

# Cost-Effective Electrical Power Control and Monitoring System Using Hybrid Sensing Architecture over LoRaWAN

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## Abstract

This research aims to a cost-effective electrical power control and monitoring system using hybrid sensing Architecture over LoRaWAN. The system employs a power measurement module (Pzem004t) to monitor the building's power consumption and a current sensor (ACS712-30A) to measure the electrical current of the equipment in use. The collected data is transmitted to an Arduino UNO R3 microcontroller, which is connected to an ESP32 microcontroller responsible for controlling the RFM95w module. Through the LoRa protocol, the system sends data to the CAT LoRa IoT gateway, enabling data visualization and control through a web application. In the experimental phase, the system effectively measures the energy consumption of electrical appliances and automatically responds when power consumption exceeds the specified limit. The system accurately displays total electric power consumption, power factor, total electricity cost, and voltage. Additionally, the system records the current values every minute. The experimental results demonstrated that the system operates effectively over a transmission distance of 5 km via the CAT LoRaWAN gateway. The measurement accuracy, when compared to a reference standard, showed an average discrepancy (error rate) of approximately 5.643%. In terms of control performance, the average response time (latency) for appliance shutdown commands was found to be in the range of 38.50 – 51.33 seconds, primarily due to the LoRaWAN Class A communication protocol limitations. However, it should be noted that the ACS712-30A sensor for each sub-load may have varying tolerance levels for the load's current, and transmitting the electrical control value may take more than one minute in certain cases.

**Keywords:** Power Electricity; Control and Monitoring System; LoRaWan Technology; Internet of Things

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## 1. Introduction

In recent years, the rapid expansion of the Internet of Things (IoT) has revolutionized energy management systems, transitioning from traditional metering to intelligent, real-time monitoring solutions [1, 2]. As global energy demand rises, the concept of "Smart Grids" and "Smart Homes" has become essential for enhancing energy efficiency and reducing operational costs [3]. Conventional monitoring systems often rely on short-range communication technologies such as Wi-Fi or Bluetooth. While effective for small-scale applications, these technologies face limitations in terms of high power consumption and restricted coverage range, making them less ideal for large-scale or remote deployments [4, 5].

To overcome these challenges, Low Power Wide Area Network (LPWAN) technologies, particularly LoRaWAN (Long Range Wide Area Network), have emerged as a superior alternative. LoRaWAN offers the distinct advantages of long-range

data transmission (up to 15 km in rural areas), deep indoor penetration, and minimal power consumption [6, 7]. Recent studies have demonstrated the effectiveness of LoRaWAN in various applications. For instance, [8] developed a smart meter using LoRaWAN for rural electrification, while [9] focused on environmental monitoring in smart cities. However, most existing LoRaWAN-based energy systems primarily focus on monitoring parameters without integrating real-time control capabilities. Furthermore, many solutions rely on a single type of sensor, which may either lack precision for total energy metering or be too costly for monitoring individual appliances.

This research presents a cost-effective LoRaWAN-based control and monitoring system employing a hybrid sensing architecture. Unlike typical solutions, this work balances accuracy and cost by integrating the PZEM-004T precision module for total building metering with the ACS712 sensor for individual sub-loads. The key contributions are: A scalable integration of high-precision (PZEM-004T) and cost-effective (ACS712) sensors for efficient building energy management. Enables real-time web visualization and remote appliance control over LoRaWAN, specifically addressing Class A downlink latency challenges. Validated on a commercial CAT Telecom LoRaWAN network over a 5 km range, confirming reliability and signal penetration in practical environments. This approach effectively bridges the gap between simple monitoring devices and complex industrial systems [10 – 15].

## 2. Theory and System Design

### 2.1 Theory

#### 2.1.1 Electrical measurement principles

To insure accurate energy monitoring, the system calculates the root mean square (RMS) values for voltage and current, alongside the power factor (PF). Active power (P) and electrical energy (E) are derived as follows:

$$P = V_{rms} \times I_{rms} \times \cos(\phi) \quad (1)$$

Where  $\cos(\phi)$  represents the power factor and  $t$  denotes the time interval.

