Development of an IoT-Based Smart Building Prototype with Installation Component Management Features

Muhamad Fais Halim Jauzi[1, *]
[1]Departemen Teknik Elektro dan Elektronika, Universitas Negeri Yogyakarta
[*]Correspondence: muhamadfais.2020@student.uny.ac.id

Intisari* – *Revolusi industri telah membawa perubahan besar dalam pola konsumsi energi, dari biomassa ke energi fosil, yang kemudian memicu lonjakan emisi gas rumah kaca dan perubahan iklim. Di era Revolusi Industri 4.0, teknologi seperti Internet of Things (IoT) dan Augmented Reality (AR) hadir sebagai solusi untuk menciptakan sistem yang lebih efisien dan aman. Penelitian ini mengembangkan purwarupa bangunan pintar berbasis IoT dan AR untuk meningkatkan efisiensi energi serta keamanan pengelolaan instalasi listrik. Sistem menggunakan mikrokontroler ESP32 dengan protokol HTTP untuk membaca data dari tiga jenis sensor, yaitu sensor asap MQ2, sensor flame sensor 5 channel, dan PZEM-004T yang mencatat tegangan, arus, dan daya secara menyeluruh. Semua data dikirim ke server berbasis Firestore dan divisualisasikan secara real-time melalui dashboard web yang dikembangkan dengan React dan dihosting di platform Vercel. Fitur Augmented Reality dikembangkan menggunakan AR.js untuk menampilkan diagram kelistrikan dan komponen seperti Miniature Circuit Breaker (MCB) secara visual di atas panel listrik melalui perangkat ponsel atau tablet. Teknisi cukup memindai panel untuk melihat visualisasi interaktif pasif seperti perbesaran dan rotasi guna memahami struktur instalasi tanpa membuka panel secara fisik. Sistem juga dilengkapi dengan notifikasi dini dan aktivasi otomatis seperti buzzer dan pompa air saat terdeteksi potensi kebakaran dari sensor. Selain itu, fitur manajemen komponen memfasilitasi dokumentasi riwayat perawatan yang mencakup penggantian komponen, spesifikasi teknis, dan dokumentasi visual, sehingga mempermudah teknisi dalam pemeliharaan dan audit sistem. Hasil implementasi menunjukkan bahwa sistem berhasil mengintegrasikan teknologi Internet of Things, Augmented Reality, dan web secara efektif, menjadikannya solusi potensial bagi bangunan pintar yang efisien, aman, dan terintegrasi..

Kata kunci* – *Internet of Things, Bangunan Pintar, Augmented Reality, Manajemen Instalasi.

Abstract – The industrial revolution has brought significant changes in energy consumption patterns, shifting from biomass to fossil fuels, which in turn triggered a surge in greenhouse gas emissions and contributed to climate change. In the era of Industry 4.0, technologies such as the Internet of Things and Augmented Reality have emerged as solutions for creating more efficient and safer systems. This research develops a smart building prototype based on the integration of Internet of Things and Augmented Reality to enhance energy efficiency and safety in electrical installation management. The system uses an ESP32 microcontroller with HTTP protocol to read data from three types of sensors, namely the MQ2 gas sensor, a five-channel flame sensor, and the PZEM-004T sensor for measuring voltage, current, and power comprehensively. All data are transmitted to a Firestore-based server and visualized in real time through a web dashboard built with React and hosted on the Vercel platform. The Augmented Reality feature is developed using AR.js to display electrical wiring diagrams and components such as Miniature Circuit Breakers directly on the electrical panel via mobile devices such as smartphones or tablets. Technicians simply scan the panel to view passive interactive visualizations, including zoom and rotation features, allowing them to understand the installation layout without physically opening the panel. The system is also equipped with an early warning mechanism and automatic activation features such as buzzers and water pumps in the event of fire detection. Additionally, the component management features facilitate the documentation of maintenance history, including component replacements, technical specifications, and visual records, making it easier for technicians to perform maintenance and system audits. The implementation results show that the system successfully integrates Internet of Things, Augmented Reality, and web technologies, offering a potential solution for smart buildings that are efficient, safe, and well-integrated.

Keywords – Internet of Things, Smart Building, Augmented Reality, Installation Management.

I. INTRODUCTION

The industrial revolution has dramatically transformed human life patterns, with each phase bringing significant changes in how we live and work. While the initial shift from animal and human power to steam engines marked the first industrial revolution, we are now in the fourth phase, where advanced technology and digitalization have become integral parts of human life [1]. However, this industrial progress has brought environmental challenges, particularly climate change due to fossil fuel consumption. The world's energy sources have evolved significantly, transitioning from biomass to fossil fuels like coal, oil, and natural gas, especially after the Industrial Revolution in the 1900s. This increased use of fossil fuels has led to a surge in greenhouse gas emissions, resulting in climate instability, global warming, and rising sea levels [2].

Internet of Things (IoT) emerges as one of the fundamental pillars of Industry 4.0, aiming to transform our daily lives by creating intelligent devices that can perform everyday tasks [3]. In this context, IoT offers solutions for reducing energy consumption through monitoring, control, and automation. Studies have shown that implementing IoT technology can effectively reduce building energy consumption by connecting devices that enable remote and real-time control through the internet [4]. When applied more broadly to buildings by integrating various devices and sensors, this concept is known as smart buildings - a combination of automation, communication, and environmental management designed to enhance efficiency, comfort, and security.

However, electrical installation safety presents a unique challenge in buildings. Data from the West Jakarta Statistics Agency in 2023 reveals that 267 out of 467 fire cases in West Jakarta were caused by electrical issues. Carelessness and non-compliance with regulations are the primary causes of electrical fires. These incidents often occur due to improper electrical energy usage, poor safety measures, rule-violating installations, and the use of substandard materials and equipment [5].

