Development of a Real-Time Monitoring Model for Solar-Powered Street Lighting Systems Using Internet of Things

Ratna Ika Putri
Department of Electrical Engineering, State Polytechnic of Malang, Indonesia
ratna.ika@polinema.ac.id

Donny Radianto
Department of Electrical Engineering, State Polytechnic of Malang, Indonesia
donny.radianto@polinema.ac.id

Zakiyah Amalia
Department of Electrical Engineering, State Polytechnic of Malang, Indonesia
zakiyah_amalia@polinema.ac.id (corresponding author)

Ade Gafar Abdullah
Department of Vocational and Technology Education, Universitas Pendidikan Indonesia, Indonesia
ade_gaffar@upi.edu

Diky Zakaria
Department of Vocational and Technology Education, Universitas Pendidikan Indonesia, Indonesia
dikyzak@upi.edu

Dadang Lukman Hakim
Department of Vocational and Technology Education, Universitas Pendidikan Indonesia, Indonesia
dadanglh@upi.edu

Received: 30 June 2025 | Revised: 11 August 2025 | Accepted: 30 August 2025

ABSTRACT

Street lighting is a significant component of safe driving during the afternoon and nighttime when sunlight is unavailable, as it enhances drivers' visibility of the road, other vehicles, and surrounding areas. Lately, the integration of solar panels as the primary power source for streetlights has emerged as a promising, environmentally sustainable alternative for reducing energy consumption. However, because solar energy output is strongly affected by environmental conditions, a real-time monitoring system is essential for ensuring effective operation. This study presents the design of a monitoring system for solar-powered street lighting that integrates sensors to measure temperature, humidity, sunlight intensity, the voltage and current of solar panels, batteries, and lamps, from which the power output of each component is calculated. The measured data are displayed locally on a Thin Film Transistor (TFT) Liquid Crystal Display (LCD) and simultaneously transmitted to a cloud for remote access through a web interface. Performance evaluations confirm the system's accuracy, with average measurement errors of 1.7% for temperature and humidity, 0.8% for voltage, and 1.5% for current. These results demonstrate that the system provides reliable real-time monitoring, thereby enhancing the efficiency, reliability, and maintainability of solar-powered street lighting systems.

Keywords-street lighting; monitoring; solar panel; Internet of Things (IoT)

I. INTRODUCTION

Street lighting is a public infrastructure that plays an important role in drivers' visibility during the afternoon and nighttime hours. Conventional street lighting lamps consume large amounts of electricity per year worldwide, which is generated primarily from fossil-fuel power plants. To lower energy consumption, the integration of Light Emitting Diode (LED) lamps is a very efficient solution [1-2], while the integration of renewable energy sources is also promising.

In Indonesia, solar energy is among the most widely utilized renewable energy sources, primarily using Photovoltaic (PV) panels. Solar energy offers notable advantages, including being environmentally friendly, free from greenhouse gas emissions and harmful particulates, and virtually inexhaustible [3, 4]. Nevertheless, the performance of PV systems is highly dependent on environmental conditions, as parameters such as humidity, dust accumulation, wind speed, and temperature significantly influence PV performance [5-10]. Additionally, since street lighting is required at night when solar energy is unavailable, batteries are necessary to store daytime energy. Consequently, remotely supervised monitoring systems are required to evaluate environmental factors, the operational status of solar panels, such as shortages, faults, anomalies, or the storage batteries' status.

Several studies have investigated monitoring and control systems for street lighting. For instance, activation and regulation of streetlights based on pedestrian and vehicle presence have been proposed to reduce unnecessary energy consumption, thereby improving efficiency [11-14]. Microcontroller-based battery charging control has been shown to enhance overall system performance [14], while the adoption of LED lamps has further reduced energy demand [15]. Nonetheless, effective and reliable operation still requires dedicated monitoring systems. The integration of the Internet of Things (IoT) in such systems enhances their capabilities by enabling remote monitoring and data management. Prior studies have explored a range of approaches, including monitoring of high-pressure sodium lamps [2]; Wireless Sensor Networks (WSNs) to improve data transmission efficiency [4]; web-server-based monitoring of solar-powered street lighting for maintenance support [16]; Kalman filter estimation for fault detection [17]; and IoT frameworks for solar energy monitoring [13, 18-21]. However, most existing monitoring efforts have been limited to solar panel energy output alone.

This article advances the monitoring of solar-powered street lighting by developing an IoT-embedded system capable of measuring sunlight intensity, temperature, humidity, and the voltage and current of solar panels, batteries, and lamps. From these measurements, the ESP32 microcontroller computes the corresponding power outputs of each component, providing a comprehensive assessment of system performance. Peacefair Z Energy Meter (PZEM) (Peacefair, China) sensors are employed for voltage and current measurements due to their high accuracy [22], while Digital Humidity and Temperature (DHT) (Aosong Electronics, China) sensors are used for humidity monitoring [23]. Results are displayed on a Thin Film Transistor (TFT) Liquid Crystal Display (LCD) and simultaneously transmitted to a cloud for visualization via a web interface. With this system, faults in Secure Sockets Layer (SSL) installations can be detected early, ensuring a continuous power supply. IoT-based monitoring has already been applied successfully in various domains, including air quality forecasting [24], PV systems [25], and smart waste management [26], highlighting its suitability for real-time monitoring of street lighting applications.

