

Street Lighting Design with IoT-Based Energy Management in Cibuluh Village

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ABSTRACT

This study presented the design and implementation of an Internet of Things-based public street lighting system with energy management in Cibuluh Village, Tanjung Siang District, Subang Regency. The project aimed to improve lighting reliability in areas with limited grid access while reducing energy consumption and operational costs. The system employed solar panels as the primary energy source, battery storage, and light-emitting diode lamps equipped with smart dimming features. This approach enhances system autonomy, minimizes maintenance requirements, increases operational efficiency, ensures consistent illumination quality, and provides a scalable model suitable for broader rural infrastructure deployment nationwide. Energy management was achieved through the integration of light-dependent resistor and passive infrared sensors to adapt lamp brightness based on environmental light conditions and road activity. Electrical parameters, including voltage, current, and power, were monitored using a direct current power measurement module and transmitted via long-range wireless communication to a centralized database. Data visualization was provided through a real-time monitoring dashboard. The system was developed using the ADDIE research and development model and was implemented directly in the village environment. Evaluation results showed stable electrical performance, effective energy savings, reliable data transmission in hilly areas, and improved sustainability of street lighting operations. The proposed system demonstrated its suitability as an efficient and autonomous public lighting solution for rural areas.

INTRODUCTION

Street Lighting (PJU) is one of the basic infrastructures that plays an important role in ensuring the safety, security, and comfort of community activities at night, while also encouraging regional socio-economic growth (Prabowo A. S. et al., 2021). In Indonesia, the street lighting is a vital service required by the community, which the technology has been growing significantly to obtain a lower operating expense and higher efficiency (Kurniawan, R. et al., 2022). These efficiency efforts are in line with the national energy conservation policy and the target of reducing greenhouse gas emissions through optimizing energy use and utilizing new, renewable energy in various public infrastructures (Manohara B. P. et al., 2026).

Cibuluh Village in Tanjung Siang District, Subang Regency, is a village that is developing as an agricultural area and tourist destination with increasing population activity and tourist movement, so that the need for adequate quality street lighting is increasingly urgent (Sukarno S. A. et al., 2023). The limited condition of the electricity network on several village roads and the suboptimal existing PJU system has the potential to cause safety problems, limit nighttime economic activities, and reduce the attractiveness of village tourist areas (Cinangka K. et al., 2025). On the other hand, the high operational costs of PJU become a fixed burden on the regional and village government budgets if not accompanied by good energy management and the selection of energy-efficient lighting technology (Ferza R., 2020).

The development of lighting technology, particularly the use of LED lamps and solar-powered street lighting (PJU-TS), opens up opportunities for energy savings of up to 50-60% while increasing the reliability and lifespan of the PJU system (P. Led et al., 2020). The integration of this technology with automatic control systems, such as light sensors or intensity settings, allows for more adaptive energy management to meet real-world needs, thereby reducing energy consumption without reducing the required lighting levels (Ullah A. et al., 2020). Various studies and government programs have shown that the implementation of energy-efficient PJU in rural areas not only improves the safety and comfort of residents, but also supports budget efficiency, encourages local economic activity, and strengthens efforts towards sustainable village development (Cinangka K. et al., 2025).

The design and construction of a Public Street Lighting system with energy management in Cibuluh Village is relevant to answer the need to improve the quality of lighting infrastructure while saving energy and operational costs. This research focuses on the technical design of a reliable and efficient PJU system, the selection of appropriate lighting



technology, and the application of energy management concepts that suit the characteristics of Cibuluh Village. This research emphasizes the engineering of a solar-based PJU lighting system with energy management and Internet of Things (IoT) integration, which includes system architecture design, selection of main components, and implementation of power control, dimmers, and monitoring systems to improve operational efficiency and reliability.

LITERATURE REVIEW

Solar-powered street lighting utilizes solar panels as the primary energy source, batteries for energy storage, LED lights as the lighting load, and sensors as control parameters (Samala S.R.K. et al. 2024). This system is widely used in areas with limited electricity access because it can reduce operational costs and greenhouse gas emissions (Saputra T. et al., 2024).

