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Design and implementation of an iot-based electrical energy monitoring system in commercial buildings

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A R T I C L E I N F O

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ABSTRACT

This study presents the design and implementation of an Internet of Things (IoT)-based electrical energy monitoring system tailored for commercial buildings. With the growing demand for energy efficiency and sustainability, real-time monitoring has become essential for reducing operational costs and improving energy management practices. The proposed system utilizes microcontroller-based hardware (ESP32) integrated with current and voltage sensors to capture real-time electrical parameters such as power consumption, voltage levels, current flow, and energy usage patterns. Data acquisition is achieved through wireless communication via Wi-Fi, with all measurements transmitted to a cloud-based platform for storage, visualization, and analysis. A web-based dashboard and mobile interface provide users with intuitive access to energy usage statistics, historical trends, and anomaly alerts. The system was tested in a mid-sized commercial building, and results demonstrated high accuracy in energy readings, low latency in data transmission, and effective identification of peak consumption periods. This IoT-based approach offers scalability, affordability, and flexibility, making it a viable solution for smart energy management in commercial environments. The findings support the integration of IoT technologies into building energy systems to promote real-time decision-making and reduce overall energy consumption.

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1. INTRODUCTION

The exponential growth of commercial infrastructure around the globe has brought with it a surge in electrical energy consumption. Commercial buildings including office complexes, shopping malls, hotels, educational institutions, and hospitals are among the largest energy consumers in urban environments. In most countries, the commercial sector accounts for a significant portion of total electricity demand, driven by the use of lighting, HVAC (heating, ventilation, and air conditioning), elevators, office equipment, and other electrical appliances. This high level of energy use not only strains power systems but also contributes to increased operational costs and greenhouse gas emissions. Consequently, improving energy efficiency in commercial buildings has become a critical priority for stakeholders including building owners, managers, policymakers, and environmental advocates.

To achieve significant energy efficiency, one of the foundational requirements is real-time monitoring of energy consumption. Traditional energy monitoring methods often rely on monthly utility bills or manual meter readings, which are insufficient for understanding consumption patterns, detecting anomalies, or implementing timely interventions. These conventional approaches lack granularity and responsiveness, thereby limiting their usefulness in energy optimization strategies. In contrast, modern energy monitoring systems equipped with real-time data acquisition and analytics capabilities allow stakeholders to gain actionable insights into how and when energy is used within a facility.

The advent of the Internet of Things (IoT) has revolutionized numerous sectors by enabling the interconnection of physical devices with computing systems over the internet. In the context of electrical energy monitoring, IoT technologies facilitate the seamless collection, transmission, analysis, and visualization of real-time data from electrical systems. IoT-based monitoring systems typically consist of sensors, microcontrollers, communication modules, cloud storage, and user interfaces, all working together to provide a comprehensive and continuous view of energy usage. Unlike traditional energy management systems, IoT-based solutions offer several advantages: Real-time data access and historical tracking, Remote monitoring and control, Scalability and easy integration with other smart systems, Automated alerts for anomalies and threshold breaches, User-friendly dashboards accessible through mobile or web interfaces. By providing fine-grained energy data and intelligent analytics, IoT systems enable informed decision-making, support predictive maintenance, and ultimately reduce operational costs while enhancing sustainability.

Commercial buildings are typically equipped with multiple electrical loads and systems that vary in usage throughout the day. HVAC systems, in particular, are energy-intensive and contribute significantly to peak demand periods. Without real-time monitoring, building managers are often unaware of inefficiencies such as: Equipment running outside operational hours, Load imbalance across phases, Overloaded circuits, Energy waste due to human error (e.g., lights or appliances left on). Furthermore, commercial tenants increasingly demand transparency and accountability regarding energy usage, particularly in multi-tenant facilities where billing is based on individual consumption. In this scenario, IoT-based monitoring systems serve as a critical tool for: Sub-metering and tenant billing, Energy benchmarking, Compliance with energy efficiency regulations, Supporting green building certifications (e.g., LEED, BREEAM). Thus, the integration of intelligent energy monitoring infrastructure is no longer a luxury but a necessity for efficient commercial building operation.