To minimize the risk of short circuit-induced fires, it is crucial to have a comprehensive understanding of electrical installations and implement modern technology in their management. Understanding the technical specifications of each installation component and conducting regular checks can minimize fire potential. This is particularly important because replacing components with incompatible specifications can lead to fires, as each component has different capabilities in conducting or breaking electrical current during short circuits [6].

The development of efficient building management requires a robust component management system that enables proper monitoring, identification, and updating of installation components according to appropriate specifications. Smart building implementation should focus not only on improving energy efficiency and comfort but also on security aspects, particularly concerning the management of electrical installation components. In smart buildings, installation component management becomes crucial considering the potential hazards that can arise from arbitrarily replaced installation components due to user ignorance.

To support effective component management, modern technologies such as Augmented Reality (AR) can provide innovative solutions. AR can assist technicians and users in understanding hidden or complex installation components within electrical panels, thereby facilitating problem identification and ensuring proper component replacement. Although the current implementation focuses on a single panel within a scaled-down prototype, the system can be adapted for larger buildings or residential use. To achieve this, several modifications are required, including the ability to manage multiple electrical panels, extend sensor coverage, and implement scalable AR visualization. This can be addressed by assigning unique markers for each panel and developing a web-based panel directory interface, allowing users to select specific panels before triggering the AR visualization. These enhancements would improve flexibility and scalability, making the system more applicable for real-world smart building environments.

II. METHODOLOGY

This study employs the ADDIE (Analysis, Design, Development, Implementation, Evaluation) framework to develop a smart building system focused on installation component management. The methodology was chosen for its systematic approach and iterative nature, which aligns with the complex requirements of smart building systems. In the Analysis phase, we identified core requirements for electrical component tracking, documented specifications and maintenance history needs, and determined component status monitoring requirements. The Design phase involved creating system architecture for the management system, developing specifications for AR visualization features, and establishing integration protocols between system components.

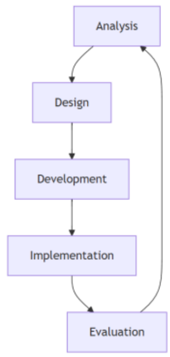

Figure 1. ADDIE Framework Flowchart for Smart Building System Development

During the Development phase, we built the component specification database, developed the real-time monitoring system, and implemented AR visualization tools. The Implementation phase focused on integrating all system components, establishing user access protocols, and configuring maintenance alert systems. Finally, the Evaluation phase consisted of testing system accuracy and reliability, assessing user interface functionality, and validating AR feature effectiveness. This methodological approach ensures systematic development and validation of the smart building management system while maintaining focus on user accessibility and practical functionality.

A. Hardware Components

1) Control Circuit: The control system is built around an ESP32 microcontroller, chosen for its robust capabilities in handling multiple I/O operations and wireless connectivity [7]. The system integrates several sensors: PZEM-004T for electrical parameter monitoring, MQ2 gas sensor for smoke detection, and a 5-Channel flame sensor for fire detection.

2) As demonstrated in [8], the PZEM-004T sensor provides reliable measurements with relatively small error margins: 2% for voltage, 10% for current, and 5% for energy consumption. The control circuit on figure 2 also includes relay modules for electrical control, a buzzer for alarm notifications, and a water pump for emergency fire suppression. All components are connected through a custom-designed PCB to ensure reliable operation and proper signal routing.

3) *Scale Model*: A physical scale model (45cm × 50cm × 20cm) serves as the demonstration platform, featuring four rooms (20cm × 20cm × 20cm each) and one corridor (5cm × 40cm). The model incorporates LED lighting installations and power outlets in each room, with integrated sensor placement for smoke and fire detection.

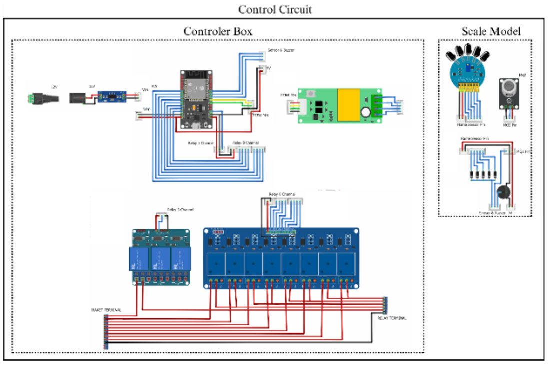

Figure 2. Control Circuit Design

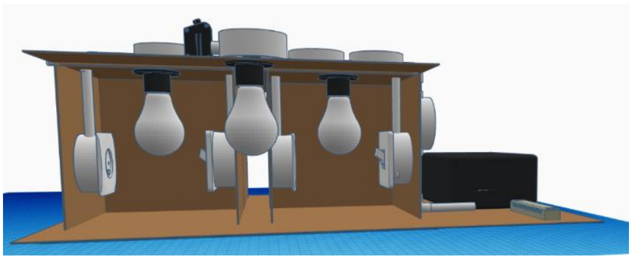

Figure 3. Scale Model in 3D

The MQ2 sensor's effectiveness depends not on distance but on gas concentration levels, making it ideal for room-level monitoring [9]. The scale model on Figure 3 also includes a water pump system for fire suppression, activated automatically when the flame sensor detects fire.

4) *Electrical Panel:* The electrical distribution system is implemented through a main panel that follows standard safety requirements while incorporating smart monitoring capabilities. As outlined by [10], the panel includes a main MCB (40A) for overall system protection and individual MCBs (10A) for each room. The integration of PZEM-004T enables real-time power monitoring, while proper cable sizing (2.5mm² for room circuits, 6mm² for main supply) ensures safe current handling capacity. This design on Figure 4 aligns with [11] findings on factors affecting electrical installation reliability, particularly regarding component specifications and monitoring systems

B. Software Development

1) *Microcontroller Programming:* Arduino IDE serves as the primary development environment for ESP32 programming. As described in [12], Arduino IDE provides a straightforward interface for writing, editing, and uploading code to microcontroller boards. The platform's extensive library support and simple operation make it particularly suitable for IoT applications, allowing developers to focus on implementation rather than complex configuration settings.