#### 2.1.2 Sensor selection and rationale

A hybrid sensing architecture is employed to optimize cost and precision:

**PZEM-004T (Main Metering)**: Selected for main line monitoring due to its high accuracy ( $\pm 1\%$ ) and ability to measure AC voltage (80 – 260V), current (0 – 100A), active power, and energy via a non-invasive current transformer (CT). It utilizes the SD3004 energy metering SoC to perform internal True-RMS calculations, ensuring robustness against waveform distortion.

**ACS712-30A (Sub-load Monitoring)**: Chosen for individual appliance monitoring due to its cost-effectiveness and ease of integration. It operates on the Hall Effect principle, converting magnetic fields from current flow into proportional analog voltage. To mitigate inherent noise and zero-current offset ( $V_{cc}/2$ ), the system implements software calibration and a 1,000-point averaging algorithm.

#### 2.1.3 LoRaWAN communication protocol

The system utilizes the LoRaWAN protocol operating in the AS923 band. A critical aspect of the system design is the device class configuration. The end-node operates as a Class A device to minimize power consumption. In Class A, the device can only receive downlink messages (control commands) from the server during two short receive windows immediately following an uplink transmission.

This architecture introduces a latency in control commands. If a user sends a "Turn OFF" command via the web dashboard, the command is queued at the network server and is only executed when the device wakes up to send its next scheduled sensor data packet (every 1 min). This trade-off is inherent to the Class A specification to ensure extended battery life for remote nodes.

### 2.2 System Design

The hardware architecture consists of two main subsystems in Fig. 1. Sensing & Control Node: The Arduino UNO R3 acts as the primary data acquisition unit, reading analog signals from the ACS712 via a multiplexer and digital data from the PZEM-004T via software serial. It controls an 8-channel relay module for appliance switching. Communication Node: An ESP32 microcontroller interfaces with the RFM95W LoRa module. It receives the aggregated data frame from the Arduino via I2C and handles the LoRaWAN stack (AES-128 encryption) for transmission to the CAT Telecom IoT Gateway. The gateway is connected to a Raspberry Pi 4 B, which runs Node-Red (API) and a Web Dashboard, with a Database for data storage.

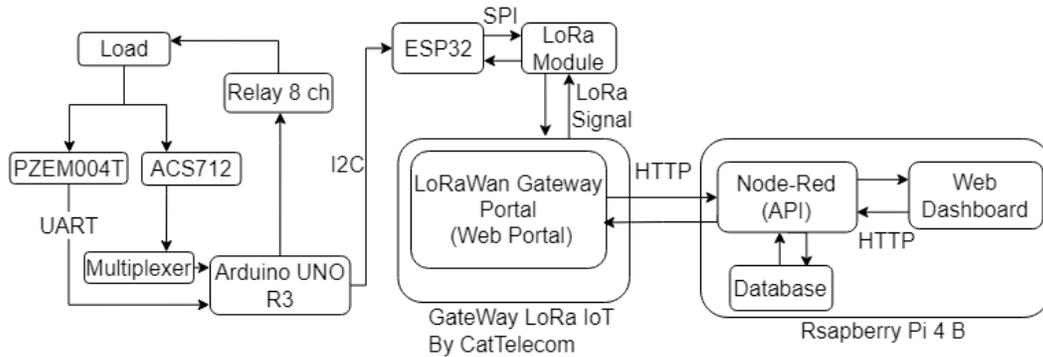


Fig. 1 Power electricity control and monitoring system design.