II. LITERATURE REVIEW AND PROBLEM STATEMENT

A considerable body of research has addressed solar panel monitoring systems and their application in street lighting. For example, authors in [27] developed a control system that integrates Light-Dependent Resistor (LDR) sensors with Internet Protocol (IP) cameras to minimize energy consumption by autonomously regulating LED operation. This system demonstrated economic feasibility, reduced startup costs, and significant energy savings. In [12], solar panels and wind turbines were combined with IoT-based microcontroller control for street lighting. This approach facilitated real-time control, fault detection, and preventive maintenance, while reducing labor costs and improving energy efficiency. Similarly, authors in [11] proposed an IoT-based solar-powered street lighting system with an anti-vandalism mechanism. This autonomous system utilized LDRs, Infrared (IR) sensors, and microcontrollers to modulate LED brightness, conserve energy, and extend system lifespan, while also integrating a vandalism tracking module and a Wi-Fi-enabled user interface. In [15], solar street lighting powered by panels and batteries was monitored through voltage, current, and battery status metrics to optimize system scheduling and control. Battery charging was further investigated in [22] using PZEM-004T sensors, with results confirming reliable sensor performance. Wireless remote monitoring of solar-powered street lighting systems was also studied in [4], demonstrating improvements in system reliability. In [16], real-time monitoring through integrated sensors and communication systems was employed for maintenance planning, while authors in [14] developed streetlamps with current and voltage monitoring to enhance reliability and longevity. Intelligent lighting control, though not solar-based, was investigated in [3] to improve energy efficiency. In a related domain, authors in [23] explored greenhouse automation and monitoring systems powered by solar panels, monitoring variables such as current, voltage, pH, water flow, humidity, and temperature, thereby reducing personnel costs and improving productivity.

Moreover, authors in [28] provided a comprehensive review of PV monitoring systems, highlighting advancements in architecture, algorithms, and IoT integration for improved fault detection and predictive maintenance. However, their study lacked experimental validation and full-scale integration in real-world conditions. Authors in [29] designed an IoT-based monitoring system for solar power plants capable of measuring real-time electrical parameters (voltage, current, and power) and transmitting them to a web-based platform, but without quantitative sensor accuracy assessment. Additionally, authors in [18] developed an IoT-based solar panel monitoring system for street lighting, smart communities, and microgrids, using a Raspberry Pi to measure current, voltage, and temperature and visualize data on a website. Similarly, authors in [25] implemented a real-time IoT monitoring system for Building-Integrated Photovoltaics (BIPVs) to track voltage, current, power, and irradiance, thereby improving transparency and management. However, their study did not evaluate sensor accuracy nor fully incorporate environmental variables.

III. MATERIALS AND METHODS

The design of the energy monitoring system (Figure 1) for solar-powered street lighting involves several key stages: system design, sensor and equipment calibration, and equipment testing.

The remote monitoring system for solar street lighting comprises the following components: solar panels, temperature and humidity sensors, sunlight intensity sensors, PV current and voltage sensors, battery current and voltage sensors, lamp voltage and current sensors, embedded systems, TFT screens, batteries, and web-based interfaces. The embedded system utilized in this study is the ESP32 V4, which functions as the central data processing unit, receiving the measurement data from all system components.

Data from the voltage and current sensors are transmitted to the ESP32 via the Modbus RS485 protocol with a sampling interval of 10 seconds. Outputs from temperature, humidity, and sunlight intensity sensors are transmitted directly to the ESP32's digital inputs with a sampling time of 2 seconds. The embedded processor calculates the output power of the PV system, battery, and lamps based on these measurements. Additionally, the embedded system controls a battery charge controller based on battery current and voltage readings. If the battery reaches full charge, the controller disconnects it to prevent overcharging, thereby prolonging battery lifespan

Measurement data, including temperature, humidity, sunlight intensity, current, voltage, and calculated power, are displayed on the TFT LCD and transmitted via the IoT module to a dedicated website (Figure 2). Upon activation, the ESP32 first verifies the internet connection. If a stable connection is present, it processes temperature, humidity, light intensity, voltage, and current data for display. The monitoring system workflow is illustrated in Figure 3.

A. *Sensor Specifications*

Temperature measurement in the monitoring system covers a range of 15 °C to 50 °C, with a sampling time of 1 second. The DS18B20 (Maxim Integrated, USA) sensor is used for temperature detection, offering a measurement range of -55 °C to 125 °C and an accuracy of ± 0.5 °C, producing a 12-bit digital output and operating on a supply voltage of 3-5.5 V. The sensor is connected to the ESP32 via digital input pins, as illustrated in Figure 3. A pull-up resistor is connected to the data pin to maintain a high logic level when no signal is transmitted, preventing floating conditions that could cause erroneous readings.

Humidity is measured within a range of 20%-90% with a resolution of 1%, using the DHT-21 (Aosong Electronics, China) sensor, which covers a range of 0-100%. The DHT-21 provides digital output via a single-wire Serial Data Line (SDA) and connects to the ESP32's digital input.

Light intensity is measured by the SEN0390 (DFRobot, China) sensor, which offers a range of up to 200,000 lux and an accuracy of 0.054 lux. Operating at 2.7-6 V with a current draw of 0.7 mA, it outputs digital data via the I^2C protocol, using the Serial Clock Line (SCL) for synchronization and the SDA for data transfer.

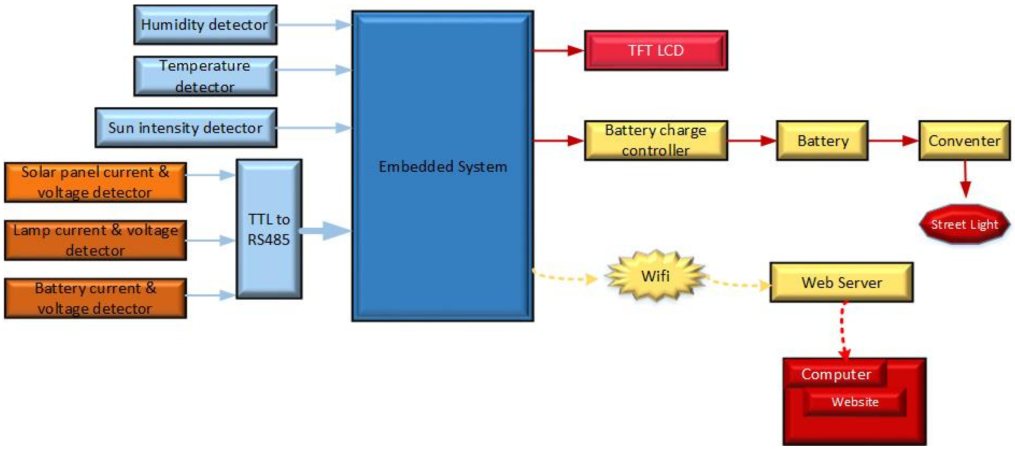
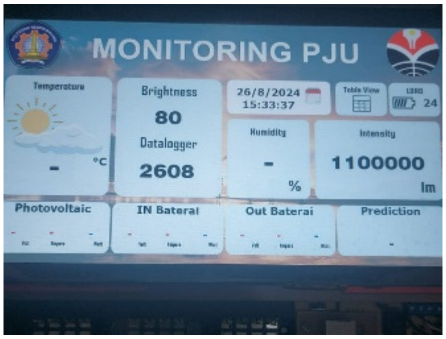


Fig. 1. Diagram of a solar-powered street lighting monitoring system.

