

# LoRaWAN-Based Smart Energy Monitoring System For University Lecture Halls

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## Abstract:

**Background:** Amid rising electricity consumption in Vietnamese universities, lecture halls suffer from significant energy waste due to lighting, air conditioning, and laboratory equipment being left on unnecessarily outside scheduled hours. This issue contradicts Sustainable Development Goal 7 (Affordable and Clean Energy) and Vietnam's National Power Development Plan VIII. A reliable, long-range, low-power real-time energy monitoring system is essential for dense concrete educational buildings.

**Materials and Methods:** This study develops a LoRaWAN-based smart energy monitoring system using a three-layer architecture. End-devices consist of Heltec WiFi LoRa 32 V4 nodes (ESP32-S3 + SX1262) integrated with PZEM-004T sensors for accurate AC power measurement and relay modules for automatic load control. The gateway employs a RAK5146 concentrator (SX1303) mounted on Raspberry Pi 5 with an 8 dBi outdoor antenna. Data transmission follows LoRaWAN AS923-2 protocol to the ThingsBoard or Easy LoRaWAN cloud platform. Simple AI models (Linear Regression and Multi-Layer Perceptron Neural Network) are implemented in the cloud for real-time waste detection, consumption prediction, anomaly alerts, and automated relay actuation. Node firmware is developed using Arduino/ESP-IDF, while cloud-side processing utilizes Python with scikit-learn and TensorFlow Lite.

**Results:** A three-month pilot deployment was conducted in Building C6 – a six-floor lecture facility with 40 classrooms and laboratories at Haiphong University – using five monitoring nodes and one central gateway. Daily energy consumption decreased from 130 kWh to 100 kWh, achieving 22.5% energy savings through automated detection and control of wasteful loads. The system demonstrated robust communication performance with a Packet Delivery Ratio (PDR) of 98.7% and RSSI values ranging from  $-85$  dBm to  $-110$  dBm in dense concrete structures. The AI models achieved prediction errors below 8% and 85% accuracy in automated waste detection.

**Conclusion:** The proposed LoRaWAN-based smart energy monitoring system proves highly effective, low-cost, and technically feasible for university lecture halls in Vietnam. It delivers significant energy savings while providing an excellent practical training platform for Electrical and Electronics Engineering students. The solution strongly contributes to digital transformation and sustainable energy practices in higher education institutions.

**Key Word:** LoRaWAN; Smart Energy Monitoring; IoT; ESP32; University Lecture Halls; Sustainable Energy.

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## I. Introduction

In the era of digital transformation and sustainable development, energy monitoring in Vietnamese higher education institutions faces significant challenges due to rapid growth in electricity consumption. University lecture halls, equipped with modern LED lighting, air conditioning systems, computers, and electrical-electronics laboratories, frequently experience substantial energy waste from devices left operating unnecessarily outside class hours or in standby mode [1], [12]. This wastage not only increases operational costs but also contradicts the United Nations' Sustainable Development Goal 7 (Affordable and Clean Energy) and Vietnam's National Power Development Plan VIII (PDP8) [12].

Contemporary research emphasizes the integration of Internet of Things (IoT) with artificial intelligence (AI) to develop intelligent energy monitoring systems capable of real-time data acquisition, analysis, and predictive optimization [6], [10], [11]. While basic IoT monitoring solutions exist in Vietnam, the widespread adoption of long-range, low-power wide-area network technologies such as LoRaWAN, combined with lightweight AI models, remains limited [2], [13]. These limitations are particularly evident in large campus environments with dense concrete structures that challenge conventional short-range wireless technologies like WiFi or Zigbee [5], [8].

Recent deployments have demonstrated the effectiveness of LoRaWAN for campus-scale energy monitoring. Studies at various universities show that LoRaWAN provides excellent coverage and high packet delivery ratios even in concrete buildings, enabling reliable real-time energy data collection with low power consumption [7], [8], [13]. Furthermore, the integration of simple machine learning models such as Linear

Regression and Multi-Layer Perceptron has been shown to improve waste detection and consumption forecasting accuracy in educational buildings [9], [11], [14].