The first part involves measuring electrical equipment using the ACS712-30A sensor, which is connected to the Analog Multiplexer Module to expand the Analog port and read values from multiple sensors. The second part is responsible for measuring the total electric power consumption, including current, voltage, electric energy, and electric energy consumption per hour, utilizing the Pzem004t electric energy meter module. This part also incorporates the CT current sensor, which covers the main electric cable outgoing from the main circuit breaker. The data is then transmitted to an Arduino Uno R3 board via UART protocol and sent via I2C to the ESP32, which provides detailed information about electricity usage. as denoted by Fig. 2.

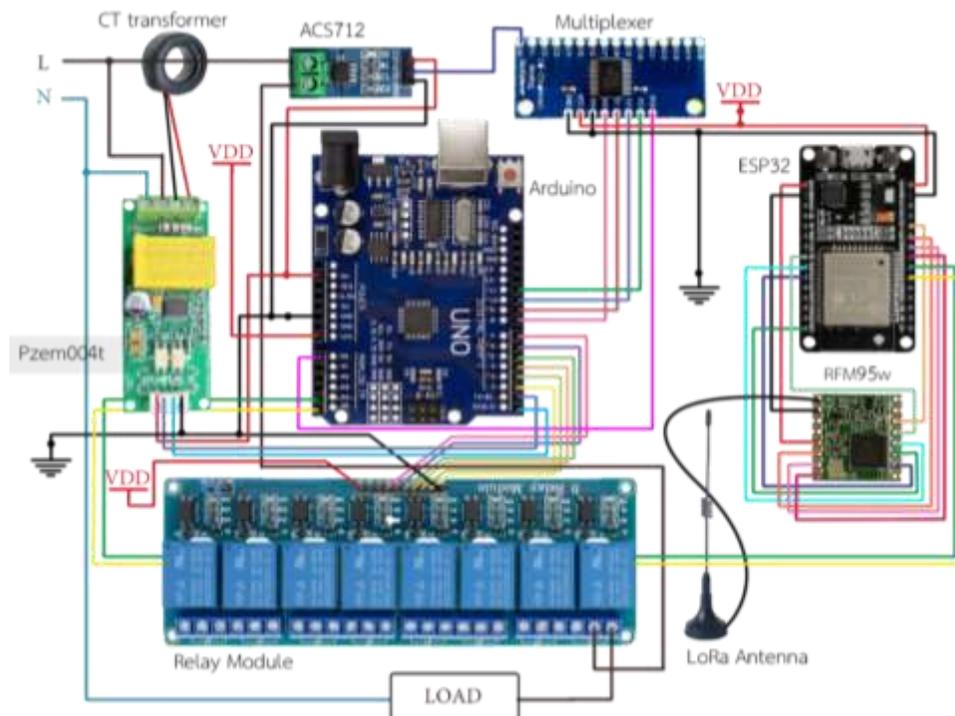


Fig. 2 The hardware design.

The system utilizes the LoRa module to send data to the gateway for display and control through a web application. The connection to the LoRa gateway and network server is established using LoRa ABP gateway. The network session key and application session key are used in the form of 128-bit AES encryption key to ensure secure communication between the end device and network server. The ESP32 microcontroller operates on the AS923 MHz frequency to connect to the CAT LoRaIoT Platform, acting as a network server for managing the data received from the LoRa node devices. Data sent from the LoRa node devices can be forwarded to the server, where Node-Red is installed, by setting a routing URL in the routing Profile section of the CAT LoRa IoT web page.

Regarding data transmission with LoRaWAN technology, data is sent in hexadecimal (Hex) format. The sensor readings are in both decimal and integer formats. Therefore, it is essential to design data transformations to achieve a byte-formatted LoRa payload. Optimizing the payload size is crucial because the number of bytes transmitted by LoRa directly impacts the transmission speed of the signal. Reducing the payload size results in shorter transmission time, known as on air time, which is advantageous for efficient data delivery.

When the user accesses the web application, the system will initiate a data request through an API to the server. Once the server receives the data request, it retrieves the requested data from the database. The database then sends back the relevant data to the server. Subsequently, the server sends the retrieved data through the API to the front-end side of the web application, which is running on a Raspberry Pi. This process ensures that the web application on the front-end side can display the data to the user seamlessly, as denoted by Fig. 3.