Current and voltage for the PV system, batteries, and lamps are measured using the PZEM-017 (Peacefair, China) sensor, capable of measuring up to 300 V and 50 A. The sensor outputs digital data to the ESP32 via the Modbus RS485 protocol, with a TTL-to-RS485 module connected to the ESP32's TX0 and RX0 pins. The TFT LCD is connected to the ESP32's TX2 and RX2 pins for serial communication, as shown in Figure 4.

Before testing, all sensors and equipment were calibrated. Voltage and current readings from the PZEM-017 were validated against calibrated voltmeters and ammeters at various load levels. Humidity readings from the DHT-21 were compared with a standard HTC-1 hygrometer, and temperature readings from the DS18B20 were compared with a standard thermometer. Light intensity readings from the SEN0390 were validated against a UT-383 luxmeter. Differences between sensor outputs and reference instruments were recorded and applied as correction factors where necessary. Field testing was conducted over multiple days to verify measurement stability under varying environmental conditions.



MONITORING PJU

Temperature: - °C

Brightness: 80

Datalogger: 2608

26/8/2024 15:33:37

Table View

LOAD 24

Humidity: - %

Intensity: 1100000 lm

Photovoltaic

IN Baterai

Out Baterai

Prediction

Fig. 2. System monitor display.

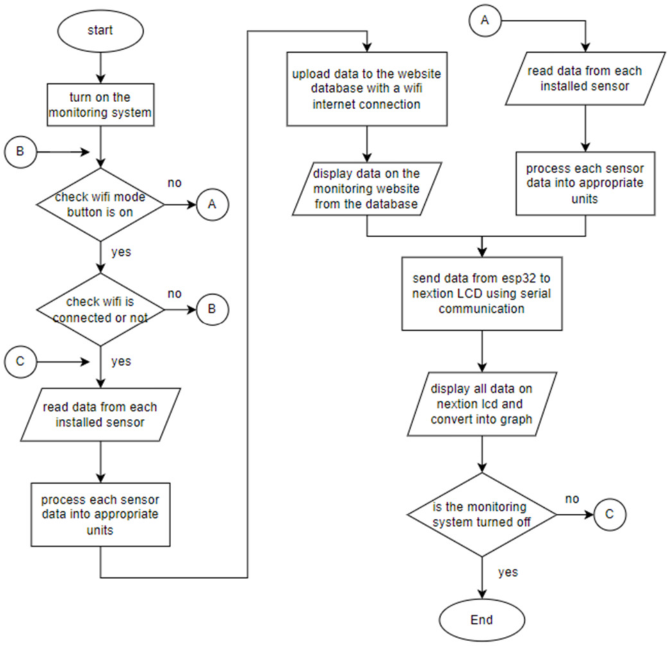


Fig. 3. The monitoring system flowchart.

IV. RESULTS AND DISCUSSION

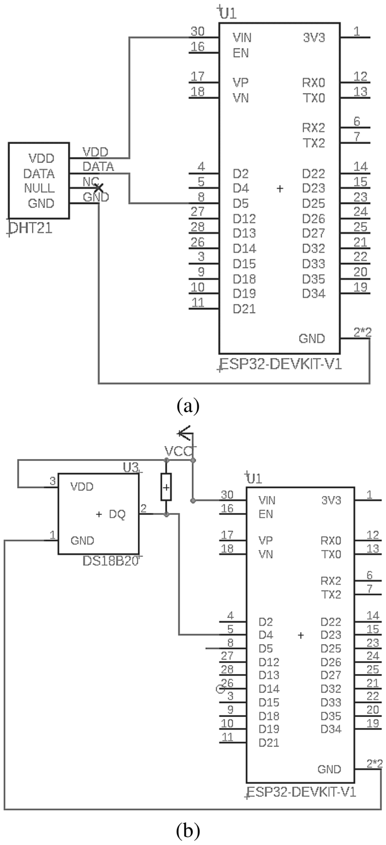
A. Sensor Performance

In this study, the metrics of sensitivity and accuracy were quantitatively derived from sensor calibration tests conducted against standard reference instruments. Sensitivity was defined as the slope of the linear regression between sensor outputs and corresponding reference measurements, representing how much the sensor output changes in response to variations in the true value. Accuracy was evaluated based on the Mean Absolute Percentage Error (MAPE) between the sensor readings and the reference instrument, calculated as:

$$Accuracy = 100\% - MAPE \qquad (1)$$

Figure 5 presents the Printed Circuit Board (PCB) design for the monitoring system, which serves as the central integration platform for all sensors and devices. The PCB consolidates the signal pathways, power supply circuits, and data communication interfaces, providing stable and reliable system operation. Following hardware assembly, sensor testing and calibration were carried out to verify sensor performance and quantify measurement errors. The percentage error of the sensor reading is determined based on the difference between the sensor reading M_{sensor} and the measurement results obtained with standard instruments $M_{instrument}$, as stated in (2):

$$Sensor\ error = \frac{M_{instrument} - M_{sensor}}{M_{instrument}} \cdot 100\% \qquad (2)$$



(a)

(b)

Fig. 4. (a) Humidity and (b) temperature detector circuit

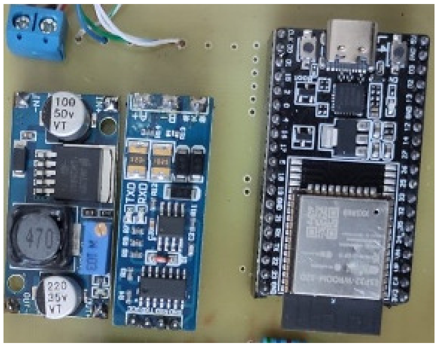


Fig. 5. Monitoring system circuit PCB board.