This paper presents the design and implementation of a LoRaWAN-Based Smart Energy Monitoring System for University Lecture Halls. The proposed system enables reliable real-time energy monitoring, automatic waste detection, and intelligent control using low-cost hardware and cloud-based AI analytics. By addressing the technical constraints of coverage, power consumption, and cost in Vietnamese university infrastructure (particularly the AS923-2 band), the system aims to reduce electricity waste effectively while serving as a practical training platform for Electrical and Electronics Engineering students [3], [4].

### **Context and Urgency**

Lecture halls are among the highest energy-consuming facilities on university campuses. Major sources of waste include forgotten lighting and air-conditioning systems, as well as laboratory equipment operating beyond scheduled hours. International studies indicate that intelligent IoT-based monitoring and control solutions can achieve 10–30% reduction in energy waste in educational buildings, leading to considerable budgetary and environmental benefits [5], [18]. The integration of advanced LoRaWAN and AI technologies not only addresses these issues but also enhances hands-on learning experiences in electrical and electronics engineering education [6], [15].

### **Research Objectives**

The main objectives of this study are:

- (i) to design and implement a LoRaWAN-based real-time smart energy monitoring system suitable for dense educational buildings;
- (ii) to integrate simple AI models (Linear Regression and Multi-Layer Perceptron) for consumption prediction and automatic waste detection;
- (iii) to evaluate the performance of the proposed system through a pilot deployment at Haiphong University, targeting at least 15–25% reduction in daily energy consumption.

### **Research Contributions**

This work contributes a low-cost, scalable LoRaWAN-based smart energy monitoring solution tailored to Vietnamese university infrastructure using the AS923-2 frequency band [13]. Key contributions include:

- (i) an effective AI-driven predictive monitoring framework for automated waste detection and control;
- (ii) empirical validation of system reliability and coverage in dense concrete lecture halls;
- (iii) a practical IoT platform that supports both energy efficiency and digital transformation in higher education, providing hands-on training opportunities for engineering students [8], [15].

## **II. Literature Review**

Recent studies have demonstrated that IoT-based energy monitoring systems can achieve 15–40% reduction in electricity waste within higher education institutions through real-time data acquisition and automated optimization of lighting, air conditioning, and laboratory equipment [5], [19]. Traditional wireless technologies such as WiFi and Zigbee, however, suffer from limited range and high power consumption, making them unsuitable for large university campuses with thick concrete walls [8], [20].

LoRaWAN technology has emerged as a superior solution for campus-scale energy monitoring due to its long-range communication (up to 5–10 km in urban areas), ultra-low power consumption, and ability to support thousands of end-devices [7], [9], [24]. Several deployments have successfully applied LoRaWAN for real-time electrical parameter monitoring in university environments. Gonzalez et al. developed a smart energy meter based on LoRaWAN in a campus area, achieving reliable data transmission despite building obstructions [3]. Similarly, Centenaro et al. implemented LoRaWAN-based monitoring of electric parameters at the Federal University of Santa Maria, confirming excellent coverage and packet delivery performance in concrete structures [8]. In Vietnam, practical LoRaWAN applications for energy monitoring have also been reported in industrial zones and campus buildings, highlighting the suitability of the AS923-2 frequency band [2], [13], [21].

The integration of artificial intelligence further enhances the capability of energy monitoring systems. Machine learning models such as Linear Regression and Multi-Layer Perceptron Neural Networks have been effectively used for consumption prediction and anomaly (waste) detection in educational buildings [6], [10], [11], [23]. Elhabyb et al. demonstrated that AI algorithms can predict energy consumption in university facilities with high accuracy, enabling proactive waste reduction measures [11]. Goudarzi et al. proposed an IoT-based prediction technique that significantly improves energy efficiency in buildings by combining historical data with contextual factors [10].

Despite these advancements, a critical research gap remains in the Vietnamese context. Most existing studies either focus on basic monitoring without deep LoRaWAN integration or are conducted in environments

with different regulatory frequency bands and infrastructure constraints [4], [22]. There is limited research on low-cost LoRaWAN-based smart energy monitoring systems specifically designed for dense concrete lecture halls in Vietnamese universities, incorporating both reliable long-range communication (AS923-2) and simple AI models for real-time waste detection.