Fig. 3 The web application.

### 3. Experimental

Present The experimental power electricity control and monitoring system is designed based on LoRaWAN technology. It is capable of connecting to five types of electrical equipment: light bulbs, televisions, fans, air conditioners, and computers. These devices are interconnected using relays to control their operation. The system enables control of electrical appliances within the building by sending data to turn them on and off. To test this functionality, the control system will initially be connected to an electric bulb instead of an electrical appliance. All six channels will undergo testing to ensure proper operation and functionality.

The precision tabular measurements involve capturing current and voltage readings to calculate the power consumed by each electrical appliance load. The goal is to evaluate the accuracy of the energy consumption metering system in comparison to the Uni-t 202A+ digital clamp meter, as denoted by Fig. 4 and Fig. 5.



**Fig. 4** Setup of interconnected using device control.



**Fig. 5** Setup of power electricity control and monitoring system.

In this experiment, the control device located at point B sends data signals to point A, which serves as the gateway of CAT Telecom, the provider of LoRaWAN technology. The transmission distance between point B and the gateway (point A) is approximately 5 km. as denoted by Fig. 6.



Fig. 6 Distance of data transmission with LoRaWAN (5 km).

### 3. Results and Discussions

The experimental results are categorized into four main aspects: operational control performance, measurement accuracy, economic energy-saving analysis, and a comparison with existing systems.

Part 1, The system's ability to control electrical appliances remotely was evaluated by sending ON/OFF commands via the web application to 6 different devices. The test was repeated 3 times to ensure consistency. The results, as summarized in Table 1, indicate an average response time ranging from 38.50 – 51.33 s.

Table 1 The parameters of the sensor.

No.	Device	Data Transmission Time (seconds)			Status
		1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	
1	light	14	49	45	Open – Close
2	televisions	63	53	50	Open - Close
3	fans	N/A	52	53	Open - Close
4	Air conditioners	N/A	52	52	Open - Close
5	computers	N/A	51	51	Open - Close

Part 2, The accuracy of the hybrid sensing module (PZEM-004T and ACS712) was validated against a standard digital clamp meter (Uni-t 202A+). Voltage, current, and power consumption were measured over 10 iterations.

Accuracy : The comparative data in Fig. 7 – 9 demonstrates that the proposed system tracks the reference meter closely. The average mean absolute percentage Error (MAPE) was calculated at 5.643%.

Repeatability : To assess reliability, the standard deviation (S.D.) for the current measurements (Fig. 7) was analyzed, yielding a standard deviation of approximately 0.102 A. The low S.D. confirms that the system maintains consistent reading patterns with no significant outliers. Discussion on Error : While utility-grade billing meters typically require an error rate of less than 1%, the 5.643% discrepancy observed in this study is considered acceptable for energy management and load profiling

purposes. The error is largely due to the inductive noise sensitivity of the ACS712 Hall-effect sensor at lower current ranges. However, for identifying trends and "energy hogs" in a building, this precision level is sufficient and cost-effective.