Figure 6 shows the results of temperature measurements using the DS18B20 sensor compared to a standard thermometer. The x-axis label "Data" denotes the sequential measurement index acquired during calibration tests. The temperature detector exhibited a mean error of 0.48 °C, ranging from 0.07 °C to 1.2 °C. The average percentage error for temperature measurement was 1.7%, corresponding to an accuracy of 98% and a sensitivity of 0.5 °C.

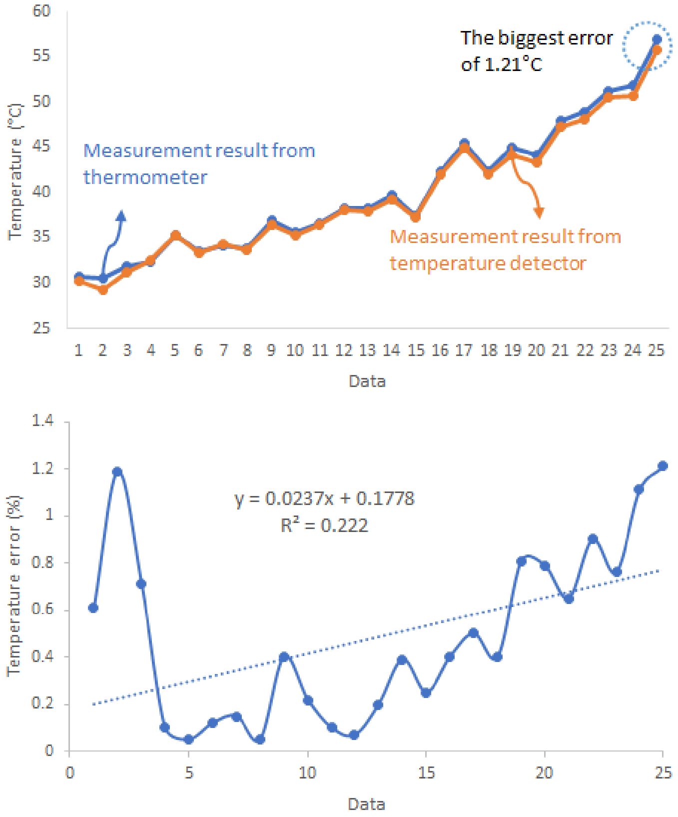


Fig. 6. Measurement result from the temperature detector and the error of the detector reading.

Humidity measurements of the sensor and reference instrument are illustrated in Figure 7. The DHT21 measured humidity levels within the 36%-90% range with a sensitivity of 1%. Compared with the reference instrument, it showed an average absolute error of 0.91% and a percentage error of 1.7%.

The performance of the PZEM-017 sensor was evaluated by comparison with a calibrated voltmeter and ammeter, as depicted in Figure 8. Based on testing results, voltage measurement errors ranged from 0.05 V to 1 V, with an average error of 1.6 V and a mean percentage error of 0.8%, yielding a sensitivity of 0.1 V and an accuracy of 99%. For current measurement, the sensor exhibited an average error of 0.02 A, with a maximum error of 0.1 A and an average percentage error of 1.5%, corresponding to a sensitivity of 0.01 A and an accuracy of 98%. Authors in [20] reported a PZEM voltage monitoring error below 1%; the lower error achieved in this study demonstrates improved measurement performance.

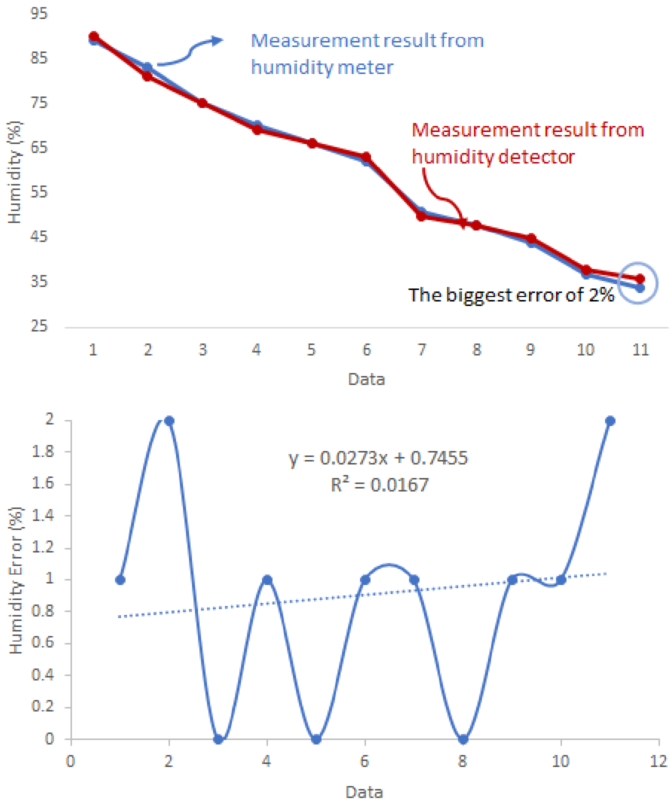


Fig. 7. Measurement result from the humidity detector and the error of the detector reading.