Recent studies have demonstrated the effectiveness of IoT in building energy management. Systems integrating microcontrollers like Arduino, ESP32, or Raspberry Pi with current and voltage sensors have shown promising results in terms of performance and cost-effectiveness. These systems utilize protocols such as MQTT, HTTP, or LoRaWAN for communication and employ platforms like ThingSpeak, Blynk, or custom dashboards for data visualization. However, despite this growing body of work, several research gaps persist: Most systems are developed for residential settings, which are relatively simpler than commercial environments. There is limited focus on scalability and integration for multi-zone commercial buildings. Reliability and accuracy of low-cost sensor-based systems in high-load environments remain underexplored. Many existing implementations lack robust software architecture to handle large data volumes, secure communication, or advanced analytics. User interfaces are often not optimized for facilities management needs. Therefore, there is a need for a robust, scalable, and secure IoT-based electrical energy monitoring system specifically designed for the complexity and demands of commercial buildings.

This study aims to design and implement an IoT-based electrical energy monitoring system that addresses the specific requirements of commercial buildings. The main objectives are: To design a hardware architecture capable of accurately measuring key electrical parameters (voltage, current, power, energy consumption) using cost-effective sensors and microcontrollers. To implement a wireless communication system for real-time data transmission using reliable IoT protocols such as Wi-Fi and MQTT. To develop a cloud-based data storage and dashboard that provides real-time visualization, historical analytics, and alerts. To validate the system's performance in a real-world commercial building environment, assessing accuracy, reliability, and usability. To evaluate the system's potential to improve energy awareness, reduce consumption, and support energy management decisions. By achieving these objectives, the study seeks to contribute a practical, low-cost, and scalable solution to the problem of energy inefficiency in commercial infrastructure.

The significance of this research lies in its contribution to both technological development and sustainable practice. As energy prices rise and carbon reduction targets become more stringent, commercial building operators are under pressure to adopt smarter energy solutions. This IoT-based monitoring system provides them with a tool that is: Affordable and accessible for small and medium-sized buildings, Modular and scalable for expansion across zones or floors, Flexible to integrate with building management systems (BMS), User-centric with intuitive dashboards and actionable insights. Furthermore, by enabling real-time energy data collection, the system supports: Behavioral change among occupants and facility managers, Load shifting and demand response strategies, Preventive maintenance by identifying abnormal consumption trends, Increased operational transparency and energy accountability. From an academic perspective, the project bridges the gap between IoT engineering and building energy management, contributing practical knowledge for further innovation in smart building systems.

2. RESEARCH METHOD

This study employed an applied research methodology focused on the design, development, and implementation of an Internet of Things (IoT)-based electrical energy monitoring system tailored to commercial buildings. The research process was divided into several structured phases: system design, hardware prototyping, software development, data transmission integration, cloud infrastructure setup, and field testing. The hardware components were centered around the ESP32 microcontroller, chosen for its processing capability and integrated Wi-Fi. For electrical parameter measurement, the system used non-invasive current sensors (SCT-013) and voltage sensors (ZMPT101B) to monitor load consumption. These sensors captured real-time data on current, voltage, power, and energy usage. Firmware was developed using the Arduino IDE to program the ESP32 for data acquisition and preprocessing. Sensor readings were collected at defined intervals and transmitted wirelessly using the MQTT protocol to a cloud-based platform (Firebase or InfluxDB), ensuring efficient, lightweight communication with minimal latency. A web-based dashboard was built using JavaScript and HTML, enabling users to view real-time and historical energy data, visualize trends, and receive alerts for anomalies or threshold exceedances. For validation, the system was deployed in a medium-sized commercial building. The measured data were compared against readings from calibrated commercial energy meters to evaluate accuracy. Metrics such as data transmission reliability, latency, and system uptime were also recorded. The study followed a quantitative approach to assess system performance and used descriptive analysis to interpret the monitored energy patterns and anomalies observed during field testing. This methodical approach ensured that both the technical feasibility and practical applicability of the IoT-based system were critically evaluated, offering a scalable solution for energy monitoring in commercial environments.

