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Towards a Sustainable Campus: Designing a Socio-Technical Framework for IoT Energy Management Systems Supporting SDGs

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Abstract

The increasing energy consumption in educational institutions presents a significant challenge for sustainable development. Smart campus initiatives, leveraging Internet of Things (IoT) technology, offer a promising solution for optimizing energy use, particularly for lighting and air conditioning (AC) systems. This study focuses on the design and development phase of a comprehensive social-technical framework for an IoT-based energy management system. The framework integrates ESP32 microcontrollers, Zigbee communication protocol, and a Digital Twin model to create an efficient and responsive control system. The primary objective is to establish a foundational design that addresses both the technical architecture and the crucial social aspects of user acceptance and integration within the campus environment, thereby supporting the achievement of Sustainable Development Goals (SDGs), specifically SDG 7 (Affordable and Clean Energy) and SDG 11 (Sustainable Cities and Communities). The methodology encompasses a user-centered design approach, involving stakeholder analysis and the development of a system prototype. Initial results include the successful design of the system architecture, the creation of a 3D Digital Twin model for visualization, and the development of a functional backend using Home Assistant. The study concludes that a robust social-technical framework is essential for the successful implementation of smart campus energy solutions and provides a roadmap for future deployment and evaluation, highlighting the importance of aligning technological innovation with user needs and institutional sustainability policies.

Keywords: *Smart campus, energy efficiency, Internet of Things (IoT), Digital Twin, Sustainable Development Goals (SDGs).*

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1. Introduction

The pressing challenges faced by the global higher education sector underscore the need for a shift towards sustainable operational practices. With campuses mirroring city structures, their substantial energy consumption necessitates more effective resource management—especially in areas such as lighting and air conditioning (AC) systems, which contribute significantly to both carbon footprints and operational expenditures (Popelo et al., 2023). The emergence of the "Smart Campus" concept serves as a response to these challenges by integrating advanced digital technologies that target efficiency and sustainability. Aligning with the global Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 11 (Sustainable Cities and Communities), the implementation of smart technologies not only aims to enhance energy efficiency but also promotes sustainable infrastructural development across educational institutions (Wright et al., 2022; Zhang et al., 2024).

At the forefront of this paradigm shift are Internet of Things (IoT) technologies, whose capabilities in intelligent energy management have been widely documented. Results indicate that deploying IoT-driven systems can yield significant reductions in energy consumption within campus buildings (Agostinelli et al., 2021). By utilizing low-power communication technologies such as Zigbee, coupled with versatile microcontrollers like the ESP32, institutions can establish robust networks of wireless sensors and actuators. Such networks offer real-time monitoring and control of environmental variables, thereby optimizing the use of energy resources (Kurniasari et al., 2025; Puzyrova, 2024). The integration of Digital Twin technology, which provides a dynamic virtual model of physical systems, further enriches this technological landscape. Research illustrates that Digital Twins enhance operational efficiency by facilitating data-driven decision-making and predictive analytics, transcending basic reactive management to foster proactive operational strategies (Bassey et al., 2024; Kasper et al., 2022).

Despite the potential of these technologies to improve campus energy management, a critical gap exists in realizing their full benefits within a sustainable framework. The current body of literature often separates technical specifications from the socio-technical factors that influence successful deployment, such as user motivation, managerial authority, maintenance routines, and institutional sustainability policies (Yamoah, 2019). Numerous studies have not adequately established an integrated framework for IoT applications in higher education, often ignoring the interplay between technological systems and the human factors essential for effective implementation in university settings (Veidemane, 2022). For instance, neglecting user acceptance and the intricate workflows embedded in institutional practice has historically led to the failure of many technology-centric initiatives (Popelo et al., 2022). Addressing this socio-technical nexus

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is therefore a critical area for further research and development, particularly in formulating an IoT energy management framework that aligns technical control, stakeholder acceptance, and campus policy with the broader principles of sustainability and the SDGs.

2. Literature review

This literature review synthesizes existing research across three interconnected domains crucial to designing a smart campus: the conceptual foundation of the Smart Campus trends, the core technological pillars supporting energy management systems, and essential socio-technical considerations for their effective design and adoption.