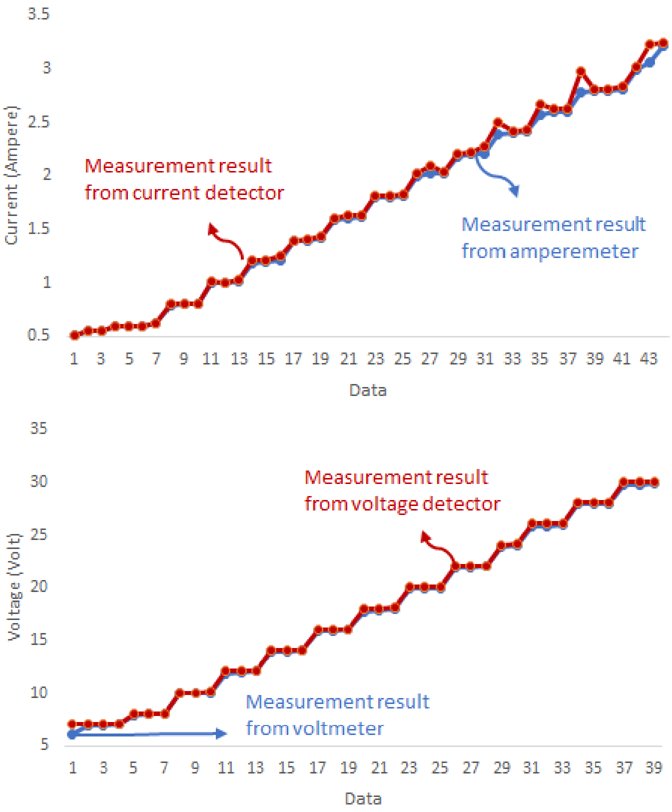


Fig. 8. Measurement result of the voltage and current detector.

The results of the light intensity sensor readings are compared with those of a standard UT-383 luxmeter, as shown in Figure 9. The largest recorded error in light intensity measurement was 250 lux, with an average error of 130 lux. The mean percentage error was approximately 5%, corresponding to an accuracy of 95%.

The final phase involved system-level testing of the complete monitoring equipment to ensure proper integration and reliable data display. Measurement results are shown on both the 7-inch TFT LCD and the web-based monitoring interface. The TFT LCD presents real-time data and tabulated measurement records, while the website provides both tabular and graphical representations of the monitored parameters. The monitoring homepage displays all active sensor data shown in Figure 10.

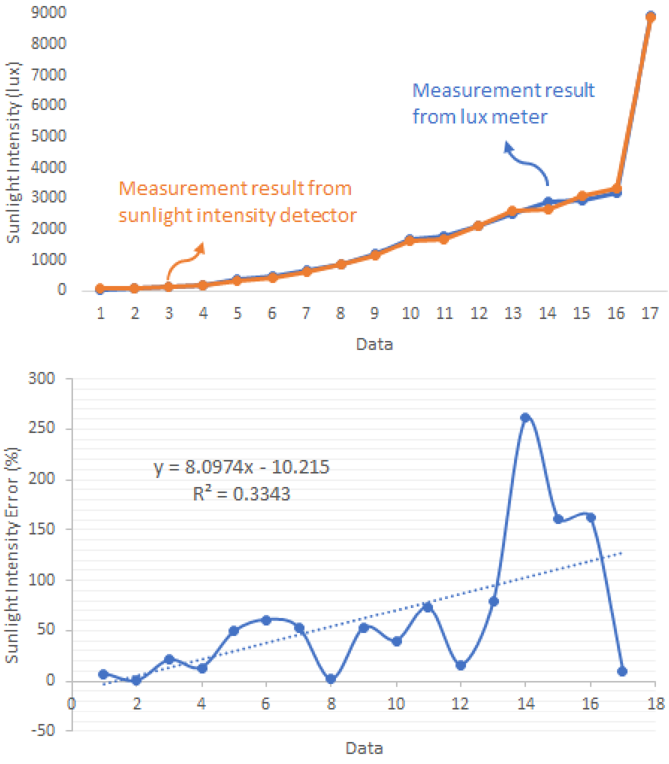
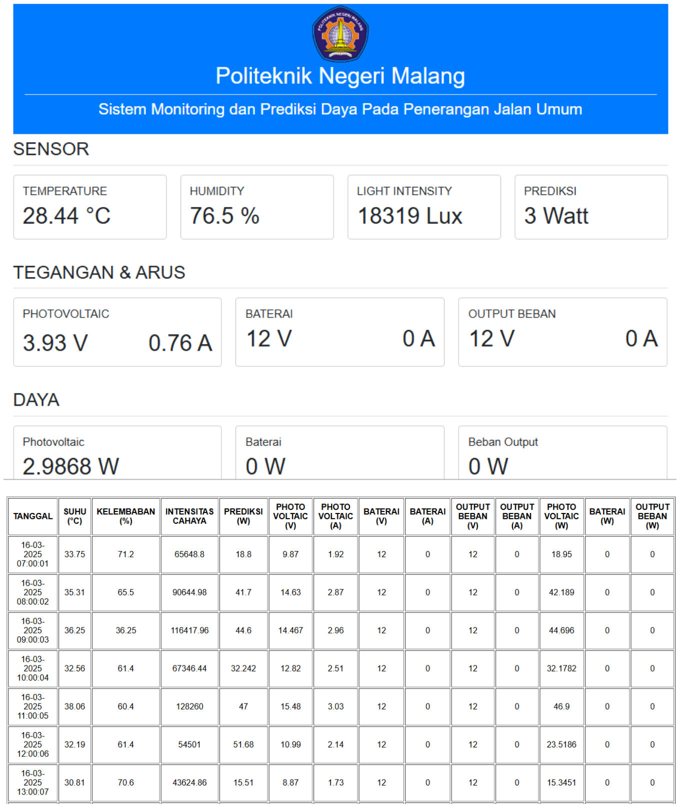


Fig. 9. Measurement result of the sunlight intensity detector.

B. *Real-Time Measurements*

Real-time measurements of temperature, humidity, sunlight intensity, and PV power were conducted continuously over three days in Malang City, East Java, Indonesia. Figure 11 presents the ambient temperature variations during this period. On the first day, the minimum temperature was 21.56 °C, while the maximum reached 38.06 °C at 11:00. On the second day, temperatures ranged from 19.06 °C to 42 °C, peaking again at 11:00. On the third day, the lowest temperature was 20.19 °C, and the highest, 41.31 °C, occurred at 12:00.