2) *Web Interface Development:* The web interface is built using React JS as the core framework, enhanced by Next.js for improved performance. According to [13], React JS employs a declarative approach with component-based architecture, enabling the creation of interactive user interfaces while maintaining code efficiency.

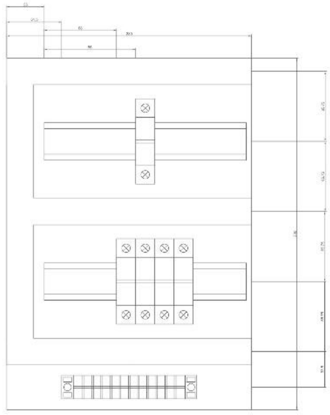

Figure 4. Electrical Panel 2D Design

3) *Database Management:* Firebase Realtime Database is implemented as the backend infrastructure. As noted in [14], Firebase functions as a Backend-as-a-Service (BaaS), storing data in JSON format and synchronizing it in real-time with connected clients. This architecture is particularly beneficial for IoT applications, enabling immediate data updates across platforms and supporting cross-platform development with Android, iOS, and JavaScript SDKs.

4) *Augmented Reality:* Augmented Reality (AR) combines real-world environments with computer-generated elements in real-time [15], enabling users to interact with virtual objects overlaid on physical surroundings [16]. The implemented system utilizes passive AR to display 3D objects of electrical panel components along with their wiring diagrams, facilitating maintenance procedures. The AR visualization was developed using AR.js due to its simplicity and ease of integration. Technicians can scan physical markers attached to the electrical panel using a mobile web application to reveal virtual components, such as Miniature Circuit Breakers (MCBs), and their wiring diagrams. The diagrams incorporate universal electrical symbols, allowing professional technicians to easily interpret component information. One key challenge in designing the AR interface was ensuring marker recognition stability, particularly under poor lighting or reflective conditions, which could affect the alignment of virtual objects. Additionally, while an initial idea involved visualizing the complete wiring network of all components connected to the panel, this approach was deemed inefficient for the prototype. Instead, a focused

visualization on the panel and its internal wiring was chosen to maintain clarity and usability. For future scalability, adopting more robust AR frameworks may allow multi-panel visualization and greater interaction, improving system flexibility in large-scale smart building deployments.

C. System Integration

The integration process on Figure 5 combines hardware and software components into a cohesive smart building system. The ESP32 microcontroller serves as the central hub, processing sensor data and controlling actuators while maintaining communication with the Firebase backend [7]. Sensor readings from PZEM-004T, MQ2, and flame sensors are continuously monitored and transmitted to Firebase through ESP32's Wi-Fi connectivity. As outlined in [14], Firebase's real-time database enables immediate data synchronization, allowing the web interface to reflect current system conditions without manual refresh.

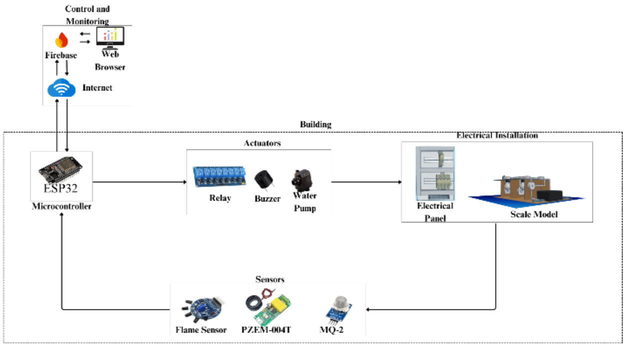

Figure 5. System Block Diagram

The web interface, developed with React JS and Next.js, provides a clean and minimalistic dashboard designed specifically for technicians, allowing real-time monitoring and control of electrical systems. The layout includes intuitive navigation panels, real-time indicators for voltage, current, and fire safety, as well as quick-access switches for component control. Status indicators use universally recognized icons and color-coded labels (e.g., “Secure” with green indicators) to ensure clarity during operation. Through Firebase integration, users can remotely control electrical components via relay modules, with the system maintaining state synchronization between the web interface and physical devices [13]. The interface also incorporates an augmented reality feature for component management, accessible through mobile devices, providing visual information about electrical installation specifications and maintenance history [16].

For system security and data integrity, Firebase handles user authentication and real-time data validation. The system implements automated safety protocols, such as activating the water pump and buzzer when fire or smoke is detected, while simultaneously updating the web interface with alert notifications [8]. This integrated approach ensures reliable operation and immediate response to potential hazards while maintaining accessible remote monitoring and control capabilities.

III. RESULTS AND DISCUSSION

This section presents the findings of the implemented smart building prototype, focusing on hardware components, software functionality, and system testing. The discussion includes an analysis of the control and sensor circuits, the hub board, and the scale model, followed by an evaluation of the web-based monitoring and control system. Additionally, testing results for sensor accuracy, response time, and overall system reliability are examined to assess the performance of the prototype against the initial design objectives.

A. Hardware Components

The hardware implementation of this smart building system consists of interconnected components designed for monitoring, control, and automation. Key elements include a scale model, an electrical panel with energy monitoring, a control circuit based on the ESP32 microcontroller, and various sensors to enhance safety and functionality.

1) Control Circuit: The control circuit serves as the central intelligence of the smart building system, managing sensors, actuators, and communication with the web-based interface. At its core, the ESP32 microcontroller processes data from the MQ2 smoke sensor and a 5-channel flame sensor, triggering appropriate responses such as activating the buzzer for smoke detection or turning on the water pump when fire is detected. The MQ2 sensor was selected due to its wide detection range for combustible gases and smoke, its low cost, and its compatibility with the ESP32’s analog input. The 5-channel flame sensor was chosen for its multi-directional detection capability and its sensitivity to infrared wavelengths emitted by fire, making it suitable for early fire detection. It also controls lights and sockets through relays, enabling remote operation via Firebase. The circuit is implemented on a custom PCB designed to optimize component placement and reduce wiring complexity. Built using an etching process with ferric chloride $FeCl_3$, PCB integrates all essential components, ensuring a stable and reliable system that seamlessly connects to the distribution panel and the overall smart building prototype. Both sensors were tested across multiple conditions, and the results confirmed their ability to reliably detect fire-related hazards at varying distances and angles. Their integration contributed directly to achieving the project’s objective of enhancing building safety through automated hazard monitoring and response.

