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Smart Building Energy Management Using Digital Twins Technology

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Abstract

Digital twin–based smart building energy management systems enable real-time monitoring, simulation, and optimization of building operations using data from sensors and IoT devices. By integrating advanced analytics and predictive control, these systems significantly reduce energy consumption, operational costs, and carbon emissions while maintaining occupant comfort. Although challenges related to interoperability, cybersecurity, and scalability remain, ongoing advances in AI, semantic modeling, and standardized architectures are improving practical adoption. Future developments will focus on renewable energy integration, occupant-centric control, and smart city–level energy optimization.

Keywords: Artificial Intelligence; Resume Analyzer; Resume Parsing; Natural Language Processing; Machine Learning; Recruitment Automation; Skill Matching; Human Resource Analytics.

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Introduction

Rapid urbanization and growing sustainability concerns have made efficient building energy management a global priority, as buildings account for nearly 40% of total energy consumption and greenhouse gas emissions. Smart building energy management systems have therefore emerged to monitor, analyze, and optimize energy use using advanced digital technologies[1]. Among these, digital twin technology plays a pivotal role by creating a real-time virtual replica of a building that reflects its structural, operational, and environmental conditions. By integrating digital twins with sensor networks and IoT devices, real-time data on energy consumption, indoor conditions, and occupancy can be continuously analyzed. Advanced analytics and machine learning techniques enable pattern recognition, demand forecasting, and intelligent control strategies such as adaptive HVAC operation, equipment scheduling, and demand response[2]. These capabilities lead to improved energy efficiency, reduced operational costs, enhanced occupant comfort, and lower environmental impact. Furthermore, global experiences in digitalization and intelligent energy management highlight the broader role of digital twins in supporting sustainable industrial and economic development [3,4].Please see figure1.