Figure 12 shows the ambient humidity results for the same period. On the first day, humidity varied between 60.4% (minimum at 11:00) and 85.3% (maximum). The second day recorded a range of 47.5% to 86%, with the lowest value also observed at 11:00. On the third day, humidity ranged between 48.6% (12:00) and 85.7% (maximum).


Politeknik Negeri Malang

Sistem Monitoring dan Prediksi Daya Pada Penerangan Jalan Umum

SENSOR

TEMPERATURE 28.44 °C

HUMIDITY 76.5 %

LIGHT INTENSITY 18319 Lux

PREDIKSI 3 Watt

TEGANGAN & ARUS

PHOTOVOLTAIC 3.93 V 0.76 A

BATERAI 12 V 0 A

OUTPUT BEBAN 12 V 0 A

DAYA

Photovoltaic 2.9868 W

Baterai 0 W

Beban Output 0 W

TANGGAL	SUHU (°C)	KELEMBABAN (%)	INTENSITAS CAHAYA	PREDIKSI (W)	PHOTO VOLTAIC (V)	PHOTO VOLTAIC (A)	BATERAI (V)	BATERAI (A)	OUTPUT BEBAN (V)	OUTPUT BEBAN (A)	PHOTO VOLTAIC (W)	BATERAI (W)	OUTPUT BEBAN (W)
16-03-2025 07:00:01	33.75	71.2	65648.8	18.8	9.87	1.92	12	0	12	0	18.95	0	0
16-03-2025 08:00:02	35.31	65.5	90644.98	41.7	14.63	2.87	12	0	12	0	42.189	0	0
16-03-2025 09:00:03	36.25	36.25	116417.96	44.6	14.467	2.96	12	0	12	0	44.696	0	0
16-03-2025 10:00:04	32.56	61.4	67346.44	32.242	12.82	2.51	12	0	12	0	32.1782	0	0
16-03-2025 11:00:05	38.06	60.4	128260	47	15.48	3.03	12	0	12	0	46.9	0	0
16-03-2025 12:00:06	32.19	61.4	54501	51.68	10.99	2.14	12	0	12	0	23.5186	0	0
16-03-2025 13:00:07	30.81	70.6	43624.86	15.51	8.87	1.73	12	0	12	0	15.3451	0	0

Fig. 10. Data logger display on website.

Figure 13 illustrates the measured sunlight intensity over the three days. On the first day, light intensity ranged from 8.65 lux to 128,260.2 lux at 11:00. On the second day, values spanned from 8.37 lux to 177,130.5 lux at 11:00, while on the third day, the intensity varied between 8.43 lux and its daily maximum at 11:00.

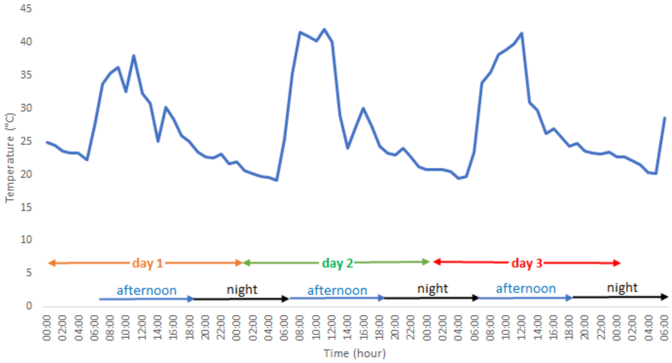


Fig. 11. Real-time temperature measurement results.

The highest temperature, lowest humidity, and maximum sunlight intensity consistently occurred between 11:00 and

12:00, corresponding to peak PV output. This relationship is confirmed by the current and voltage sensor data shown in Figure 14, where the maximum PV power outputs were 46.90 W (day 1, 11:00), 48.79 W (day 2, 12:00), and 50.21 W (day 3, 11:00).

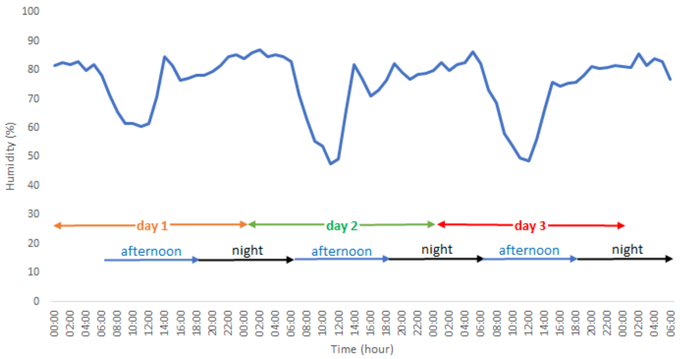


Fig. 12. Real-time humidity measurement results.

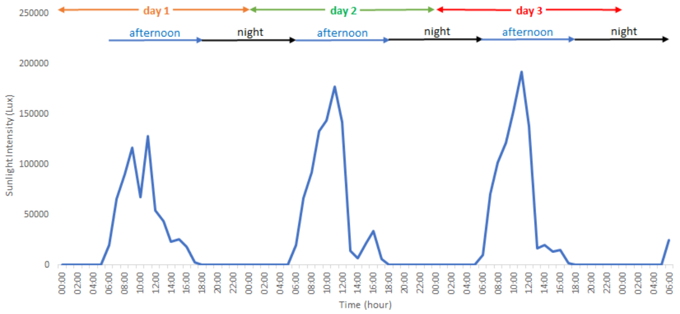


Fig. 13. Real-time sunlight intensity measurement results

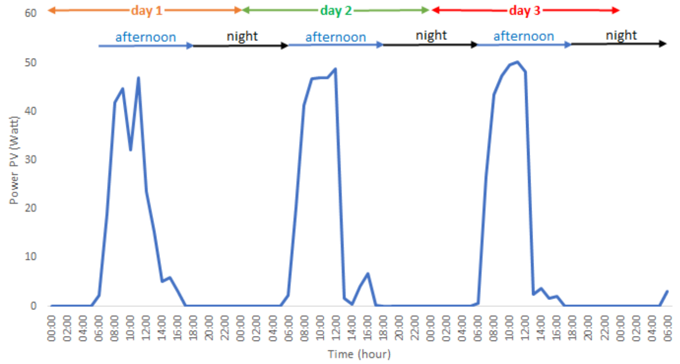


Fig. 14. Real-time PV power measurement results.