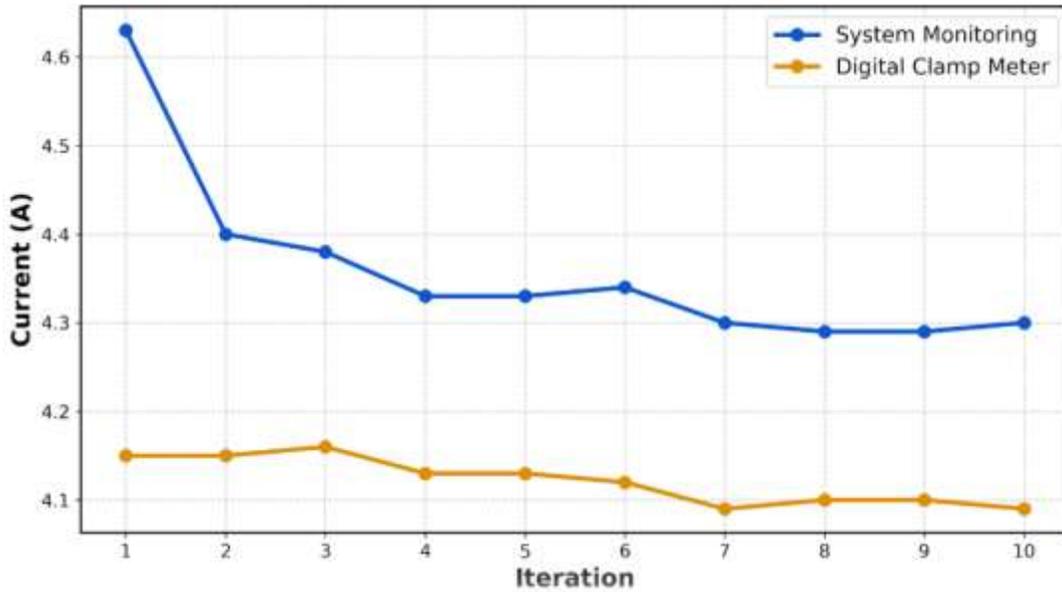


Fig. 7 The measurement of current between system monitoring and digital clamp meter.

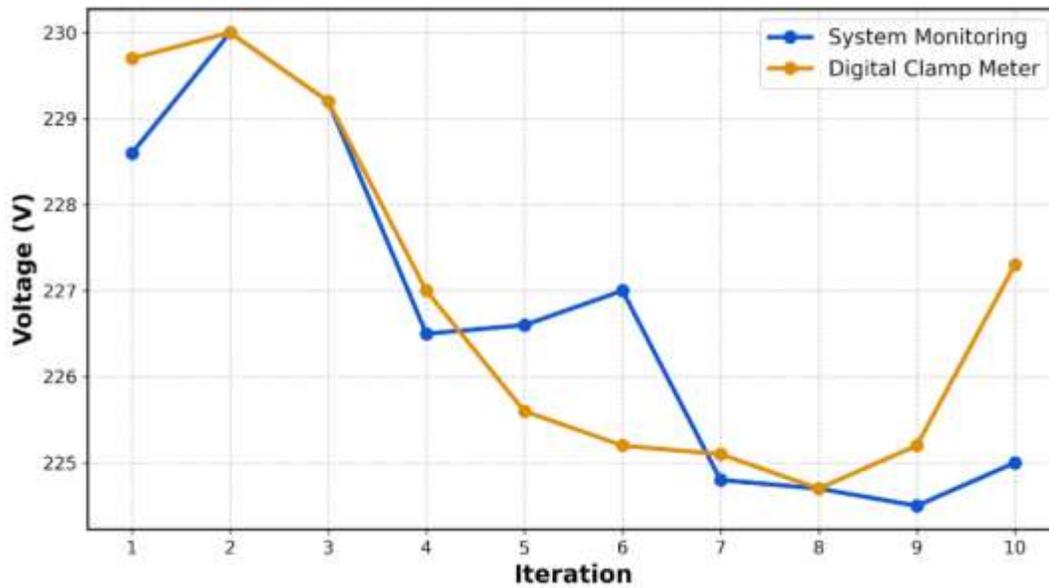


Fig. 8 The measurement of voltage between system monitoring and digital clamp meter.