A Light Dependent Resistor (LDR) is a sensor used to control the on/off of lights. The working principle of this sensor is to convert the received light intensity into resistance; the greater the light intensity, the greater the resistance produced by the LDR (Arati S. 2022). In street lighting applications, the LDR is used to replace a manual switch, where the lights will turn on when the light intensity decreases, allowing the lights to be active at night (Ganis S. et. all., 2022).

Passive Infrared (PIR) sensors regulate light brightness when a moving object is present. These sensors detect changes in infrared radiation from moving objects, such as people and vehicles. Lights will illuminate at maximum brightness when an object is detected and dim again when there is no activity nearby, thus reducing energy consumption without compromising road safety (Arati S. 2022).

The Internet of Things (IoT) is a concept for developing internet network connectivity where physical devices such as sensors, actuators, and microcontrollers work in an integrated manner to receive, send, and process information over the internet (Marianis E. 2022). The IoT system will display current, voltage, and power readings, as well as light status on the dashboard.

The PZEM-017 is a DC power measurement module capable of reading voltage, current, and power parameters. To measure current, the PZEM 017 sensor requires the assistance of an external shunt resistor (Delila A. et al., 2025). In practice, data obtained from the PZEM-017 sensor will be sent to the ESP32 using an RS-485 communication line with the Modbus RTU protocol.

METHOD

The development of Public Street Lighting (PJU) devices with IoT-based energy management in this activity adopted the research and development method with the ADDIE model (Rustandi A., 2024). The ADDIE model is a systematic development model consisting of five main stages, namely Analysis, Design, Development, Implementation, and Evaluation, which are used to produce products that are in accordance with user needs and development objectives (Prambayu R. M. et al., 2025). Figure 1 shows the research stages carried out by adopting the ADDIE model.

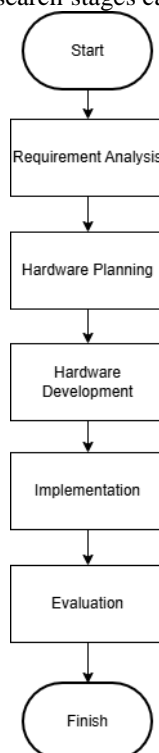


Fig. 1 Methodology Process

Analysis The analysis phase identifies existing problems at the activity location, particularly those related to suboptimal street lighting and inefficient energy use. Furthermore, a system requirements analysis is conducted, including street lighting specifications, energy source requirements, and an energy management system appropriate to environmental conditions and community needs.

Design The design stage is carried out based on the results of the needs analysis. At this stage, the design of the street lighting system with energy management is prepared, which includes designing a system block diagram, selecting main components, and designing the system workflow. The system uses a 20 W DC LED lamp that operates for 12 hours from 6:00 PM to 6:00 AM and is equipped with a dimmer feature. The system is also equipped with a monitoring and control module with a power consumption of 5 W so that the total daily energy requirement of the system is 250 Wh. To support these operations, a 12 V battery with a capacity of 40 Ah and a solar panel with a capacity of 100 Wp are used as the main energy sources.

The design of Block System Diagram

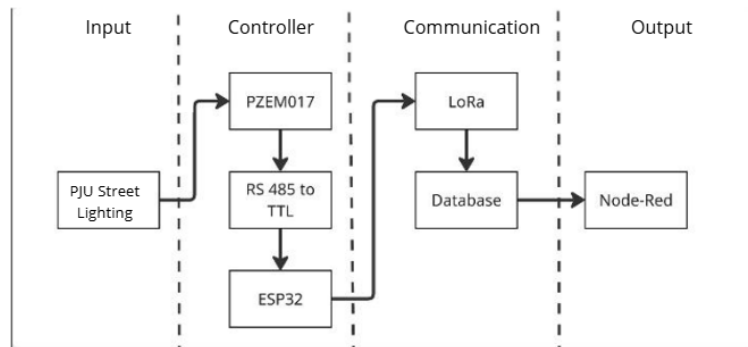


Fig. 2 Block System Diagram

Figure 2 shows a block diagram of a LoRa-based street lighting (PJU) system designed to remotely monitor voltage and current parameters. The system starts with the PJU lamp as a load source that produces electrical quantities in the form of voltage and current as a representation of the lamp's operational condition. The voltage and current values are measured using the PZEM017 module which functions as an electrical sensor with an RS485 communication interface, then the measurement data is forwarded to the ESP32 microcontroller through an RS485 to TTL converter circuit so that it can be processed according to the microcontroller's logic signal level. The ESP32 acts as a data processing center by packaging and adjusting the data format before being sent wirelessly using LoRa technology which has a wide range and low power consumption. Data sent via the LoRa network is then stored in a database as a centralized storage medium, then the data is parsed and visualized using Node-RED in the form of a dashboard, so that information on the PJU's electrical condition can be monitored and analyzed in real-time or based on historical data.