C. Advantages of the Proposed System

When compared to the BIPV monitoring system developed in [25], which focuses on real-time acquisition of voltage, current, power, and solar irradiance data through an IoT-based web interface, the system presented in this study is tailored for solar-powered street lighting applications. Both systems employ IoT architectures and microcontrollers (ESP32 or Arduino) with cloud-based data access. However, the proposed system extends functionality by including environmental parameters (temperature, humidity, and sunlight intensity) that directly affect power generation efficiency, while also providing local visualization via a TFT LCD screen.

A further distinction lies in the validation methodology. The present system emphasizes sensor calibration and verification using standard instruments, achieving a high accuracy level with average measurement errors below 2%. In contrast, authors in [25] primarily focus on system design and data visualization without reporting quantitative validation metrics. Similarly, authors in [29] did not include sensor validation or comparisons with reference instruments. Experimental testing of the proposed system demonstrates high performance, with consistently low average sensor errors. Measurement data can be accessed in real time via the web interface, consistent with previous studies [18, 25, 29], and are also displayed locally on the integrated TFT LCD.

V. CONCLUSION

The use of solar panels as a power source for street lighting significantly reduces dependence on fossil fuel-based electricity, thereby lowering energy costs and greenhouse gas emissions. However, continuous monitoring is essential to ensure adequate energy supply and reliable streetlight operation.

This study presented the design and validation of a solar street lighting monitoring system capable of measuring key parameters such as temperature, humidity, and sunlight intensity, which influence Photovoltaic (PV) panels' performance. Electrical parameters, including the current and voltage of the solar panel, battery, and lamp, were also monitored to calculate power output. The ESP32 microcontroller employed processed sensor data, displayed it on a 7-inch Thin Film Transistor (TFT) Liquid Crystal Display (LCD), and uploaded it to a dedicated cloud for web-based access.

Performance validation against standard instruments yielded average percentage errors of 1.7% for temperature and humidity, 0.8% for voltage, and 1.5% for current. These results demonstrate that the proposed system delivers accurate and reliable measurements while supporting efficient real-time monitoring of solar-powered street lighting systems.

ACKNOWLEDGMENT

The authors gratefully acknowledge the State Polytechnic of Malang for supporting this research through a domestic collaborative research funding scheme.

REFERENCES

[1] S. Sarkar, K. Mohan, and P. Vankhande, "Smart street-lighting using green energy designing a novel stand-alone solar powered lighting system," in 2017 International Conference on Intelligent Computing and Control Systems (ICICCS), Madurai, Jun. 2017, pp. 157–163, https://doi.org/10.1109/ICCONS.2017.8250701.

[2] A. Thungtong, C. Chaichan, and K. Suwannarat, "A web-based control system for traditional street lighting that uses high-pressure sodium lamps," *Heliyon*, vol. 7, no. 11, Nov. 2021, Art. no. e08329, https://doi.org/10.1016/j.heliyon.2021.e08329.

[3] M. Mahoor, F. R. Salmasi, and T. A. Najafabadi, "A Hierarchical Smart Street Lighting System With Brute-Force Energy Optimization," *IEEE Sensors Journal*, vol. 17, no. 9, pp. 2871–2879, May 2017, https://doi.org/10.1109/JSEN.2017.2684240.

[4] M. S. B. S. Rizam, Md. T. Nooritawati, J. Haffiz, and M. Y. Yusnani, "Solar streetlight remote monitoring system using WASPMOTE wireless sensor network module (WSN) for system efficiency enhancement," in *2014 IEEE Conference on Systems, Process and Control (ICSPC 2014)*, Kuala Lumpur, Malaysia, Dec. 2014, pp. 153–156, https://doi.org/10.1109/SPC.2014.7086248.

[5] A. Y. Jaen-Cuellar, D. A. Elvira-Ortiz, R. A. Osornio-Rios, and J. A. Antonino-Daviu, "Advances in Fault Condition Monitoring for Solar Photovoltaic and Wind Turbine Energy Generation: A Review," *Energies*, vol. 15, no. 15, Jul. 2022, Art. no. 5404, https://doi.org/10.3390/en15155404.

[6] A. Peinado Gonzalo, A. Pliego Marugán, and F. P. García Márquez, "Survey of maintenance management for photovoltaic power systems," Renewable and Sustainable Energy Reviews, vol. 134, Dec. 2020, Art. no. 110347, https://doi.org/10.1016/j.rser.2020.110347.

[7] L. Hernández-Callejo, S. Gallardo-Saavedra, and V. Alonso-Gómez, "A review of photovoltaic systems: Design, operation and maintenance," *Solar Energy*, vol. 188, pp. 426–440, Aug. 2019, https://doi.org/10.1016/j.solener.2019.06.017.

[8] D. Gaurav, D. Mittal, B. Vaidya, and J. Mathew, "A GSM based low cost weather monitoring system for solar and wind energy generation," in *The Fifth International Conference on the Applications of Digital Information and Web Technologies (ICADIWT 2014)*, Bangalore, India, Feb. 2014, pp. 1–7, https://doi.org/10.1109/ICADIWT.2014.6814689.

[9] C. M. C. Creayla, F. C. C. Garcia, and E. Q. B. Macabebe, "Next Day Power Forecast Model Using Smart Hybrid Energy Monitoring System and Meteorological Data," *Procedia Computer Science*, vol. 105, pp. 256–263, 2017, https://doi.org/10.1016/j.procs.2017.01.219.

[10] S. Karad and R. Thakur, "Efficient monitoring and control of wind energy conversion systems using Internet of things (IoT): a comprehensive review," *Environment, Development and Sustainability*, vol. 23, no. 10, pp. 14197–14214, Oct. 2021, https://doi.org/10.1007/s10668-021-01267-6.