2) Scale Model: The scale model serves as the physical representation of the smart building prototype, integrating essential components such as lights, sensors, and actuators in a compact and functional layout. Constructed using plywood, the model is designed to reflect real-world installation scenarios, ensuring accurate placement of electrical components. Lights and sockets are installed in each room, while the corridor houses the MQ2 smoke sensor, a 5-channel flame sensor, and a buzzer for fire detection. Wiring is carefully arranged to connect all components to the control circuit and distribution panel, maintaining both functionality and aesthetic appeal. This scale model not only demonstrates the integration of smart building features but also provides a tangible platform for testing and validation of the system's performance.

3) Electrical Panel: The electrical panel, or Panel Hubung Bagi (PHB) serves as the central distribution unit for the smart building's power system, ensuring efficient and safe electricity management. It houses multiple miniature circuit breakers (MCBs) that function as overcurrent protection, preventing excessive loads and short circuits. Each MCB is assigned to a specific section of the building, distributing power to different rooms and components while maintaining electrical safety. The panel is wired following a structured layout to ensure secure and reliable connections, as illustrated in the design schematics. Additionally, a PZEM-004T energy monitoring module is integrated into the panel to measure voltage, current, power, and energy consumption, providing real-time data for system monitoring. The PZEM-004T module was selected for its capability to provide real-time electrical parameter readings (voltage, current, power, and energy) with built-in serial communication, low power consumption, and compatibility with microcontroller-based systems. Despite minor deviations in low-current measurements, the module consistently delivered accurate voltage and power readings under normal to high loads, aligning with the research objective of achieving reliable energy monitoring for automation and safety applications. This setup ensures that all electrical components operate within safe limits, contributing to the overall stability and efficiency of the smart building system.

B. Software Implementation

The web-based application was developed using Next.js framework, designed to provide responsive interfaces for both desktop and mobile platforms. The development stack incorporates Tailwind CSS for styling components and Shadcn/UI for pre-built UI components, enabling efficient and consistent interface development. Firebase was integrated as the backend service, handling real-time data management, user authentication, and database operations. The system architecture utilizes Firebase Realtime Database for sensor data streaming and real-time monitoring, while Firestore handles structured data storage for maintenance records, user profiles, and component management. Firebase Authentication ensures secure user access management through email/password authentication. The entire application was deployed on Vercel platform, ensuring reliable hosting with automatic deployment capabilities and optimal performance through edge network distribution.

1) Desktop Interface: The desktop interface comprises several key pages designed for comprehensive system management. The login page serves as the entry point, implementing secure user authentication through username and password verification. Upon successful authentication, users are directed to the dashboard that displays real-time sensor data from PZEM-004T, including voltage, current, and power consumption metrics, alongside environmental sensor readings for smoke and fire detection. The dashboard also features a quick access panel for immediate control of actuators. The control interface enables granular management of electrical installations, organized by room sections for intuitive navigation. Each room's components, including lights and power outlets, can be individually controlled through this interface. The monitoring page extends the dashboard's functionality by providing detailed visualizations through interactive graphs, displaying real-time trends of electrical parameters. For maintenance purposes, the management interface facilitates component tracking and maintenance logging. Users can record both repair activities and component replacements, with each action automatically logged in the history page. This systematic approach ensures proper documentation of all maintenance activities. The interface also provides detailed component listings for each room, accessible through an expandable room selector.

2) Mobile Interface: The mobile interface maintains core functionalities while optimizing for smaller screens. The dashboard is streamlined to display four essential sensor readings, ensuring clarity and usability on mobile devices. Navigation is facilitated through a bottom menu bar for easy access to key features. A unique feature exclusive to the mobile interface is the Augmented Reality (AR) capability, accessible through an AR icon in the bottom-right corner. This feature enables users to visualize installation components in real space, enhancing maintenance and inspection processes. The mobile implementation prioritizes essential functions while maintaining system integrity, ensuring that critical monitoring and control capabilities remain accessible on portable devices. The responsive design automatically adapts to different screen sizes, providing consistent user experience across various mobile devices.

C. Testing and Result

The testing phase was conducted to verify both hardware sensor performance and web interface functionality, ensuring comprehensive system validation. Testing procedures focused on sensor accuracy, interface responsiveness, and overall system integration.

1) Sensor Testing Result: Initial testing focused on the PZEM-004T sensor's current measurement capabilities. As presented in Table 1, the sensor achieved a median error of 9.09%, with improved accuracy observed for higher current loads such as electric irons, which displayed a significantly lower error of 1.94%. Meanwhile, smaller loads like phone chargers tended to show higher error margins.

Table 1. Current Testing Results

Load Tested	**Current Value (A)**		**Error (%)**
	Sensor	**Measurement**	
Iron	1.58	1.55	1.94
Phone Charger	0.12	0.08	50.00
Two Phone Charger	0.20	0.44	11.11
2 Phone Chargers & Iron	1,70	1.68	1.99
Laptop Charger	0.36	0.33	9.09
Median Error (%)			**9.09**

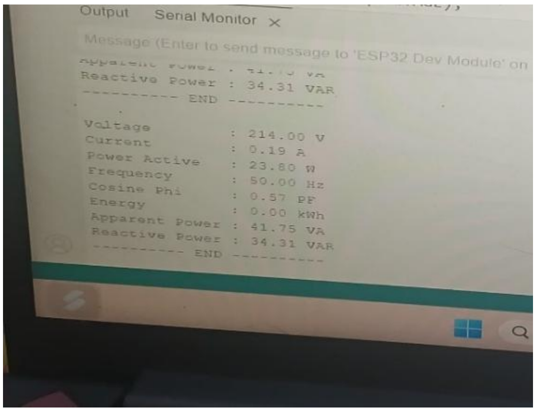

Figure 6. Serial Monitor PZEM-004T

Figure 6 illustrates the real-time output on the serial monitor, showing raw current readings from the PZEM-004T sensor during the test. Additionally, Figure 7 shows the sensor's visual output when compared to a panel meter reading.