Component selection

The components to be created are selected using the hardware schematic shown in Figure 3.

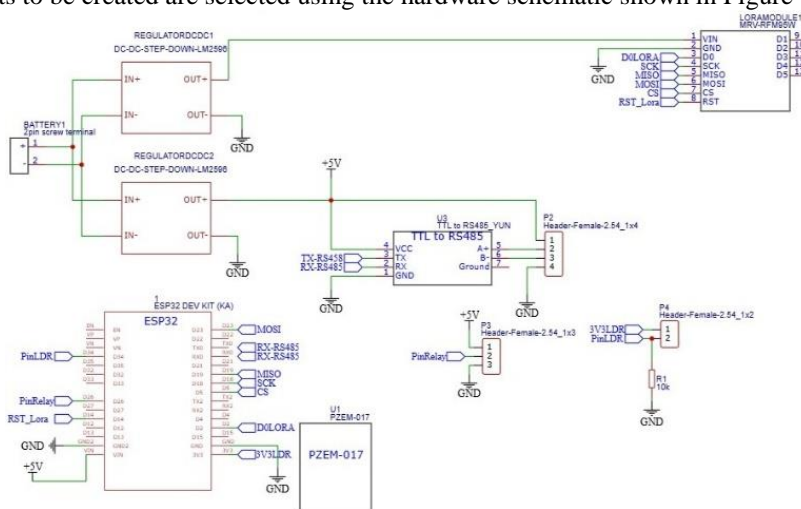


Fig. 3 Hardware Schematic Design

This schematic shows a solar-powered smart street lighting control system based on an ESP32 Dev Kit, integrating sensing, communication, and power management modules. Power from a battery is regulated using LM2596 DC-DC step-down converters to supply stable voltages for the ESP32, LoRa module (MRF RFM95W), RS485 interface, PZEM-017 power sensor, LDR sensor, and relay control. The system enables energy monitoring, smart dimming, and long-range data transmission via LoRa, while RS485 is used for reliable communication with the PZEM-017 power meter.

Web-Based Smart PJU Lighting Power Monitoring



Fig. 4 Hardware System Design

Figures 4 illustrate the overall hardware architecture of the IoT-based public street lighting monitoring system. Each street lamp is equipped with a PZEM-017 module to measure electrical parameters, which are transmitted to the ESP32 microcontroller through an RS485-to-TTL interface. The ESP32 processes the data and sends it wirelessly using LoRa communication technology, enabling long-range and low-power data transmission. The collected data are forwarded to a web server via an application programming interface (API) for centralized monitoring and analysis.

Table 1. Component Requirements

No	Component	Function
1	Battery 12V	As a power supply source
2	Module step down	As a power supply voltage regulator
3	Module LoRa	As a long-distance communication medium
4	Module RS485 to TTL	As a data communication interface
5	PZEM017	As a sensor for measuring electrical parameters
6	ESP32	As a data control and processing center
7	Database (MySql)	As a centralized data storage medium
8	Dashboard (Node-Red)	As a data visualization

Table 1 presents the main hardware and software components used in the proposed system along with their respective functions. The battery and step-down module provide a stable power supply, ensuring reliable operation of the monitoring and control units. Communication and sensing components, including the LoRa module, RS485 to TTL module, PZEM-017, and ESP32, enable data acquisition, processing, and long-distance transmission. The database and Node-RED dashboard support centralized data storage and real-time visualization of electrical parameters.