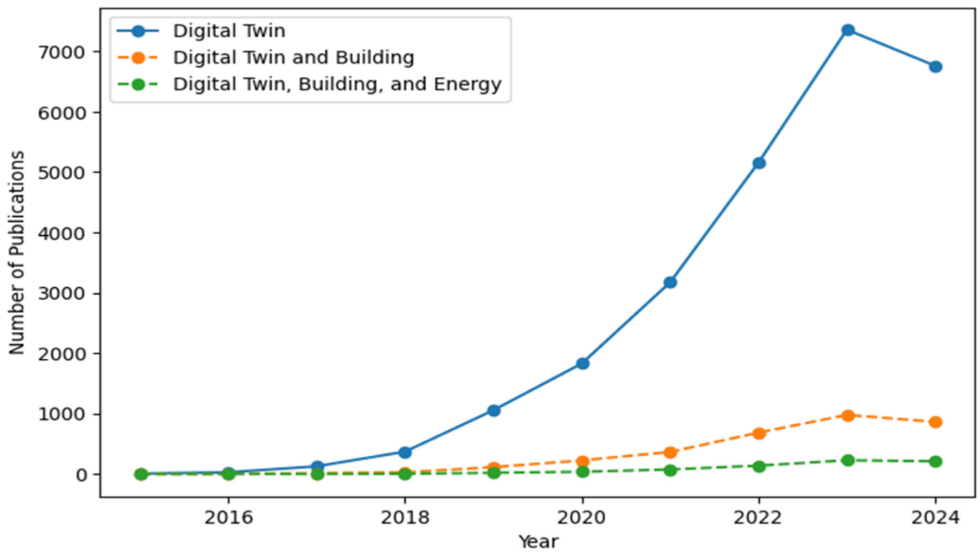

Fig. 1. *Digital Twins Development*

Literature Review

The concept of **digital twins** (DTs) has gained significant momentum in recent years as a transformative approach for enhancing building energy management, operational efficiency, and occupant comfort. A digital twin represents a virtual replica of a physical system that is continuously updated using real-time data from sensors and IoT devices, enabling monitoring, simulation, prediction, and optimization of system behavior.Early foundational studies emphasized the role of digital twins in bridging the gap between physical assets and cyber models. Francisco et al. [3] introduced the concept of digital twin–enabled energy management for smart cities, focusing on real-time urban building energy benchmarking. Their work demonstrated how digital twins can integrate real-time data streams with simulation models to enable comparative energy performance assessment across multiple buildings, laying the groundwork for scalable urban energy optimization.As research progressed, attention shifted toward framework development and system integration. Agouzoul et al. [5] proposed a digital twin model for building energy management in the Moroccan context, highlighting the integration of building information models (BIM), sensor data, and simulation tools. Their case study demonstrated improved energy monitoring and decision-making, though challenges related to data interoperability and model accuracy were identified. Similarly, Lamagna et al. [6] provided a comprehensive review of digital twins in smart energy management systems, categorizing DT applications into design optimization, operational control, fault detection, and predictive maintenance. Their study emphasized the importance of real-time data synchronization and advanced analytics for effective energy optimization.Recent works have focused on semantic modeling and service-oriented architectures to enhance scalability and interoperability. Zheng and Yahia [1] proposed a semantic digital twin framework for smart building energy management, employing ontology-based models to represent building assets, energy flows, and control services. Their service-oriented approach enables flexible integration of heterogeneous data sources and supports intelligent energy services such as demand response and predictive control. This work represents a significant advancement in addressing data heterogeneity and system extensibility.The convergence of digital twins and smart energy networks has also been explored extensively. Sirchia et al. [2] reviewed current and future trends in digital twins for buildings and smart energy networks, emphasizing the role of DTs in integrating renewable energy sources, energy storage systems, and grid-interactive buildings. Their findings highlight the growing importance of digital twins in achieving energy flexibility and resilience within smart grids.Thermal comfort and occupant-centric energy management have emerged as critical research themes. Arowoiya and Moehler [7,9] presented a state-of-the-art review on the use of digital twin technology for thermal comfort and energy efficiency in buildings. Their work demonstrated how DTs can combine environmental sensing, occupant behavior modeling, and control strategies to balance comfort and energy savings. However, they also identified limitations related to computational complexity and the need for high-quality real-time data.Building operation and maintenance (O&M) is another major application area. Puiu et al. [4] conducted a literature review on the efficiency of building maintenance using digital twins, concluding that DT-based predictive maintenance significantly reduces downtime and energy waste. Zhao et al. [12] further developed a conceptual framework for applying digital twins to revamp building operation and maintenance processes, emphasizing lifecycle integration, continuous feedback loops, and data-driven decision-making.Several studies have critically examined the benefits and limitations of digital twin adoption. Tahmasebinia et al. [10] explored the advantages of DTs in building energy analysis, such as improved visualization, scenario testing, and operational transparency, while also highlighting challenges including high implementation costs, data privacy concerns, and lack of standardization. These findings were reinforced by Bortolini et al. [8], who reviewed digital twin applications for building energy efficiency and identified gaps in real-time control implementation and cross-platform interoperability.More recently, Elnour and Naji [11] investigated the role of digital twins in empowering smart cities through data-driven energy modeling of buildings. Their study emphasized implementation considerations such as sensor deployment strategies, cloud infrastructure, and stakeholder involvement, underscoring the need for scalable and secure DT architectures in urban environments. Table1 Comparision of various methods.