Figure 7. Panel Meter Reading

Table 2. Voltage Testing Results

Load Tested	Voltage Value (V)		Error (%)
	Sensor	Measurement	
Iron	208.4	209.0	0.29
Phone Charger	212.7	213.0	0.12
Two Phone Charger	213.0	213.0	0.00
2 Phone Chargers & Iron	208.8	209.0	0.10
Laptop Charger	213.3	214.0	0.33
Median Error (%)			**0.14**

In terms of voltage, the sensor demonstrated exceptional accuracy, achieving a median error of only 0.14% as seen in Table 2. This high precision was maintained across various load types, confirming the sensor's reliability for continuous voltage monitoring.

Environmental sensor testing included performance assessments of the MQ2 gas sensor. As detailed in Table 3, the sensor successfully detected smoke at varying distances ranging from 5 cm to 80 cm.

Table 3. Smoke Sensor Testing Results

Test Distance (cm)	Test Scenario	Sensor Reading	Test Status
-	No Smoke	High	Success
5	Smoke	Low	Success
10	Smoke	Low	Success
20	Smoke	Low	Success
40	Smoke	Low	Success
80	Smoke	Low	Success

Figure 8 visualizes the setup used for testing the smoke sensor under controlled conditions. The 5-channel flame sensor was tested across various angles (30°–90°) and distances (30–90 cm). The results, summarized in Table 4, confirmed reliable detection coverage suitable for environmental safety monitoring.

Figure 8. Smoke Sensor Testing Setup

Table 4. Flame Sensor Testing Results

Test Distance (cm)	Angle (°)	Sensor Reading	Test Status
30	30	High	Success
30	60	High	Success
30	90	High	Success
60	30	High	Success
60	60	High	Success
60	90	High	Success
90	30	High	Success
90	60	High	Success
90	90	High	Success

2) Web Interface Testing Result: The web interface was evaluated based on its control capabilities and monitoring functionalities. Control feature testing validated the system's ability to toggle lights and power outlets across multiple rooms. As summarized in Table 5, the system achieved a 100% success rate in all control operations.

Table 5. Control Feature Testing Results

Load	Toggle Condition ON	Toggle Condition OFF	Load Condition ON	Load Condition OFF	Test Status
Lamp A	✓		✓		Success
		✓		✓	Success
Socket A	✓		✓		Success
		✓		✓	Success
Lamp B	✓		✓		Success
		✓		✓	Success
Socket B	✓		✓		Success
		✓		✓	Success
Lamp C	✓		✓		Success
		✓		✓	Success
Socket C	✓		✓		Success
		✓		✓	Success
Lamp D	✓		✓		Success
		✓		✓	Success
Socket D	✓		✓		Success
		✓		✓	Success

Figures 9 and 10 display the real-time monitoring interface, which presented electrical data through interactive graphs. These graphs effectively visualized real-time voltage (0–240 V), current (0–10 A), and power usage (0–12 kW) parameters.

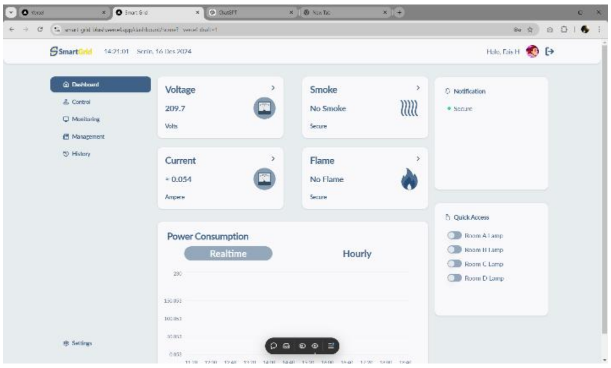

Figure 9. Dashboard Monitoring Interface

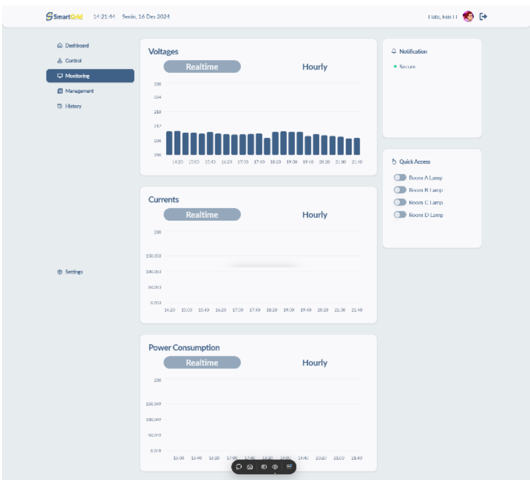

Figure 10. Real-time Monitoring Graphs

Table 6 presents the system's performance in terms of data refresh rate and measurement accuracy during prolonged testing periods. The system’s maintenance management capabilities were assessed through the component management interface. Figure 11 shows the dashboard for managing maintenance records and component statuses.

Figure 12 and Figure 13 represent the input forms used for recording component replacements and maintenance actions, respectively. A chronological view of recorded maintenance history is shown in Figure 14. The system’s ability to export records in PDF and CSV formats is illustrated in Figures 15 and 16, demonstrating compatibility for report generation and archival.