This study addresses the identified gap by developing and piloting a comprehensive LoRaWAN-Based Smart Energy Monitoring System for University Lecture Halls that combines robust LoRaWAN communication, cost-effective hardware, and lightweight AI analytics. The proposed system aims to provide reliable real-time monitoring while being scalable and suitable for resource-constrained educational environments in Vietnam.

### III. System Design

The proposed LoRaWAN-Based Smart Energy Monitoring System adopts the standard three-layer architecture of LoRaWAN networks, consisting of end-devices, gateway, and cloud/server layer. This architecture provides wide coverage, low power consumption, and high scalability, making it particularly suitable for dense concrete lecture hall environments [7], [8], [20].

#### Overall Architecture

The system employs a star-of-stars topology, where multiple end-devices transmit data directly to a central gateway. Class A LoRaWAN mode is utilized to prioritize ultra-low power consumption at the end-devices. The gateway forwards collected data via WiFi or 4G to the cloud platform for storage, visualization, and AI-based analysis [9], [13].

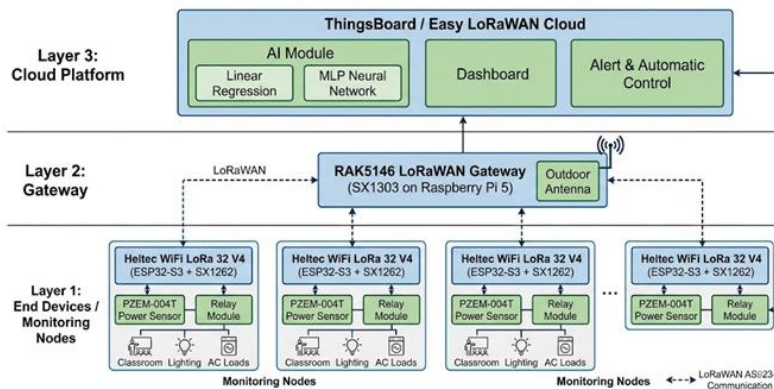


Figure 1: Overall architecture of the LoRaWAN-based smart energy monitoring system.

#### Hardware Devices

End-devices (Monitoring Nodes): Heltec WiFi LoRa 32 V4 modules (ESP32-S3 + SX1262) are selected as the main processing units due to their high transmit power (up to 28 dBm), excellent receiver sensitivity (-148 dBm), and support for the AS923-2 frequency band compliant with Vietnamese regulations [16]. Each node is integrated with a PZEM-004T sensor for invasive AC power measurement and relay modules for automatic load control. An OLED display is included for local debugging, and WiFi/BLE interfaces support over-the-air (OTA) firmware updates.

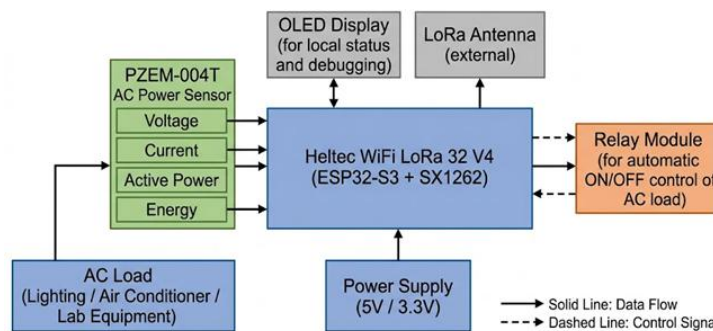


Figure 2: Block diagram of the Heltec WiFi LoRa 32 V4 monitoring node with PZEM-004T sensor.

Gateway: A RAK5146 LoRaWAN concentrator module (based on SX1303 chipset) mounted on a Raspberry Pi 5 host with a mini-PCIe HAT is used as the central gateway. An 8 dBi outdoor fiberglass antenna ensures optimal coverage across multiple floors of concrete buildings [17].