System Workflow

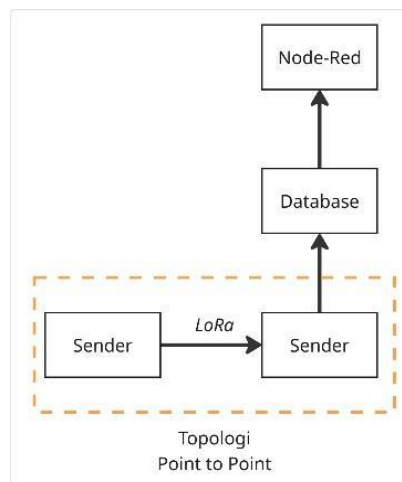


Fig. 5 System Workflow

Figure 5 shows the workflow of data transmission and processing in the proposed system using a point-to-point topology. Electrical data collected by the sender node are transmitted via LoRa communication to the receiver node connected to the server side. The received data are stored in a centralized database for further processing and historical analysis. Finally, the processed data are displayed on a Node-RED dashboard, providing real-time visualization to support system monitoring and energy management.

This system operates using a point-to-point communication topology, where one sending unit acts as the data source and one receiving unit serves as the data reception and processing center. The system workflow begins with data collection from sensors and measurement modules installed on the sending end. This data is then processed by a microcontroller as the primary controller. After the initial processing is complete, the data is sent directly via wireless communication to the receiving end without any intermediary nodes, ensuring a simple and efficient transmission process. The received data is then stored in a database, which serves as a centralized storage medium, enabling continuous and structured data recording. The data stored in the database is then accessed and processed using Node-RED to be displayed in a visual dashboard, allowing users to monitor system conditions in real time and based on historical data, with an informative and easy-to-understand display.

Development During the development phase, street lighting devices are manufactured and assembled according to the predetermined design. The manufactured devices are then tested to ensure all system functions are functioning properly.

Implementation The implementation phase is the application of the developed equipment at the activity location. At this stage, street lights are installed and operated directly in the community.

Evaluation The evaluation phase is the final stage in the ADDIE model. This phase evaluates the performance and benefits of the implemented street lights. Evaluation is conducted through direct observation of the system and community feedback as a basis for assessing the success of the development.

RESULT

In accordance with the stages of the ADDIE method, the results of this study are obtained from the Implementation stage, while system performance data are collected as inputs for the Evaluation stage. The developed smart street lighting system was successfully installed at a partner location in Desa Cibuluh, Tanjungsang, Subang. Considering the hilly geographical conditions and limited cellular network availability in the area, the system architecture was designed using a LoRa (Long Range)-based Internet of Things (IoT) topology to ensure reliable data transmission over long distances.

In the physical implementation phase illustrated in Figure 6, the system hardware—including solar panels, batteries, charge controllers, radar sensors, and LoRa communication modules—was integrated into streetlight poles in accordance with local public lighting (PJU) standards. The system operates in a stand-alone mode, fully powered by solar energy, without dependence on the PLN electricity grid. Energy harvesting, storage, and utilization were configured to support continuous nighttime operation while maintaining system reliability.

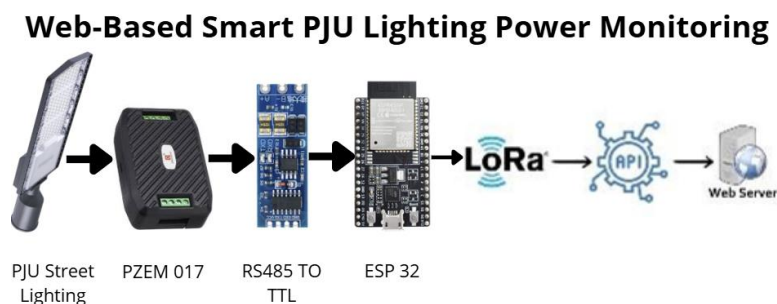


Fig. 6 Web-Based Smart PJU Lighting Power Monitoring

System Performance Result

System performance was evaluated through real-time monitoring of sensor data to assess electrical stability, energy consumption, and communication reliability. Performance testing focused on validating the effectiveness of the energy management algorithm and the stability of the power system under actual operating conditions. Monitoring data collected on November 4–5, 2025 are presented in the following figure.