Table 1. *Literature Survey*

Ref.	Authors & Year	Focus Area	Methodology / Approach	Application Domain	Key Contributions	Identified Limitations / Gaps
[1]	Zheng & Yahia, 2024	Semantic digital twins	Service-oriented and ontology-based framework	Smart building energy management	Proposes semantic DT architecture enabling interoperability and intelligent energy services	High modeling complexity; limited embedded-level implementation
[2]	Sirchia et al., 2023	DTs for buildings & energy networks	State-of-the-art review and trend analysis	Smart buildings and smart grids	Identifies integration of DTs with smart energy networks and renewables	Lack of real-time deployment case studies
[3]	Francisco et al., 2020	DT-enabled smart cities	Real-time data integration and benchmarking	Urban building energy systems	Introduces real-time urban-scale energy benchmarking using DTs	Scalability and data heterogeneity challenges
[4]	Puiu et al., 2024	DTs for building maintenance	Systematic literature review	Building operation and maintenance	Demonstrates efficiency gains via DT-based predictive maintenance	Focuses less on real-time energy control
[5]	Agouzoul et al., 2021	Building energy DT model	BIM-based modeling with sensor integration	Smart buildings (case study – Morocco)	Presents practical DT implementation for energy monitoring	Limited generalization and automation
[6]	Lamagna et al., 2021	Smart energy management DTs	Comprehensive review	Smart energy systems	Classifies DT applications across lifecycle stages	Lack of standardized DT architectures
[7]	Arowoiya & Moehler, 2024	Thermal comfort & energy efficiency	State-of-the-art review	Smart buildings	Integrates occupant comfort modeling with DT-based energy optimization	Requires dense sensing and high computational effort
[8]	Bortolini et al., 2022	DTs for energy efficiency	Systematic review	Building energy efficiency	Highlights DT benefits in monitoring and optimization	Limited real-time control and interoperability

[9]	Arowoiya & Moehler, 2024	Thermal comfort & efficiency	Analytical review	Smart buildings	Discusses future research directions for comfort-aware DTs	Data quality and model validation issues
[10]	Tahmasebinia et al., 2006	DT benefits & limitations	Conceptual and analytical study	Building energy analysis	Early identification of DT advantages and constraints	Outdated implementation technologies
[11]	Elnour & Naji, 2024	DTs for smart cities	Data-driven energy modeling	Smart city buildings	Emphasizes scalable DT deployment and stakeholder roles	Security and privacy concerns
[12]	Zhao et al., 2022	DTs for O&M processes	Conceptual framework	Building operation and maintenance	Proposes lifecycle-based DT framework for O&M	Lacks experimental validation

Design and Implementation

The design of a smart building energy management system using digital twins begins with the development of a comprehensive cyber–physical system architecture, as illustrated in the block diagram. The physical layer consists of an ESP32 development board interfaced with multiple sensors, actuators, and communication modules, while the cyber layer comprises a cloud/server platform hosting the digital twin model of the building's energy system.At the physical layer, the ESP32 functions as the central IoT controller responsible for data acquisition, local processing, and actuation. See Figure2.

A regulated power supply ensures reliable operation of the system. Environmental and electrical parameters are continuously monitored using sensors such as the LDR for ambient light intensity, DHT11 for temperature and humidity, voltage sensor for supply voltage monitoring, and a current sensor for real-time load current measurement. These sensors provide granular, real-time data reflecting the actual operating conditions of the building and its electrical loadThe collected sensor data is transmitted by the ESP32 to the cloud/server via built-in wireless connectivity. In the cloud environment, a digital twin of the building's energy system is created, representing a virtual replica of the physical system. This digital twin continuously synchronizes with real-time sensor data, enabling accurate modeling of energy consumption patterns, environmental conditions, and load behavior. Advanced analytics and control algorithms operating on the digital twin allow prediction of energy demand, detection of anomalies, and evaluation of optimization strategies without directly disturbing the physical system.At the control and actuation layer, decisions generated by the digital twin—such as energy optimization or load scheduling commands—are sent back to the ESP32. Based on these commands, the ESP32 drives a relay module to control electrical loads, represented here by an LED bulb, enabling intelligent switching, dimming, or scheduling. Simultaneously, real-time system parameters and operational status are displayed locally on an I²C 16×2 LCD, providing immediate feedback to occupants or operators.This closed-loop interaction between the physical system and its digital twin enables continuous monitoring, predictive control, and adaptive energy management. Building owners and operators benefit from improved energy efficiency, reduced operational costs, and enhanced decision-making capabilities, while occupants experience improved comfort and reliability. Overall, the proposed architecture demonstrates how an ESP32-based IoT platform integrated with digital twin technology can form an effective and scalable smart building energy management solution.