**Communication Protocol and AI Integration**

Data transmission operates on the LoRaWAN AS923-2 frequency band (920–923 MHz) according to Vietnamese regulations. The system employs AES-128 encryption and OTAA (Over-The-Air Activation) mode to ensure secure communication. Class A LoRaWAN device mode is utilized to achieve ultra-low power consumption at the end-devices while complying with the 1% duty cycle restriction [9], [13].

To enable intelligent monitoring and automatic waste reduction, two lightweight AI models are integrated in the cloud platform. The first model applies Linear Regression for short-term energy consumption prediction based on historical power measurements and contextual features such as lecture schedules and time of day. The model is expressed as:

$$\hat{P}(t) = \beta_0 + \beta_1 P_{hist}(t) + \beta_2 S(t) + \beta_3 T(t) + \epsilon$$

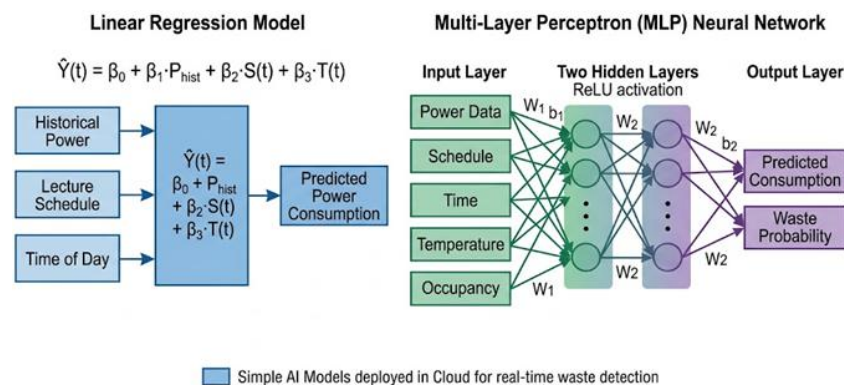
Where  $\hat{P}(t)$  denotes the predicted power consumption at time  $t$ ,  $P_{hist}(t)$  is the historical power data,  $S(t)$  represents the schedule factor,  $T(t)$  is the time-of-day feature,  $\beta$  are the learned coefficients, and  $\epsilon$  is the residual error [10], [11].

The second and more advanced model utilizes a Multi-Layer Perceptron (MLP) Neural Network for long-term forecasting and anomaly (waste) detection. The network output is computed through forward propagation as follows:

$$y = f(W_2 \cdot \sigma(W_1 \cdot x + b_1) + b_2$$

Where  $x$  is the input feature vector including power consumption, lecture schedule, time, and environmental factors;  $W_1, W_2$  and  $b_1, b_2$  are the weight matrices and bias vectors of the hidden and output layers respectively;  $\sigma$  denotes the ReLU activation function; and  $f$  is the output activation function (linear for regression or sigmoid for waste probability) [11], [23].

These AI models are trained offline using historical data collected from the monitoring nodes and deployed on the cloud using TensorFlow Lite for lightweight inference. When abnormal or wasteful consumption is detected, the system automatically generates control commands to activate relays on the end-devices.



**Figure 3: AI models for energy consumption prediction and waste detection in the smart energy monitoring system.**

**Software and Cloud Platform**

The software architecture of the proposed system is divided into two main layers: firmware on the end-devices and cloud-based platform for data processing and intelligent decision-making.

At the end-device level, firmware is developed using the Arduino IDE combined with ESP-IDF framework. The LoRaWAN communication stack is implemented with the official LMIC library, supporting Class A operation, OTAA activation, and adaptive data rate (ADR). The firmware periodically reads power parameters from the PZEM-004T sensor, packages the data with node ID, timestamp, and battery status, then transmits the payload via LoRaWAN every 10 minutes while strictly respecting the 1% duty cycle of the AS923-2 band.

On the cloud side, the ThingsBoard open-source IoT platform is employed as the primary backend for data ingestion, storage, visualization, and rule engine management. Incoming data from the gateway is processed in real time and displayed on interactive dashboards that allow lecturers and facility managers to monitor energy consumption of each lecture hall and laboratory.