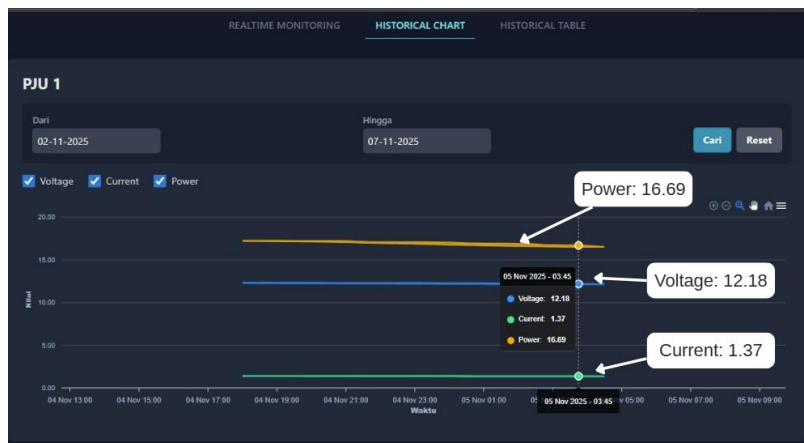


Fig. 7 Real-Time Monitoring

The monitoring results in Figure 7 show that the battery voltage decreased from 12.30 V to 12.18 V over approximately 11 hours of operation, indicating a relatively small voltage drop during overnight use. Current consumption remained within the range of 1.36 A to 1.40 A, with power consumption fluctuating between 16.69 W and 17.22 W. These values indicate stable electrical performance during system operation.

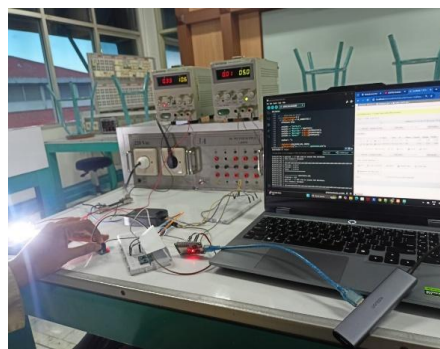


Fig. 8 Hardware Testing

Software functionality testing displayed in Figure 8, confirmed that the control logic operates as intended. When the LDR sensor detects light intensity below the threshold value of **1500**, the system activates the relay to turn on the streetlight automatically. This behavior is consistent with the logic defined in the `controlLamp()` function.

```
void sendDataToServer() {
  if (wifi.status() == WL_CONNECTED) {
    HTTPClient http;
    postData = "pju1_id=" + String(dataPJU1.id) +
      "&pju1_status=" + String(dataPJU1.lampStatus) +
      "&pju1_voltage=" + String(dataPJU1.voltage) +
      "&pju1_current=" + String(dataPJU1.current) +
      "&pju1_power=" + String(dataPJU1.power) +
      "&pju2_id=" + String(dataPJU2.id) +
      "&pju2_status=" + String(dataPJU2.lampStatus) +
      "&pju2_voltage=" + String(dataPJU2.voltage) +
      "&pju2_current=" + String(dataPJU2.current) +
      "&pju2_power=" + String(dataPJU2.power);

    Serial.println("Mengirim data gabungan ke server...");
    Serial.println(postData);
    http.begin(serverUrl.c_str());
    http.addHeader("Content-Type", "application/x-www-form-urlencoded");
    int httpResponseCode = http.POST(postData);
    if (httpResponseCode > 0) {
      Serial.print("Kode respons HTTP: ");
      Serial.println(httpResponseCode);
    } else {
      Serial.print("Gagal mengirim data, kode error: ");
      Serial.println(httpResponseCode);
    }
    http.end();
  }
}
```

Fig. 9 Logic Control System

Figure 9 explains the structure of data transmission, which was successfully validated through the serial monitor and dashboard interface. The Sensor Data data structure ensures that all electrical parameters, such as voltage, current,

and power, are transmitted intact from the Slave device to the Master via the LoRa protocol, which is then forwarded to the server using the http.POST command. Test images show that the data read by the PZEM-017 sensor is accurately displayed on the monitoring screen, indicating that the integration between programming logic and hardware has functioned perfectly in maintaining the operational efficiency of the street lighting system.