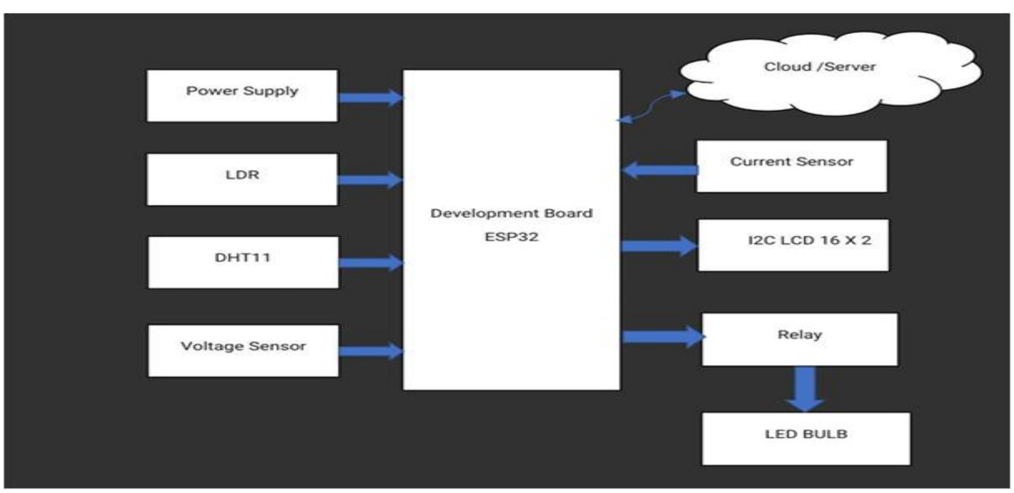

Fig. 2. *Block Diagram Digital Twin Development*

Results and Discussion

Digital twin continuously synchronizes with real-time sensor data, enabling accurate modeling of energy consumption patterns, environmental conditions, and load behavior. Advanced analytics and control algorithms operating on the digital twin allow prediction of energy demand, detection of anomalies, and evaluation of optimization strategies without directly disturbing the physical system.As shown in Figure 3 .Over a two-day observation period, the temperature varied between 26 °C and 34 °C, while relative humidity increased from 56% to 64%, showing time-dependent variations in real-world data. As illustrated in Figure 4, the supply voltage remained constant at 12 V throughout the experiment. Based on the measured voltage and current, power and power factor were derived, exhibiting corresponding increases and decreases over time. During the two-day monitoring period, the power consumption ranged from 0 to 50 W, and the power factor varied between 0 and 1, reflecting changes in load conditions.