3. RESULTS AND DISCUSSIONS

3.1. Accuracy of Energy Measurements

Accuracy testing was conducted by comparing the IoT system's readings with a calibrated Class 0.5 commercial-grade reference meter. Table 1 shows the mean absolute percentage error (MAPE) across both buildings.

Table 1. Measurement Accuracy Performance

Parameter	Building A MAPE (%)	Building B MAPE (%)	Overall MAPE (%)
Voltage	0.42	0.47	0.44
Current	1.15	1.32	1.23
Power	1.38	1.54	1.46
Energy	1.05	1.17	1.11

The results indicate that the system achieved overall measurement accuracy within 1.5%, meeting IEEE Std 1459-2010 requirements for non-commercial billing applications. Voltage accuracy was especially high due to the stable nature of commercial grid supply, while current and power readings showed slightly higher variance due to transient load fluctuations.

The achieved accuracy level is adequate for energy management purposes but not yet suitable for revenue-grade billing without further calibration. Factors contributing to measurement deviations include sensor tolerance (±1% for CTs) and the effect of reactive power on real power calculation. This aligns with findings by Li et al. (2023), who reported that low-cost IoT energy meters typically maintain MAPE below 2% in non-industrial environments.

3.2. System Latency and Data Transmission Reliability

Latency was defined as the time between data acquisition and successful display on the dashboard. Across both buildings, the average latency was measured at 2.1 seconds, with 95% of transmissions under 3 seconds. Reliability, measured as the percentage of successfully transmitted data packets, was 99.2%.

Table 2. Latency and Reliability Metrics

Metric	Building A	Building B	Overall
Avg. Latency (s)	2.0	2.2	2.1
Packet Loss (%)	0.7	0.9	0.8
Dashboard Update Rate/s	1.0	1.1	1.05

The high reliability and low latency confirm that the system is suitable for near real-time monitoring, enabling rapid detection of abnormal consumption spikes. Occasional packet loss was attributed to Wi-Fi signal interference and network congestion during peak hours. Compared to similar implementations (Rashid et al., 2022), which reported average latencies of 4–5 seconds, this design demonstrates significant improvement, partly due to optimized MQTT protocol usage and lightweight JSON data formatting.

3.3. Energy Consumption Patterns and Anomalies

The system revealed distinct load profiles for the two buildings. Building A: Peak demand occurred between 09:00–11:00 and 14:00–16:00, primarily due to HVAC operation. Nighttime loads (~40 kW) persisted due to server rooms and security lighting. Building B: Load fluctuations were more irregular, with weekend peaks from 12:00–15:00 due to retail traffic, and low early morning loads (~10 kW). During week 5, Building B recorded a sudden 15% increase in nighttime consumption. The IoT system's alert function flagged the anomaly within 15 minutes, prompting an inspection. It was found that three HVAC units had malfunctioned and continued operating overnight. The fault was corrected, saving an estimated 1,250 kWh/month (~USD 125/month at local tariffs).

This result highlights the practical value of IoT monitoring in preventive maintenance. Similar studies (Chen et al., 2021) report that anomaly alerts can reduce wasted consumption by 5–12% annually in commercial facilities. In this case, the savings potential extrapolated over one year is approximately USD 1,500, covering 20% of the system's installation cost.

3.4. Load Disaggregation Insights

By tagging specific circuits (HVAC, lighting, office equipment), the system provided partial non-intrusive load monitoring (NILM) capability. In Building A, the HVAC system accounted for 48% of total consumption, lighting for 27%, and office equipment for 15%. Building B's breakdown was more varied, with refrigeration units contributing 22% due to retail food storage.

Such granular insights empower targeted efficiency measures. For example, in Building A, adjusting HVAC setpoints by +1°C during peak hours could yield 5–7% savings without impacting comfort. In Building B, upgrading refrigeration insulation and adopting LED lighting could significantly cut base load. This supports the theory proposed by Darby (2020) that disaggregated feedback drives stronger behavioral and operational changes than aggregate data alone.

3.5. User Experience and Dashboard Utility

A user satisfaction survey (n=18 facility managers and technicians) rated the system on ease of use, data clarity, responsiveness, and perceived usefulness. Scores were based on a 5-point Likert scale.

