must be addressed to ensure data integrity and confidentiality. The proliferation of IoT devices expands the potential attack surface for cyber threats, as these devices often serve as entry points for malicious actors [11]. Security issues in smart grid architectures, particularly regarding IoT device communication, remain pressing concerns that require further research. Current studies often overlook the specific needs of low-latency and massive connectivity applications, especially in resource-constrained environments [86]. Optimizing AI models for resource-constrained edge devices exacerbates security and privacy concerns, as these models must balance performance with edge computing limitations [6]. Challenges persist in achieving interoperability among different IoT standards and ensuring security within decentralized edge computing environments [22].

Methods employed in some systems may struggle in highly dynamic environments or with numerous sensor nodes, where real-time adjustments become challenging [87]. In unpredictable settings characterized by erratic user mobility and task arrivals, real-time decision-making can be complicated, further raising security and privacy concerns [88]. Existing studies face scalability and integration limitations that may hinder the widespread adoption of advanced technologies like quantum computing in smart building systems [5].

To mitigate these security and privacy issues, implementing robust encryption methods and secure communication protocols across all devices and networks is essential. Integrating blockchain technology can provide a decentralized and tamper-resistant framework for data transactions, enhancing security and trustworthiness. Developing adaptive security measures that dynamically respond to changing network conditions, alongside advanced machine learning techniques for effective anomaly detection, is crucial for bolstering the resilience of smart building systems against cyber threats. This approach not only addresses the rising risks associated with IoT device proliferation but also leverages real-time monitoring capabilities to identify potential vulnerabilities. By employing deep learning models and edge computing strategies, smart buildings can achieve more efficient data processing and improved security, ultimately safeguarding critical operational technology and ensuring the seamless functioning of interconnected systems [20, 73, 89, 90]. Prioritizing security and privacy in the design and implementation of smart building technologies is vital for ensuring their safe and reliable operation in increasingly interconnected urban environments.

8 Conclusion

Real-time monitoring, energy efficiency optimization, edge computing, and IoT technologies collectively revolutionize smart buildings, enhancing operational efficiency and sustainability within intelligent infrastructures. The application of AI techniques holds considerable promise for optimizing power consumption and decision-making processes, underscoring the transformative potential of AI-driven methodologies. Establishing comprehensive IoT frameworks is pivotal for enabling immersive experiences while addressing essential challenges such as security, privacy, and interoperability, which are crucial for the successful implementation of smart building technologies.

The environmental advantages of carbon-aware scheduling in edge-cloud applications are evident, with systems like GreenScale demonstrating significant reductions in carbon emissions compared to traditional methods. This highlights the importance of developing advanced scheduling frameworks to achieve sustainability goals in smart building environments. Furthermore, the imperative for robust security measures to address vulnerabilities in communication protocols is particularly pronounced, especially in enhancing productivity and efficiency in smart farming technologies.

AI techniques are instrumental in managing task offloading, despite the potential increase in processing demands and energy consumption. The integration of enabling technologies is essential for establishing a resilient Fog-IoT architecture, which is crucial for supporting future IoT applications. In the context of port operations, the synergy of operational improvements, technological advancements, and effective energy management can lead to notable energy savings and emission reductions, demonstrating the wide-ranging applicability of smart building technologies.

The convergence of edge computing and IoT technologies significantly bolsters sustainability and performance, setting the stage for future innovations in urban infrastructure. By leveraging these integrated technologies, smart buildings can achieve enhanced energy efficiency and operational effectiveness, contributing to the creation of sustainable urban environments.

AI-generated, for reference only.

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