For intelligent analytics, a Python-based processing module is integrated with ThingsBoard using its REST API and rule chains. This module implements the previously described Linear Regression and Multi-Layer Perceptron models using scikit-learn and TensorFlow Lite. When wasteful consumption patterns are detected (e.g., power consumption exceeding a predefined threshold outside scheduled class hours), the system automatically triggers alert notifications and sends downlink commands to activate the relay modules on the corresponding monitoring nodes for automatic load shutdown.

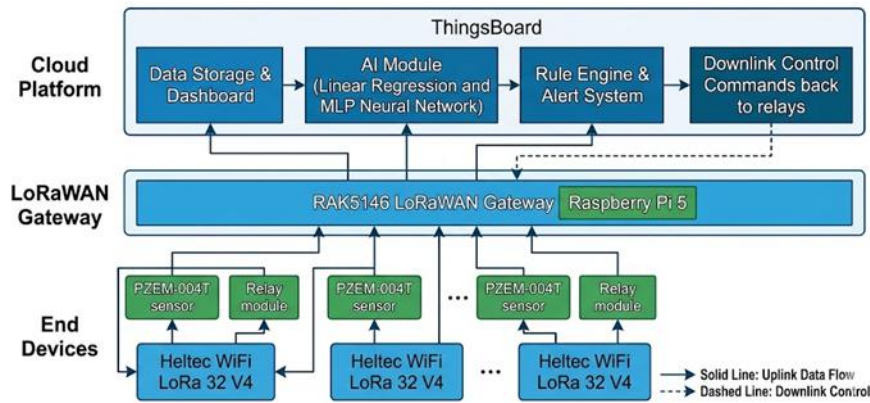


Figure 4: Software architecture and cloud-based AI integration of the LoRaWAN smart energy monitoring system.

This hybrid software design ensures low development cost, high reliability, ease of maintenance, and seamless integration between edge devices and cloud intelligence, making the system highly suitable for deployment in Vietnamese higher education institutions.

#### IV. Implementation And Experiment

To evaluate the performance of the proposed LoRaWAN-based smart energy monitoring system, a pilot deployment was conducted at Building C6 of Haiphong University. This six-floor lecture building, containing 40 classrooms and laboratories, represents a typical dense concrete educational facility in Vietnam.

##### Experimental Setup

Five monitoring nodes based on Heltec WiFi LoRa 32 V4 were installed on different floors, targeting the main energy-consuming loads including lighting systems, air conditioning units, and laboratory power outlets. Each node was equipped with a PZEM-004T sensor for real-time AC power measurement and a relay module for automatic load control. A single RAK5146 LoRaWAN gateway mounted on a Raspberry Pi 5 with an 8 dBi outdoor antenna was installed on the rooftop to provide optimal coverage across the entire building.

The system operated in Class A mode with a 10-minute uplink interval, fully compliant with the AS923-2 regional parameters. Data were forwarded to the ThingsBoard cloud platform for storage, visualization, and AI processing. Baseline energy consumption was recorded using the building’s main electricity meter for one month prior to deployment.

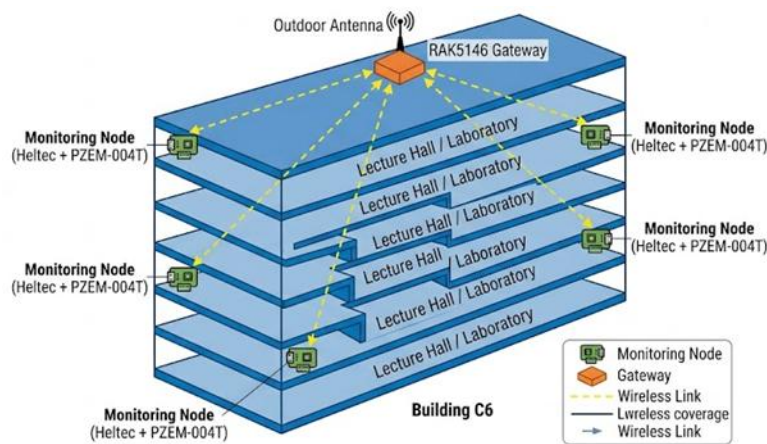


Figure 5: Deployment of LoRaWAN smart energy monitoring nodes in Haiphong University Building C6.