Table 3. User Satisfaction Survey Results

Metric	Mean Score	Std. Dev.
Ease of Use	4.6	0.4
Data Clarity	4.5	0.5
Responsiveness	4.7	0.3
Usefulness	4.8	0.2
Overall Satisfaction	4.65	0.35

Feedback indicated that real-time visualizations and mobile accessibility were most valued. Several respondents suggested integrating predictive analytics to forecast peak demand and recommend preventive actions. While current functionality addresses monitoring and alerting, integrating machine learning-based forecasting could further optimize energy management, as shown in works by Ahmed et al. (2022).

3.6. Energy Savings and ROI Analysis

Over the 12-week period, both buildings implemented minor operational adjustments based on system feedback: Building A: Reduced HVAC operating hours by 30 minutes/day; implemented staggered elevator shutdown during low occupancy. Building B: Timed lighting controls; repaired faulty HVAC units. These measures resulted in average reductions of 6.2% and 5.4% in monthly energy consumption for Buildings A and B respectively.

Table 4. Energy Savings Achieved

Building	Baseline Monthly Consumption (kWh)	Post-Implementation (kWh)	Reduction (%)	Cost Savings (USD)
A	124,500	116,750	6.2	775
B	62,800	59,400	5.4	340

The combined monthly savings (~USD 1,115) project to USD 13,380 annually, exceeding the system's installation cost (~USD 6,800) within the first year, yielding an ROI period of 7.3 months. This is consistent with case studies by the International Energy Agency (IEA, 2021), which report typical IoT-based monitoring ROI in commercial facilities at 6–12 months.

3.7. Comparative Evaluation with Existing Solutions

When benchmarked against three commercial off-the-shelf energy monitoring platforms, the proposed system demonstrated competitive performance at significantly lower cost.

Table 5. Comparative Performance

Feature	Proposed System	Vendor X	Vendor Y	Vendor Z
Accuracy (%)	98.54	99.2	98.8	99.1
Latency (s)	2.1	3.5	4.0	3.2
Packet Loss (%)	0.8	0.5	0.9	0.6
Cost (USD)	6,800	14,500	12,800	15,200
Cloud Subscription	None	Yes	Yes	Yes

While some commercial systems slightly outperformed the proposed design in accuracy, the cost-effectiveness of the IoT approach is evident less than half the capital investment and no recurring subscription fees. Additionally, open-source software and modular hardware enable customization and scalability not typically available in proprietary solutions.

4. CONCLUSION

This study demonstrates that the design and implementation of an IoT-based electrical energy monitoring system in commercial buildings can deliver high accuracy, real-time data visibility, and actionable insights at a fraction of the cost of proprietary platforms. The system, built using low-cost microcontrollers, current and voltage sensors, and cloud-based dashboards, achieved a mean absolute percentage error (MAPE) of approximately 1.1% for energy measurement, well within acceptable limits for energy management applications. With an average latency of 2.1 seconds and a data transmission reliability of 99.2%, the system proved suitable for near real-time monitoring. Its anomaly detection capability enabled the early identification of abnormal consumption patterns, leading to prompt corrective actions and measurable energy savings. Disaggregated load monitoring provided facility managers with detailed consumption profiles, enabling targeted efficiency measures such as optimized HVAC scheduling, improved lighting controls, and equipment maintenance prioritization. Operational adjustments informed by system data achieved 5–6% reductions in monthly energy consumption across the tested buildings, translating into annual cost savings exceeding the total installation cost and yielding a payback period of under eight months. These results affirm the system's economic viability and its potential role in supporting sustainability and energy efficiency objectives. While the system's current configuration meets essential monitoring needs, future enhancements could include integration with building management systems (BMS), support for larger-scale deployments using alternative communication protocols, incorporation of reactive power and power factor monitoring, and the application of predictive analytics for demand forecasting. Strengthening cybersecurity measures will also be essential for wider adoption in critical infrastructure. Overall, the findings confirm that IoT-based energy monitoring systems offer a practical, scalable, and cost-effective approach to improving energy efficiency in commercial buildings. Their deployment can significantly contribute to operational cost reduction, environmental sustainability, and informed decision-making in facility energy management..

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