Fig. 3. *Temperature and Humidity Observation*

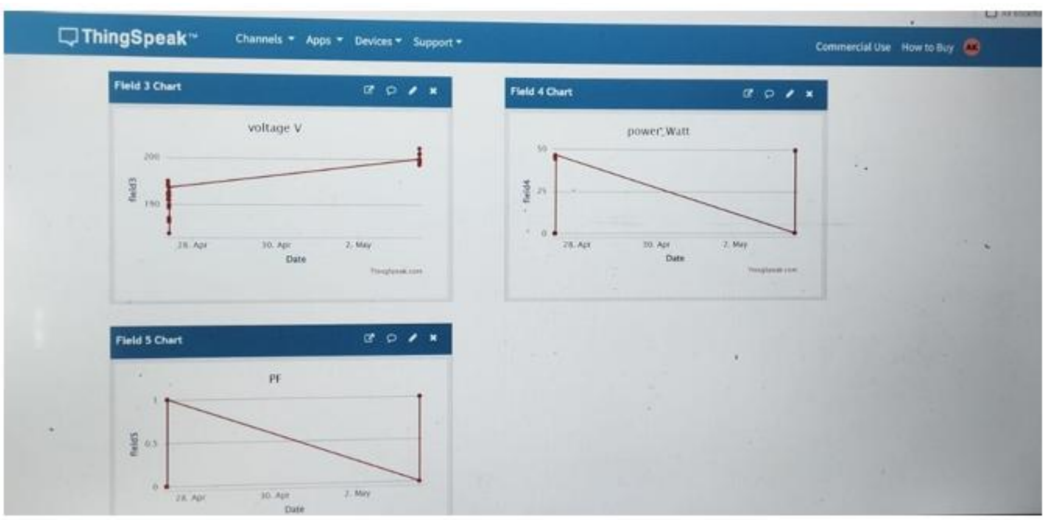

Fig. 4. *Voltage, Current and Power Observations*

Conclusion and Future Scope

The results of this study validate the effectiveness of a digital twin–based smart building energy management system in monitoring and optimizing building energy performance. Real-time experimental data collected over a two-day period demonstrated reliable tracking of environmental and electrical parameters, with temperature varying between 26 °C and 34 °C, humidity increasing from 56% to 64%, and a stable supply voltage of 12 V. Derived parameters such as power consumption (0–50 W) and power factor (0–1) reflected dynamic load behavior, confirming the system's capability to accurately represent real-world operating conditions through the digital twin. These results indicate that the proposed system can effectively support real-time monitoring, performance analysis, and energy optimization decisions.

The integration of sensor networks, IoT-enabled data acquisition, and digital twin modeling enabled predictive analysis and intelligent control, leading to improved energy awareness and operational efficiency. The close alignment between physical measurements and digital twin predictions demonstrates the reliability of the proposed framework for smart building applications. Beyond energy optimization, the system also contributes to improved indoor environmental monitoring, supporting occupant comfort and sustainable building operation.

Future work will focus on extending the system with advanced machine learning–based predictive control, integration of renewable energy sources, and long-term performance evaluation across diverse building environments. Incorporating occupant behavior modeling and expanding the framework to building clusters and smart city platforms will further enhance scalability and real-world impact. Overall, the study establishes a strong foundation for adaptive, intelligent, and sustainable building energy management using digital twin technology.

References

1. Zhiyu Zheng, Esma Yahia, et al., “Semantic Digital Twin for Smart Building Energy Management Systems: Services-Oriented Framework and Implementation,” SSRN, 2024.
2. Sirchia, T., et al., “Towards Digital Twins of Buildings and Smart Energy Networks: Current and Future Trends,” IEEE, 2023.
3. Abby Francisco, J. E., Neda Mohammadi, et al., “Smart City Digital Twin–Enabled Energy Management: Toward Real-Time Urban Building Energy Benchmarking,” ResearchGate, 2020.
4. Puiu, I. L., et al., “The Efficiency of Building Maintenance Using Digital Twins: A Literature Review,” Springer, 2024.
5. Agouzoul, A., Tabaa, M., et al., “Towards a Digital Twin Model for Building Energy Management: Case of Morocco,” *Procedia Computer Science*, 2021.
6. Lamagna, M., Groppi, D., et al., “A Comprehensive Review on Digital Twins for Smart Energy Management Systems,” *International Journal of Energy Production and Management*, vol. 6, no. 4, pp. 323–334, 2021.
7. Arowoiya, V. A., Moehler, R. C., et al., “Digital Twin Technology for Thermal Comfort and Energy Efficiency in Buildings: A State-of-the-Art Review and Future Directions,” *Energy and Built Environment*, 2024.
8. Bortolini, R., Rodrigues, R., Forcada, N., et al., “Digital Twins’ Applications for Building Energy Efficiency: A Review,” *Energies*, 2022.
9. Arowoiya, V. A., Moehler, R. C., et al., “Digital Twin Technology for Thermal Comfort and Energy Efficiency in Buildings: A State-of-the-Art and Future Directions,” *ScienceDirect*, 2024.
10. Tahmasebinia, F., Lin, L., Sepasgozar, S., et al., “Exploring the Benefits and Limitations of Digital Twin Technology in Building Energy Management,” *Applied Sciences*, 2020.
11. Elnour, M., Naji, K., et al., “Empowering Smart Cities with Digital Twins of Buildings: Applications and Implementation Considerations of Data-Driven Energy Modelling in Building Management,” *SAGE Journals*, 2024.
12. Zhao, J., Feng, H., et al., “Developing a Conceptual Framework for the Application of Digital Twin Technologies to Revamp Building Operation and Maintenance Processes,” 2023.