Table 6. Real-time Monitoring Test Results

Feature	Test Parameter	Test Condition	Expected Result	Test Status
Voltage	Voltage	Input 0-240V	Real-time voltage display on graph	Success
Current	Current	Input 0-10A	Real-time current display on graph	Success
Power	Power	Dynamic load 0-12kW	Real-time power display on graph	Success

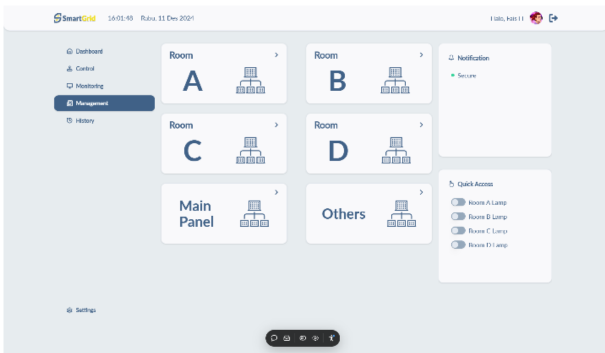

Figure 11. Component Management Interface

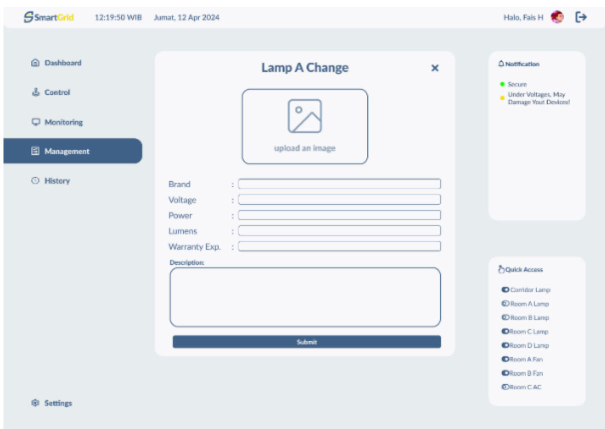

Figure 12. Component Replacement Form

E-ISSN: 2746-2536

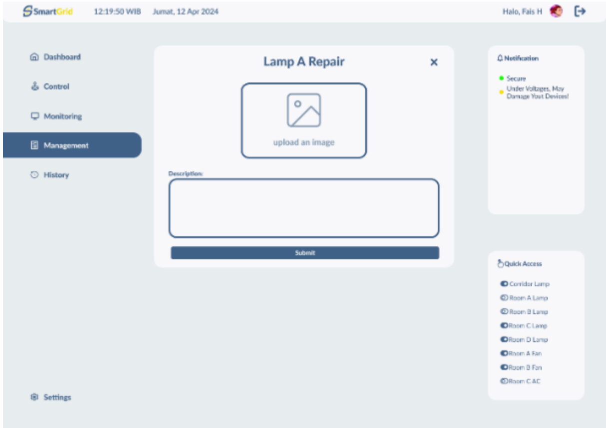

Figure 13. Maintenance Record Form

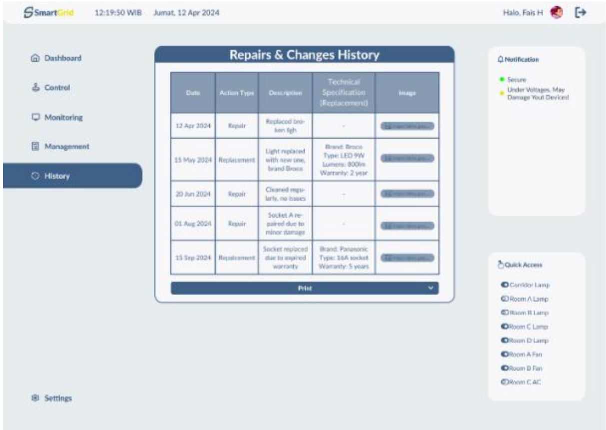

Figure 14. History Page

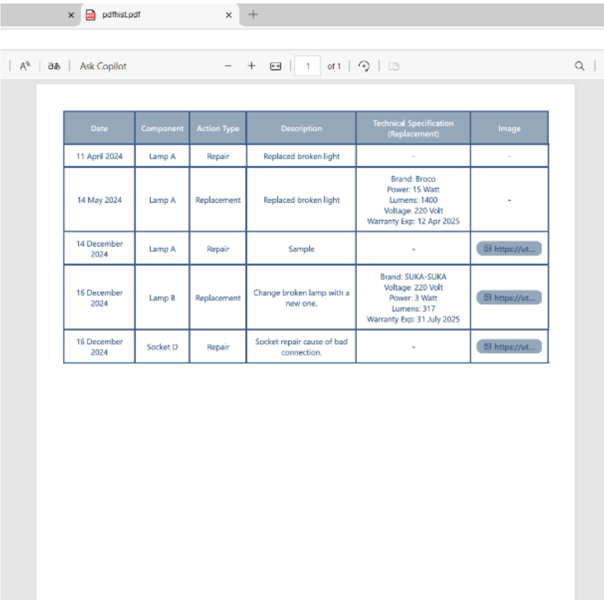

Figure 15. PDF Export

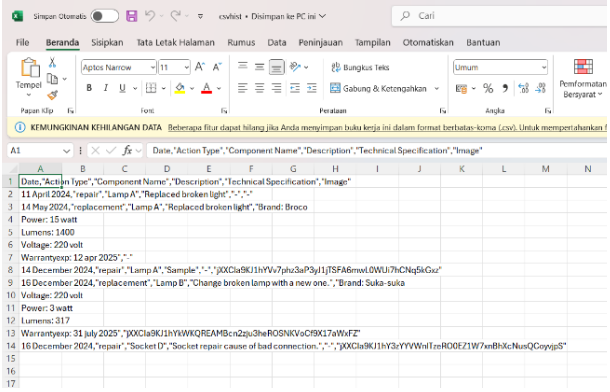

Figure 16. CSV Export

The Augmented Reality (AR) feature was tested under different lighting conditions. Figure 17 illustrates marker detection results under sunlight, while Figure 18 presents similar results under artificial lighting conditions. Both tests confirmed reliable performance at distances ranging from 30–90 cm and angles between 30°–90°.