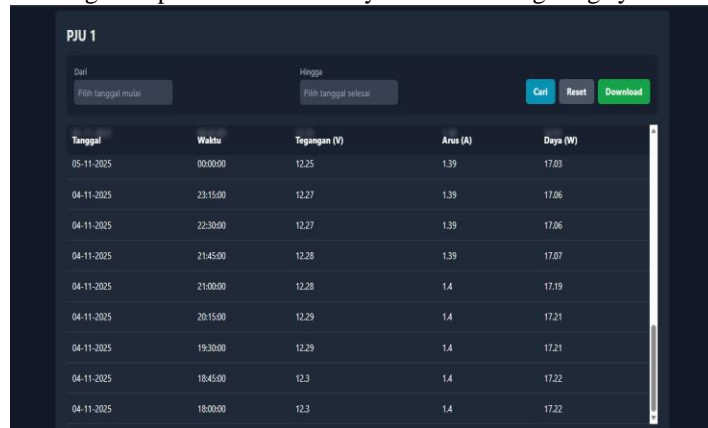


Fig. 10 Parameter Monitoring Dashboard

The dashboard system in Figure 10 provides data transparency, including monitoring of voltage, current, and power parameters. Furthermore, a feature for downloading historical data in .csv format makes it easier for village technicians or managers to evaluate long-term performance and predict device maintenance.

DISCUSSION

Energy Management and Battery Performance

The observed battery voltage drop of only 0.15 V over 11 hours demonstrates that the battery capacity is sufficient and does not experience excessive discharge. This result indicates that the implemented energy management strategy effectively balances energy consumption and storage. The stable voltage profile also suggests that the system avoids deep discharge conditions, which is critical for extending battery lifespan and maintaining long-term system reliability.

The effectiveness of the radar sensor-based smart dimming algorithm plays a significant role in reducing energy consumption. By dynamically adjusting lamp brightness based on the detection of moving objects such as pedestrians or vehicles, the system minimizes unnecessary power usage during periods of low activity. When no movement is detected, the lamp automatically dims, resulting in reduced current consumption and improved overall energy efficiency.

Load Stability and Lighting Performance

The relatively stable current range of 1.36 A to 1.40 A and power output of approximately 17 W indicate that the street lighting system provides consistent illumination without noticeable flicker. This stability is particularly important in solar-powered systems, where voltage fluctuations may occur due to battery discharge. The results confirm that the developed system is capable of maintaining optimal lighting performance even under gradual battery voltage decline.

Reliability of Communication and Monitoring System

One of the main challenges in Desa Cibuluh is the hilly terrain, which causes weak and inconsistent internet connectivity. The implementation of LoRa communication technology has proven effective in overcoming this limitation. Sensor data were transmitted reliably at predetermined intervals with no significant packet loss, demonstrating that LoRa is well suited for rural and geographically challenging environments.

The monitoring dashboard enhances system transparency by providing real-time and historical data on voltage, current, and power parameters. The availability of historical data download in .csv format supports long-term performance evaluation and predictive maintenance planning. This feature enables village technicians or system managers to identify trends, detect potential faults early, and optimize maintenance schedules, thereby improving the sustainability of the smart street lighting system.

CONCLUSION

The implementation of a solar-powered street lighting system with energy management in Cibuluh Village was successfully implemented using the ADDIE (Analysis, Design, Development, Implementation & Evaluation) development model. Based on the results of the activities and system evaluation, it can be concluded that.

- a. The system functions optimally in providing automatic lighting in areas with limited electricity, supported by a radar sensor-based smart dimming algorithm that maintains battery voltage stability (the battery only decreased by 0.15V during 11 hours of operation).
- b. The use of LoRa technology enables effective real-time transmission of sensor data, even in areas with hilly terrain.
- c. Through the dashboard, electrical parameters can be accurately monitored, with an average voltage of 12.18V, a current of 1.36-1.40A, and a power consumption of 16.69-17.22W.
- d. The dashboard system provides real-time monitoring, historical charts, and tables, allowing data download in .csv format for long-term performance evaluation.
- e. The implementation and evaluation phases demonstrated that the device has met the community's need for an efficient and independent alternative energy source, in line with the initial objectives of the project.

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