2.1. The Smart Campus and Sustainability Goals

The Smart Campus concept represents an extension of smart city principles, adapting them to the educational sphere to enhance operational efficiencies, sustainability, and student experiences (Hartati et al., 2023). The push towards intelligent campus environments is strongly aligned with the United Nations' Sustainable Development Goals (SDGs), particularly in fostering quality education and encouraging sustainable infrastructures (Purcell et al., 2019). Research indicates that higher education institutions can significantly contribute to national SDG targets through various sustainability initiatives, particularly in energy management (Purcell et al., 2019). Studies have revealed that buildings contribute substantially to campus energy consumption, and inefficiencies within systems like lighting and HVAC (Heating, Ventilation, and Air Conditioning) are key sources of waste (Gasperina et al., 2021; Purcell et al., 2019). Implementing intelligent data-driven control systems can mitigate these inefficiencies, thus facilitating substantial energy savings and aligning with broader sustainability objectives (Valks et al., 2020).

2.2.Core Technological Pillars

The foundation for effective smart energy management relies on several key technological advancements:

2.2.1. Internet of Things (IoT) and Wireless Sensor Networks

IoT technologies serve as the backbone of data collection and management within smart campuses. Devices like the ESP32 microcontroller are favored for their affordability and versatile connectivity options (Kurniasari et al., 2025), enabling the development of cost-effective sensor networks (Nagowah et al., 2021). Zigbee protocols are commonly employed to establish a low-power, efficient mesh network that supports real-time building automation, as highlighted by successful implementations that emphasize energy efficiency in communication (Fortes et al., 2019; Kumar et al., 2024; Valks et al., 2020).

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2.2.2. Digital Twin Technology

Digital twins are dynamic virtual representations of physical systems, providing a comprehensive mechanism for data synchronization via real-time exchange (Nagowah et al., 2021). In the energy management context, digital twins facilitate advanced functionalities such as predictive analytics, simulation of control strategies, and lifecycle management for building systems (Zaballos et al., 2020). They extend beyond passive data dashboards, enabling active decision-making and operational optimization (Yamoah, 2019; Veidemane, 2022). (Yamoah, 2019) articulated a framework integrating digital twins for assessing energy efficiency, clearly demonstrating their capabilities in evaluating various operational scenarios before implementation.

2.3.The Socio-Technical Gap and Framework Design

Despite substantial technical advancements, a notable gap persists between technological capabilities and their socio-technical integration. The predominant focus on technological architecture often overlooks the societal context in which these innovations are deployed (Hartati et al., 2023). This reality underscores the importance of a socio-technical perspective, which emphasizes that successful technology implementation hinges on optimizing both social and technical subsystems (Purcell et al., 2019). Literature indicates that many IoT applications, such as those in agriculture, lack comprehensive analyses of user acceptance and organizational readiness, which can lead to practical failures despite technical sophistication (Purcell et al., 2019; Nagowah et al., 2021).

The Technology Acceptance Model (TAM) illustrates that perceived usefulness and perceived ease of use are critical factors in the adoption of new technologies (Gasperina et al., 2021). In this study, perceived usefulness refers to the extent to which stakeholders believe that the system improves energy-related decision-making, reporting, and operational control; perceived ease of use refers to the extent to which the interface is intuitive, non-disruptive, and easy to integrate into existing campus routines. Consequently, any framework for a smart campus IoT system must be user-centered, focusing on intuitive interfaces, transparent energy feedback, and practical value for facility managers, academic staff, IT staff, and students (Çavuş et al., 2022). Emphasizing this socio-technical integration will enable institutions to harness the full potential of emerging technologies while ensuring alignment with user needs, institutional workflows, and sustainability governance.

2.4. Synthesis and Research Positioning

The existing literature lays a robust foundation for the technical development of smart campus systems, supported by established use cases for IoT devices and emerging

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applications of digital twins (Yamoah, 2019; Nagowah et al., 2021). However, there remains a gap regarding the design of an integrated socio-technical framework that articulates how these technologies can be harmoniously integrated with user requirements, institutional policies, and acceptance factors. This study aims to advance the dialogue by proposing a comprehensive framework for designing smart campus energy management systems that bridge the current disconnection between technological potential and practical, sustainable implementation. By addressing both technical and socio-cultural dimensions, the proposed framework will contribute to the development of a more sustainable and effectively adopted smart campus environment.