As shown in Figure 19, the AR interface successfully displayed 3D visualizations of electrical panel components and wiring diagrams, validating its usability in maintenance and educational contexts.

Figure 17. AR testing results under sunlight

Figure 18. AR testing results under artificial lighting

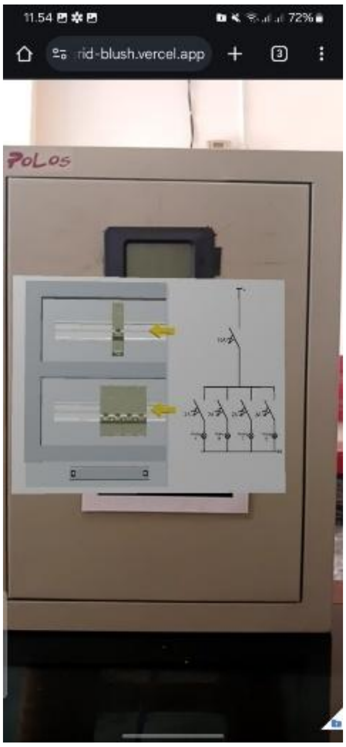

Figure 19. AR interface displaying electrical components

Finally, the notification system was evaluated for its ability to detect hazardous events and generate alerts. Table 7 lists the system's trigger-response log.

Table 7. Notification System Testing

Notification Type	Notification Display	Test Status
Smoke Detection	Yes	Success
Fire Detection	Yes	Success

To ensure data reliability despite inherent sensor inaccuracies, system calibration and design tolerances were carefully considered. For instance, while the PZEM-004T sensor exhibited a 9.09% median current error, this deviation primarily occurred in low-current measurements where the electrical load was minimal, such as phone chargers. Such conditions are considered less critical within the overall monitoring objectives and thus have minimal impact on system reliability or safety control decisions.

The entire system was evaluated under simulated real-world conditions, including various household appliances and fluctuating ambient environments, with no major disruptions or unexpected failures reported during extended operations. Environmental sensors, such as the MQ2 and flame sensors, demonstrate consistent detection accuracy across multiple scenarios.

Upon detecting hazardous conditions on Figure 20 and 21 the system successfully triggered automated mitigation protocols, including real-time alerts, buzzer activation, and relay-driven water pump control shown in Figure 22. These responses were executed with minimal delay and validated across repeated tests, confirming the system's readiness for practical deployment in safety-critical environments.

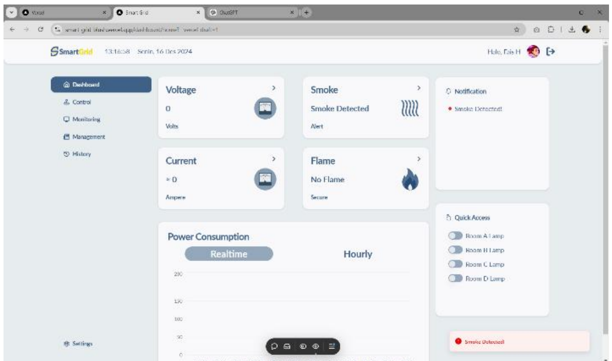

Figure 20. Smoke Detection Alert

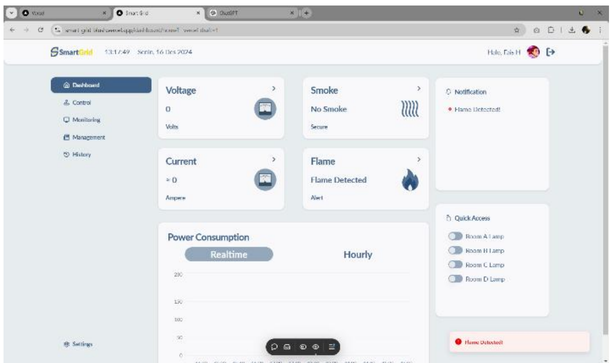

Figure 21. Fire Detection Alert

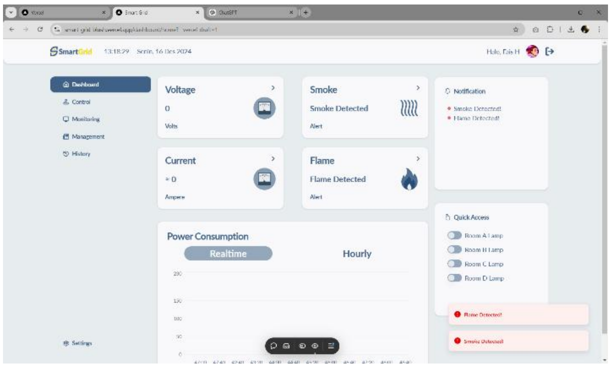

Figure 22. Combined Alert Display

IV. CONCLUSION

This research demonstrates the successful development and implementation of an IoT-based smart building prototype with installation component management features. The system achieved excellent performance across several key aspects. The real-time electrical device control and monitoring functionality demonstrated 100% success rate in load control operations and web interface status synchronization, while the smoke and fire notification system operated effectively with integrated automatic mitigation protocols to enhance safety.

The electrical component installation management system was successfully implemented, enabling structured documentation of specifications, maintenance history, and component replacements. The system's ability to export data in PDF and CSV formats streamline the maintenance and management processes of electrical installations in smart buildings. Performance evaluation revealed high reliability and accuracy across the system, with minor limitations noted in low-current measurements by the PZEM-004T sensor. Other sensors, including the MQ2 and Flame Sensor, exhibited excellent performance in detecting smoke and fire across various scenarios. The augmented reality (AR) system demonstrated stable operation across different distances and angles, effectively supporting main panel maintenance procedures.