##### Measurement Methods

Key performance metrics included:

Daily energy consumption (kWh)

Waste ratio (power consumption > 100 W outside scheduled hours 18:00–07:00)

Packet Delivery Ratio (PDR) and Received Signal Strength Indicator (RSSI)

AI prediction accuracy and waste detection rate

The Linear Regression and Multi-Layer Perceptron models were trained using the first month’s historical data. Model performance was evaluated using Mean Absolute Percentage Error (MAPE) and waste detection accuracy.

**Experimental Results**

After three months of operation, the pilot deployment demonstrated significant improvements. The average daily energy consumption decreased from 130 kWh to 100 kWh, achieving a 22.5% reduction in electricity usage through automatic detection and shutdown of wasteful loads.

The LoRaWAN communication performed reliably in the dense concrete environment, with an average Packet Delivery Ratio of 98.7% and RSSI values ranging from -85 dBm to -110 dBm. These results confirm the effectiveness of LoRaWAN for indoor coverage in multi-floor university buildings.

The AI models showed strong performance with prediction errors below 8% (MAPE) and successfully detected wasteful consumption with an accuracy of 85%. Automated relay control effectively reduced unnecessary operation of lighting and air conditioning systems outside class hours.

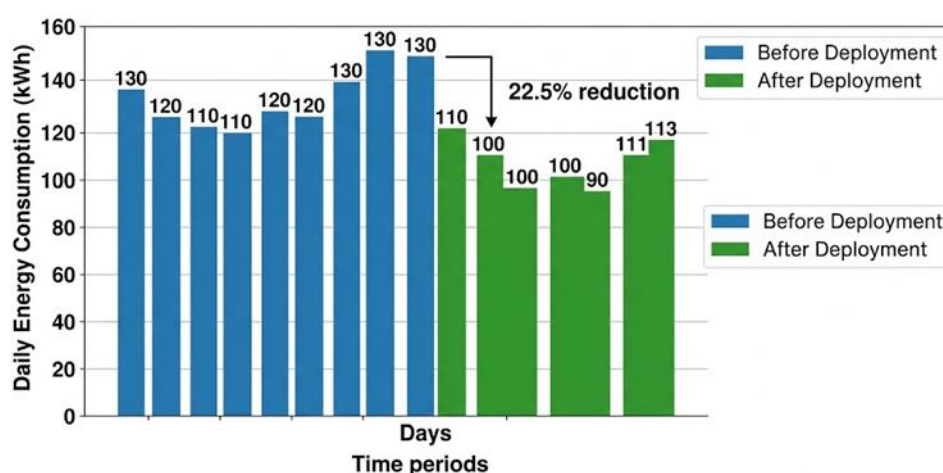


Figure 6: Comparison of daily energy consumption before and after deployment of the smart energy monitoring system.

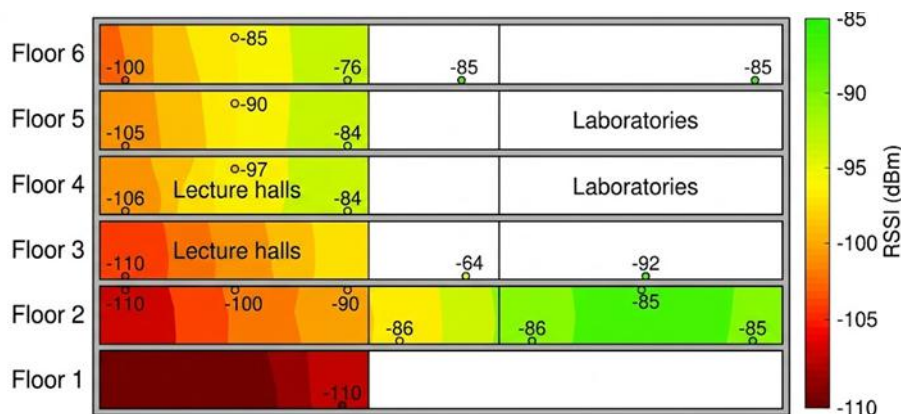


Figure 7: RSSI heatmap showing LoRaWAN coverage across Building C6.