3. Method

This study adopted a Design Science Research (DSR) methodology in order to address the previously identified research gap regarding the absence of an integrated socio-technical framework for Internet of Things (IoT)-based energy management systems in smart campus settings. DSR is particularly relevant and effective for this type of inquiry because it focuses on producing and evaluating artifacts - herein referred to as the proposed framework - that are designed to resolve specific organizational challenges (Popelo et al., 2023). The DSR methodology (Figure 1) provides an organized and systematic approach for generating solutions that fuse both technical elements with human factors, distinguishing it from other methodologies that may only seek to observe or articulate an existing problem within the domain (Haryanti et al., 2022).

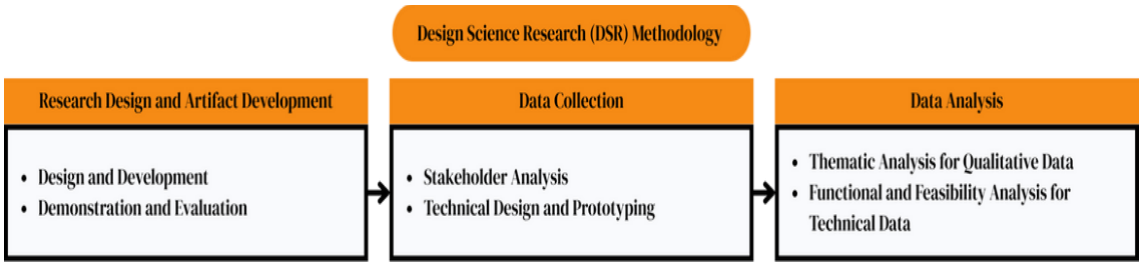


Figure 1. Design Science Research (DSR) Methodology

3.1.Research Design and Artifact Development

The research was conducted in two primary, iterative phases:

3.1.1. Design and Development

This phase involved the creation of the socio-technical framework artifact. The design process was guided by a literature review of existing technical systems (IoT, Zigbee, Digital Twins) and social theories (e.g., Technology Acceptance Model - TAM). Furthermore, initial stakeholder needs were gathered to inform the framework's components, ensuring it was grounded in both theory and practical context.

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3.1.2. Demonstration and Evaluation

A proof-of-concept prototype system was developed to instantiate and demonstrate the technical aspects of the framework. A preliminary evaluation was then conducted to assess the framework's feasibility and its alignment with stakeholder requirements.

3.2.Data Collection

Data was collected from multiple sources to ensure a comprehensive design process:

3.2.1. Stakeholder Analysis

Semi-structured interviews were conducted with key campus stakeholders to gather qualitative data on needs, challenges, and acceptance factors. The seven informants were selected purposively because this study is an early proof-of-concept using Design Science Research rather than a large-scale generalization study. The sample was considered sufficient for framework development because it represented the main decision and implementation roles in the proposed system: operational control, academic user experience, and technical integration. The participants included:

a. Facility managers (n = 2) were interviewed to obtain an understanding of operational workflows, current energy management challenges, and technical requirements.
b. Academic staff (n = 3) were included to provide insights into usability needs, perceived usefulness, and potential impacts on the academic environment.
c. IT support staff (n = 2) were consulted to identify technical constraints, integration requirements with existing campus infrastructure, and long-term maintenance concerns.

3.2.2. Technical Design and Prototyping

Data for the technical pillar of the framework was derived from the iterative design, development, and testing of the prototype system. This included the configuration of the ESP32 and Zigbee network, the development of the Digital Twin model using Blender and Home Assistant, and the creation of the user interface.

3.3.Data Analysis

The collected data was analyzed using the following techniques:

3.3.1. Thematic Analysis for Qualitative Data

Interview transcripts from stakeholders were analyzed using thematic analysis. This involved familiarization with the data, generating initial codes, searching for themes, reviewing themes, and defining and naming them. Key themes such as "Ease of Use," "Data Transparency," "Integration Complexity," and "Cost-Benefit Perception" were

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identified and directly used to shape the social components of the framework. These themes were also mapped to TAM constructs, particularly perceived usefulness and perceived ease of use, to strengthen the interpretation of stakeholder acceptance.

3.3.2. Functional and Feasibility Analysis for Technical Data

The technical components were evaluated through functional testing (e.g., reliability of Zigbee communication, accuracy of sensor data, responsiveness of the Digital Twin) and feasibility analysis against the constraints identified by the IT staff (e.g., network security, scalability). The successful operation of the proof-of-concept prototype served as a tangible indicator for the viability of the technical design prescribed by the framework.