Several technical enhancements could significantly improve system performance in future research. The PZEM-004T sensor accuracy for low-current measurements could be enhanced by implementing variant-specific sensors (such as 20A variants) for different load requirements. System security should be strengthened through dedicated server infrastructure rather than cloud-based solutions, implementation of end-to-end encryption for sensitive data, multi-factor authentication protocols, and automated backup systems with audit trails. Comprehensive safety coverage could be achieved by deploying smoke and fire detection sensors throughout all rooms rather than limiting them to corridors, enabling more effective fire mitigation strategies.

Beyond energy efficiency and safety applications, this smart building system demonstrates significant potential for implementation across various building types. The integrated monitoring, control, and management capabilities make it suitable for commercial buildings, educational institutions, healthcare facilities, hospitality establishments, and industrial complexes. The system's modular design allows for scalable deployment, accommodating different building sizes and complexity requirements while maintaining core functionalities of energy management, safety monitoring, and maintenance optimization.

Building managers and developers considering similar systems should prioritize establishing robust technical infrastructure including dedicated servers for data security, comprehensive sensor networks for complete coverage, and structured maintenance protocols. Cost-benefit analysis should consider long-term operational savings through predictive maintenance capabilities and energy optimization against initial implementation costs. Technical prerequisites include reliable network infrastructure, trained personnel for system operation, and integration planning with existing building management systems. A phased implementation approach is recommended, starting with critical safety systems before expanding to comprehensive building automation features.

ACKNOWLEDGEMENTS

The authors would like to thank Mr. Purno Tri Aji, M.Eng. for his guidance and supervision throughout this research work

REFERENCES

[1] T. Tundjung and R. Noviyanti, “REVOLUSI INDUSTRI DAN PENGARUHNYA PADA PENELITIAN SEJARAH,” Alur Sejarah: Jurnal Pendidikan Sejarah, vol. 4, no. 1, 2021.

[2] A. E. Setyono and B. F. T. Kiono, “Dari energi fosil menuju energi terbarukan: potret kondisi minyak dan gas bumi Indonesia tahun 2020–2050,” Jurnal Energi Baru Dan Terbarukan, vol. 2, no. 3, pp. 154–162, 2021.

[3] H. Mantik, “Revolusi industri 4.0: Internet of things, implementasi pada berbagai sektor berbasis teknologi informasi (bagian 1),” JSI (Jurnal sistem Informasi) Universitas Suryadarma, vol. 9, no. 2, pp. 41–48, 2022.

[4] M. Hadid and Y. Anang, “Kajian Penerapan Teknologi Internet of Things Untuk Penghematan Energi,” in Seminar Nasional Official Statistics, 2020, pp. 258–264.

[5] A. Subagyo, “Antisipasi yang diperlukan terhadap kebakaran listrik pada bangunan gedung,” JTET (Jurnal Teknik Elektro Terapan), vol. 1, no. 2, 2012.

[6] R. I. Akbar, D. G. Purnama, A. Salsabila, and A. Salsabila, “Pengembangan Model SmartHome berbasis IoT,” in Prosiding Seminar Nasional Penelitian LPPM UMJ, 2023.

[7] A. Prafanto, E. Budiman, P. P. Widagdo, G. M. Putra, and R. Wardhana, “Pendeteksi Kehadiran menggunakan ESP32 untuk Sistem Pengunci Pintu Otomatis,” JTT (Jurnal Teknologi Terapan), vol. 7, no. 1, pp. 37–43, 2021.

[8] Y. Prabowo, A. Narendro, T. W. Wisjhnuadji, and S. Siswanto, “Uji Akurasi Modul Kwh Meter Digital Pzem-004T Berbasis Pengendali Digital Esp32,” SKANIKA: Sistem Komputer dan Teknik Informatika, vol. 6, no. 2, pp. 85–96, 2023.

[9] A. Rofik, “ANALISA KEBOCORAN LPG DENGAN MENGGUNAKAN SENSOR GAS MQ-2,” SinarFe7, vol. 4, no. 1, pp. 206–208, 2021.

[10] S. Suryono and S. Supriyati, “Rancang Bangun Pengontrol Panel Listrik Menggunakan Radio Frekuensi Identifikasi (RFID),” Orbith: Majalah Ilmiah Pengembangan Rekayasa dan Sosial, vol.

14, no. 1, 2018.

[11] T. Taryana, C. Kuntadi, Y. Suprihartini, and R. Sadiatmi, “Faktor-faktor yang mempengaruhi keandalan instalasi listrik,” Jurnal Manajemen Pendidikan Dan Ilmu Sosial, vol. 4, no. 1, pp. 531–537, 2023.

[12] Kamal, Firdayanti, U. M. Tyas, A. A. Buckhari, and Pattasang, “IMPLEMENTASI APLIKASI ARDUINO IDE PADA MATA KULIAH SISTEM DIGITAL,” *Tek. J. Pendidik. Dan Teknol.*, vol. 1, no. 1, pp. 1–9, Apr. 2023, doi: 10.59638/teknos.v1i1.40.

[13] L. Iswari, “Penerapan React JS Pada Pengembangan FrontEnd Aplikasi Startup Ubaform,” AUTOMATA, vol. 2, no. 2, 2021.

[14] S. P. Santoso and J. N. Sitohang, “Perancangan Alat Kendali Penabur Pakan Ikan Otomatis Berbasis Mikrokontroler ESP32 Firebase,” Jurnal Elektro Vol, vol. 12, no. 1, 2024.

[15] M. M. Jayadi, “Perancangan Media Edukasi Berbasis Augmented Reality Sebagai Petunjuk Instalasi Listrik Dan Penggunaan Listrik Pada Perangkat Elektronik Rumah Tangga,” Institut Teknologi Sepuluh Nopember, 2017.

[16] M. A. Guslia, D. Pramana, and K. T. Parameswari, “Augmented Reality Instalasi Listrik pada PT Intek Electrical Indonesia Area Bali Berbasis Android,” in Seminar Nasional CORIS 2022, 2022.