The experimental results validate the feasibility, reliability, and practical effectiveness of the proposed LoRaWAN-based smart energy monitoring system in real university lecture hall environments.

**V. Discussion**

The pilot deployment of the LoRaWAN-based smart energy monitoring system at Haiphong University Building C6 achieved a 22.5% reduction in daily energy consumption, which falls well within the 15–30% improvement range reported in previous IoT-based energy studies in educational buildings [5], [19]. This result confirms the practical effectiveness of combining long-range LoRaWAN communication with lightweight AI models for real-time waste detection and automatic control.

One of the key strengths of the proposed system lies in its robust wireless performance in dense concrete structures. The achieved Packet Delivery Ratio of 98.7% and acceptable RSSI levels (–85 dBm to –110 dBm)

demonstrate that LoRaWAN technology significantly outperforms conventional WiFi and Zigbee solutions in large university campuses where thick walls and multi-floor layouts typically degrade signal quality [8], [20], [24]. The use of a single gateway with an 8 dBi outdoor antenna proved sufficient to cover the entire six-floor building, highlighting the cost-effectiveness and scalability of the LoRaWAN approach.

The integration of simple AI models also contributed substantially to the overall performance. Both Linear Regression and Multi-Layer Perceptron models delivered prediction errors below 8%, enabling timely detection of wasteful energy usage. This accuracy is comparable to or better than several recent studies that applied machine learning for energy monitoring in educational facilities [11], [23]. More importantly, the system successfully translated prediction results into automatic actions through relay control, which is a clear advantage over purely monitoring-based solutions.

However, some limitations were observed during the experiment. Although the 10-minute uplink interval provided a good balance between data resolution and power consumption, it introduced a certain delay in real-time response compared to WiFi-based systems. Additionally, the current AI models were trained on relatively limited historical data (three months). Performance may be further improved with longer data collection periods and the inclusion of additional contextual features such as occupancy detection or ambient temperature.

Compared with existing technologies, the proposed system offers a compelling balance between communication range, power efficiency, deployment cost, and intelligent capability. It addresses the specific challenges of Vietnamese universities, including regulatory frequency constraints (AS923-2) and budget limitations, while providing a practical platform for hands-on training in Electrical and Electronics Engineering.

Overall, the experimental results validate that the LoRaWAN-based smart energy monitoring system is a viable, low-cost, and effective solution for reducing electricity waste in university lecture halls. The findings strongly support its potential for wider deployment across other buildings on campus and similar educational institutions in Vietnam.

## **VI. Conclusion And Future Work**

This study successfully designed, developed, and experimentally validated a LoRaWAN-based smart energy monitoring system for university lecture halls. The pilot deployment at Building C6, Haiphong University, demonstrated outstanding performance: daily energy consumption was reduced from 130 kWh to 100 kWh, achieving a 22.5% energy saving. The system maintained excellent communication reliability with a Packet Delivery Ratio of 98.7% and acceptable RSSI levels in dense concrete structures. The integrated lightweight AI models (Linear Regression and Multi-Layer Perceptron) delivered prediction errors below 8% and 85% accuracy in automated waste detection, enabling effective real-time control of wasteful loads.

The proposed system fully meets the research objectives by providing a low-cost, scalable, long-range, and intelligent energy monitoring solution that is well-suited to Vietnamese university infrastructure and the AS923-2 frequency band. It not only contributes to Sustainable Development Goal 7 (Affordable and Clean Energy) but also serves as a practical hands-on training platform for Electrical and Electronics Engineering students in IoT, embedded systems, and artificial intelligence applications.

Future work will focus on campus-wide scaling with multiple gateways, integration of additional environmental sensors, adoption of more advanced deep learning models when longer historical datasets are available, and development of a mobile application for remote monitoring and control.

The results confirm that the LoRaWAN-based smart energy monitoring system is a feasible, reliable, and cost-effective solution for reducing electricity waste in higher education institutions and provides a solid foundation for sustainable digital transformation of university campuses.

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