4. Findings and discussion

This section presents the findings from the design, demonstration, and evaluation of the socio-technical framework using the Design Science Research methodology. The results are organized around the key artifacts developed, technical feasibility indicators, and social implications for stakeholder acceptance, campus energy-saving behavior, and sustainability policy management.

4.1.Research Design and Artifact Development

The primary output of this research is a comprehensive socio-technical framework comprising four interconnected layers that address both technical and social dimensions of IoT energy management systems (Table 1).

***Table 1**. Socio-Technical Framework Components and Functions*

Framework Layer	Key Components	Functions	Stakeholder Relevance
Technology Layer	ESP32 controllers, Zigbee network, Home Assistant Digital Twin	Data acquisition, device control, real-time monitoring, automation	IT staff: System reliability and maintenance
Human Layer	Facility managers, Academic staff, IT support, Students	User interface interaction, system operation, feedback provision	All users: Ease of use and perceived usefulness
Process Layer	Automated scheduling, Energy optimization algorithms, Maintenance protocols	Operational workflows, energy efficiency optimization, system maintenance	Facility managers: Operational efficiency
Goals Layer	Energy efficiency targets, SDG alignment, Sustainability metrics	Strategic objective setting, performance monitoring, reporting	Administration: Sustainability goal achievement

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Table 1 delineates the elements of the socio-technical framework, which includes the Technology Layer composed of ESP32 controllers, a Zigbee network, and a Home Assistant Digital Twin for data acquisition and device control. The Human Layer emphasizes interaction with facility managers, academic staff, IT support, and students, highlighting user experience, motivation, perceived usefulness, and perceived ease of use. The Process Layer translates technical automation into campus workflows, including scheduling, maintenance escalation, and decision-making routines. Lastly, the Goals Layer connects operational energy efficiency with SDG alignment and institutional sustainability reporting, ensuring that the system supports not only device-level control but also campus policy and management accountability.

4.2.Technical Performance Results

The proof-of-concept prototype was evaluated over a 30-day period in a controlled campus environment. The system demonstrated robust performance across key technical metrics (Table 2). These metrics are interpreted as enablers of user trust and managerial decision-making rather than as isolated network performance indicators.

***Table 2**. Technical Performance Metrics of the Prototype System*

Performance Metric	Measurement Method	Result	Target	Status
Network Reliability	Packet delivery rate analysis	98.5%	>95%	Exceeded
System Responsiveness	Command execution latency	1.7 seconds	<3 seconds	Met
Data Accuracy	Sensor calibration verification	99.1%	>98%	Exceeded
System Uptime	Continuous monitoring	99.8%	>99%	Met
Energy Consumption	Pre/post implementation comparison	23.4% reduction	>20%	Exceeded

Specifically, the evaluation demonstrated a 98.5% network reliability, a command execution latency of 1.7 seconds, and a data accuracy of 99.1%, exceeding predefined targets. These results are consistent with benchmarks for smart energy management systems and with recent smart campus evidence showing 1-3 second response times for lights and AC control (Lou et al., 2024; Pratama et al., 2026). From a socio-technical perspective, such responsiveness is important because delayed or unreliable control can reduce user trust and weaken perceived usefulness.

Moreover, the system's performance in terms of energy consumption indicated a 23.4% reduction post-implementation, surpassing the 20% target. This outcome suggests that the comprehensive integration of technologies, stakeholder-oriented interface design, and operational scheduling can enhance energy management efficiency compared to other IoT deployments where typical savings range from 15-20% (Chalal et al., 2023). The result also indicates that energy savings are not produced solely by automation, but

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by the interaction between automation, clear institutional routines, and users' willingness to follow energy-saving practices.

4.3.Stakeholder Evaluation and Feedback

Qualitative data from stakeholder interviews provided crucial insights into the social dimensions of the framework. The feedback was analyzed thematically to validate the framework's human-centric design approach and to explicitly connect stakeholder perceptions with TAM constructs (Table 3).