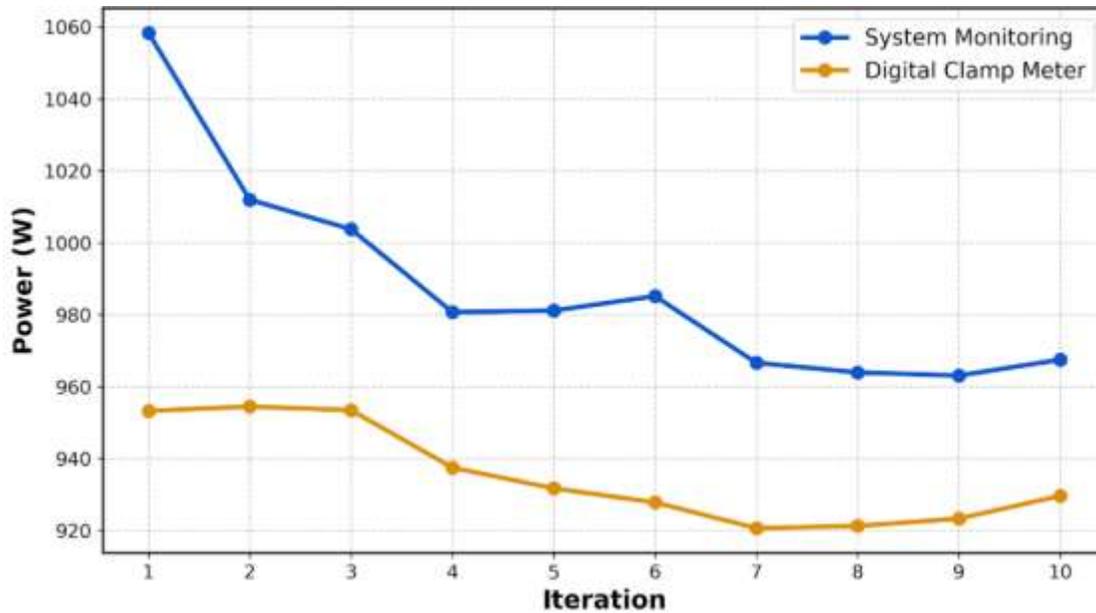


Fig. 9 The measurement of power electricity between monitoring and digital clamp meter.

Part 3, Energy saving and economic analysis to quantify the economic benefits of the proposed system, a scenario-based analysis was conducted.

Scenario : Consider a user forgetting to turn off a 1.50 kW air conditioner for 2 h daily.

Manual Operation : The appliance runs unnecessarily until the user returns.

Proposed System : The user detects the anomaly via the dashboard and remotely shuts it down within ~1 min.

Calculation:

$$\text{Energy Saved} = 1.50 \text{ kW} \times 2 \text{ h/day} \times 30 \text{ days} = 90 \text{ kWh/month}$$

Assuming an electricity rate of 4 THB/kWh, the system saves approximately 360 THB per month per appliance. This demonstrates a clear return on investment (ROI) through waste reduction.

Part 4, Comparison with existing systems Table 2 compares the proposed system with other LoRaWAN-based monitoring solutions. Unlike previous works that focus solely on monitoring [10] or use expensive industrial sensors [11], this work integrates Bi-directional control and a cost-effective hybrid sensing architecture.

Table 2 Comparison with existing LoRaWAN-based energy systems.

Features	Ref [10]	Ref [11]	Proposed System
Communication	LoRaWAN	LoRaWAN	LoRaWAN (CAT Telecom)
Functionality	Monitoring Only	Monitoring Only	Monitoring + Control
Sensing Type	Single Sensor	CT Only	Hybrid (PZEM + ACS712)
Range Tested	Lab Scale	2 km	5 km (Real-world)
Cost Efficiency	Medium	High	High

#### 4. Conclusion

This study successfully implemented a cost-effective LoRaWAN-based power electricity control and monitoring system utilizing a hybrid sensing architecture (PZEM-004T and ACS712). Field tests conducted over a 5 km range demonstrated a measurement discrepancy of 5.643% and an average control latency of 38.50 – 51.33 s, attributed to LoRaWAN Class A

limitations. Despite this latency, the system provides a viable solution for reducing unnecessary energy consumption through real-time monitoring and remote shutdown capabilities. To enhance system robustness and applicability, future research will focus on validating signal penetration in high-interference urban and deep indoor environments, assessing network scalability with multiple deployed nodes, and integrating machine learning for predictive energy management to further optimize efficiency and mitigate latency impacts.