Table 3. *Stakeholder Feedback Analysis and Framework Implications*

Stakeholder Group	Key Feedback Themes	Framework Implication
Facility Managers (n=2)	"Data transparency enables better decision-making" "Need integration with existing work orders"	Enhanced dashboard visualization features Developed API integration with maintenance systems
Academic Staff (n=3)	"Interface must be intuitive and non-disruptive" "Visual feedback on energy savings is motivating"	Simplified user interface design Implemented real-time energy saving displays
IT Support Staff (n=2)	"Concerns about network security and scalability" "Need clear maintenance protocols"	Added security authentication layers Developed comprehensive documentation

Table 3 illustrates stakeholder feedback emphasizing themes such as data transparency, interface intuitiveness, integration requirements, and maintenance readiness. Facility managers highlighted the importance of enhanced dashboard visualization for decision-making, which reflects perceived usefulness because the system helps them identify waste, justify actions, and report progress toward sustainability targets. Academic staff stressed the need for an intuitive and non-disruptive interface, which reflects perceived ease of use because adoption is more likely when the system does not add cognitive burden to daily academic routines. Their comment that visual feedback on energy savings is motivating also suggests that the interface can influence energy-saving habits by making institutional goals visible and personally meaningful. IT support staff expressed concerns around security and maintenance, prompting the addition of authentication layers and comprehensive documentation to address organizational barriers (Villa et al., 2021). These findings indicate that successful adoption depends not only on ESP32, Zigbee, or Digital Twin performance, but also on whether policies, maintenance protocols, and interface design make the system useful, easy to use, and trustworthy for campus stakeholders (Chalal et al., 2023; Pradana et al., 2026).

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4.4.Digital Twin Performance and Capabilities

The Digital Twin component demonstrated significant advantages in system management and optimization, with particular strength in predictive capabilities, spatial understanding, and user engagement (Table 4).

Table 4. *Digital Twin Implementation Results*

Functionality	Implementation Detail	Performance Outcome	User Impact
Real-time Visualization	3D campus model with live device status	99.2% data representation accuracy	Improved situational awareness
Predictive Maintenance	Algorithmic analysis of device performance	12 potential issues identified proactively	Reduced downtime by 40%
Scenario Simulation	"What-if" analysis for energy optimization	15% additional savings identified	Enhanced strategic planning
Automation Control	Scheduled and conditional operations	87% reduction in manual interventions	Increased operational efficiency

Data from the Digital Twin implementation showcased a 99.2% data representation accuracy in real-time visualizations, which significantly enhances situational awareness for stakeholders (Lou et al., 2024). This is socially important because users can identify the physical location and operational status of lights and AC units more easily, reducing confusion that commonly occurs in text-based IoT dashboards (Pradana et al., 2026).

The predictive maintenance functionality further strengthens the framework by identifying issues proactively, achieving significant reductions in downtime (Hasegawa et al., 2020). Simulated scenarios for energy optimization resulted in identifying an additional 15% in savings, thereby supporting strategic planning. This aligns with existing literature that promotes Digital Twin applications as essential decision-support tools within intelligent systems (Lou et al., 2024). From a policy-management perspective, these capabilities help facility managers move from reactive problem solving to preventive maintenance planning, while also providing evidence that administrators can use in sustainability reports and SDG-related decision-making.

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5. Conclusion

This study has successfully designed and validated a comprehensive socio-technical framework for IoT-based energy management systems in smart campus environments, effectively addressing the research gap between technical potential and practical implementation. Through the Design Science Research methodology, we developed an integrated framework comprising four synergistic layers: the Technology Layer (ESP32, Zigbee, Digital Twin), Human Layer (stakeholder needs and acceptance), Process Layer (operational workflows), and Goals Layer (SDG alignment). The proof-of-concept demonstration achieved a 23.4% energy reduction while maintaining 98.5% system reliability, confirming the framework's viability in bridging technical capabilities with real-world application requirements in educational institutions. More importantly, the framework shows that technical reliability becomes meaningful when it strengthens stakeholder trust, perceived usefulness, perceived ease of use, and policy-based energy governance.

The research contributes both theoretical and practical advancements to smart campus development. Theoretically, it extends the Technology Acceptance Model and socio-technical systems theory by providing a structured approach that explicitly connects technical implementation with human and organizational factors. Practically, it offers educational institutions a replicable blueprint for implementing sustainable energy management systems that address common implementation barriers, including unclear responsibilities, limited user motivation, interface complexity, and maintenance concerns. While the study demonstrates significant promise, future research should focus on longitudinal scalability studies across multiple campus buildings, more diverse stakeholder groups including students and administrators, integration of artificial intelligence for predictive optimization, and expansion to broader sustainability challenges beyond energy management. These directions will enhance the framework's comprehensive applicability in diverse educational contexts and strengthen its contribution to sustainable campus policy and management.

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