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## **References**

- [1] K. Agung Enriko, A. Zaenal Abidin, A.S. Noor, Design and implementation of LoRaWAN-based smart meter system for rural electrification, 2021 International Conference on Green Energy, Computing and Sustainable Technology (GECOST), Miri, Malaysia, 2021, 1 – 5.
- [2] G.B. Hmida, I.H. Smaili, Design and implementation of a smart energy meter system using the Internet of Things, *J. Eng. Appl. Sci.* 11(2) (2024) 163 – 175.
- [3] N.E. Guevara, Y.H. Bolaños, J.P. Diago, Development of a low-cost IoT system based on LoRaWAN for monitoring variables related to electrical energy consumption in low voltage networks, *HardwareX* 12 (2022) e00330.
- [4] W. Chaiyong, S. Sonasang, Applications of energy monitoring using the IoT, *SNRU J. Sci. Technol.* 14(2) (2022) 1 – 8.
- [5] N.-A. Alam, M. Ahsan, M.A. Based, J. Haider, E.M.G. Rodrigues, Smart monitoring and controlling of appliances using LoRa-based IoT system, *Designs* 5(1) (2021) 17.
- [6] K.M.W. Hidayat, M.G. Al-Faris, IoT-based electrical power consumption monitoring system in households using ESP32 and PZEM-004T, *Brilliance: Res. Artif. Intell.* 5(2) (2025) 1077 – 1081.
- [7] E.V. Murugan S., T.V. Balaji, R. Gurubaran, B. Jayapalan, A.T. Vivin, LoRa-based smart energy metering and secure billing system for rural areas, in: 2025 Int. Res. Conf. Smart Computing and Systems Engineering (SCSE), Colombo, Sri Lanka, 2025, 1 – 6. \
- [8] S.D. Putra, C.O. Sereati, H. Sutrisno, Design of IoT monitoring system based on LoRaWAN architecture for smart greenhouse, *IOP Conf. Ser.: Earth Environ. Sci.* 1012 (2022) 012090.
- [9] W.A. Jabbar, S. Annathurai, T.A.A. Rahim, M.F.M. Fauzi, Smart energy meter based on a long-range wide-area network for a stand-alone photovoltaic system, *Expert Syst. Appl.* 197 (2022) 116703.
- [10] B.K. Barman, S.N. Yadav, S. Kumar, S. Gope, IoT based smart energy meter for efficient energy utilization in smart grid, in: 2018 2nd Int. Conf. Power, Energy and Environment: Towards Smart Technology (ICEPE), Shillong, India, 2018, 1 – 5.
- [11] G.V. Bhau, R.G. Deshmukh, T.R. Kumar, S. Chowdhury, Y. Sesharao, Y. Abilmazhinov, IoT based solar energy monitoring system, *Mater. Today Proc.* 80(3) (2023) 3697 – 3701.
- [12] F. Sánchez-Sutil, A. Cano-Ortega, J.C. Hernández, Design and implementation of a smart energy meter using a LoRa network in real time, *Electronics* 10(24) (2021) 3152.
- [13] F. Sánchez-Sutil, A. Cano-Ortega, Smart public lighting control and measurement system using LoRa network, *Electronics* 9(1) (2020) 124.
- [14] D.S. Nimaje, P. Ragam, Performance evaluation of LoRa LPWAN technology for IoT-based blast-induced ground vibration system, *J. Meas. Eng.* 7(3) (2019) 119–133.
- [15] K.S. Adu-Manu, C. Tapparello, H. Ayatollahi, W. Heinzelman, Energy-harvesting wireless sensor networks (EH-WSNs): A review, *ACM Trans. Sens. Netw.* 14(2) (2018) 1 – 50.