[11] E. I. Archibong, S. Ozuomba, and E. Ekott, "Internet of Things (IoT)-based, Solar Powered Street Light System with Anti-vandalisation Mechanism," in *2020 International Conference in Mathematics, Computer Engineering and Computer Science (ICMCECS)*, Ayobo, Nigeria, Mar. 2020, pp. 1–6, https://doi.org/10.1109/ICMCECS47690.2020.240867.

[12] M. R. Hans and M. A. Tamhane, "IoT based Hybrid Green Energy driven Street Lighting System," in *2020 Fourth International Conference on I-SMAC (IoT in Social, Mobile, Analytics and Cloud) (I-SMAC)*, Palladam, India, Oct. 2020, pp. 35–41, https://doi.org/10.1109/I-SMAC49090.2020.9243365.

[13] M. Saifuzzaman, S. F. Shetu, N. N. Moon, F. N. Nur, and M. H. Ali, "IoT Based Street Lighting Using Dual Axis Solar Tracker and Effective Traffic Management System Using Deep Learning: Bangladesh Context," in *2020 11th International Conference on Computing, Communication and Networking Technologies (ICCCNT)*, Kharagpur, India, Jul. 2020, pp. 1–5, https://doi.org/10.1109/ICCCNT49239.2020.9225590.

[14] Y. Luo, Z. Chen, J. Li, and K. Sun, "Design of Solar Dual Streetlight Control System Based on Microcontroller," in *2022 International Conference on Artificial Intelligence and Autonomous Robot Systems (AIARS)*, Bristol, United Kingdom, Jul. 2022, pp. 196–201, https://doi.org/10.1109/AIARS57204.2022.00051.

[15] E. Belloni, A. Massaccesi, C. Moscatiello, and L. Martirano, "Stand-Alone LED Lighting System Powered by PV and Battery: Electrical Overall Performance Analysis of a Case Study," *IEEE Transactions on Industry Applications*, vol. 60, no. 3, pp. 5142–5149, May 2024, https://doi.org/10.1109/TIA.2024.3351091.

[16] A. Kama, M. Diallo, M. S. Drame, M. L. Ndiaye, A. Ndiaye, and P. A. Ndiaye, "Monitoring the Performance of Solar Street Lights in Sahelian Environment: Case Study of Senegal," in *2017 10th International Conference on Developments in eSystems Engineering (DeSE)*, Paris, France, Jun. 2017, pp. 56–61, https://doi.org/10.1109/DeSE.2017.43.

[17] E. R. B. Sajonia and L. M. Dagsa, "IoT-Based Smart Street Light Monitoring System with Kalman Filter Estimation," in *2021 6th International Conference on Development in Renewable Energy Technology (ICDRET)*, Dhaka, Bangladesh, Dec. 2021, pp. 1–5, https://doi.org/10.1109/ICDRET54330.2021.9751792.

[18] G. V. Bhau, R. G. Deshmukh, T. R. Kumar, S. Chowdhury, Y. Sesharao, and Y. Abilmazhinov, "IoT based solar energy monitoring system," *Materials Today: Proceedings*, vol. 80, pp. 3697–3701, 2023, https://doi.org/10.1016/j.matpr.2021.07.364.

[19] B. K. Subramanyam, K. B. Reddy, and P. A. K. Reddy, "Design and development of intelligent wireless street light control and monitoring system along with GUI," *International Journal of Engineering Research and Applications (IJERA)*, vol. 3, no. 4, pp. 2115–2119, Aug. 2013.

[20] H. Sujono, "Drip Irrigation Control System based on Mamdani Fuzzy Logic and Internet of Things (IoT)," *PRZEGLĄD ELEKTROTECHNICZNY*, vol. 1, no. 1, pp. 65–69, Jan. 2024, https://doi.org/10.15199/48.2024.01.13.

[21] T. Inthasuth, "Integrating Face Detection and Energy Monitoring for Enhanced Energy Suitability in Room Environments," *PRZEGLĄD ELEKTROTECHNICZNY*, vol. 1, no. 5, pp. 176–179, May 2024, https://doi.org/10.15199/48.2024.05.32.

[22] M. M. A. Zahra *et al.*, "Battery Charging Monitoring System Using PZEM 004t Sensor and DC Voltage Sensor," *International Journal of Renewable Energy Research*, vol. 13, no. 2, pp. 666-672, Jun. 2023, https://doi.org/10.20508/ijrer.v13i2.14152.g8736.

[23] N. Watjanatepin *et al.*, "Automated agricultural greenhouse with PV energy using IoT-based monitoring system," *International Journal of Renewable Energy Research*, vol. 13, no. 4, pp. 1581-1591, Dec. 2023. https://doi.org/10.20508/ijrer.v13i4.14228.g8836.

[24] V. Kulkarni *et al.*, "Air Quality Decentralized Forecasting: Integrating IoT and Federated Learning for Enhanced Urban Environmental Monitoring," *Engineering, Technology & Applied Science Research*, vol. 14, no. 4, pp. 16077–16082, Aug. 2024, https://doi.org/10.48084/etasr.7869.

[25] A. Ftirich, B. Bouaziz, and F. Bacha, "Real-Time Monitoring for a Building-Integrated Photovoltaic System based on the Internet of Things and a Web Application," *Engineering, Technology & Applied Science Research*, vol. 14, no. 4, pp. 15931–15937, Aug. 2024, https://doi.org/10.48084/etasr.7531.

[26] S. M. Maturi, S. R. Dhanikonda, and S. Giddaluru, "Smart Dustbins: Real-Time Monitoring and Optimization for Waste Management in Smart Cities through IoT Devices," *Engineering, Technology & Applied Science Research*, vol. 15, no. 1, pp. 19246–19252, Feb. 2025, https://doi.org/10.48084/etasr.8562.

[27] P. Chiradeja, S. Yoomak, and A. Ngaopitakkul, "Economic Analysis of Improving the Energy Efficiency of Nanogrid Solar Road Lighting Using Adaptive Lighting Control," *IEEE Access*, vol. 8, pp. 202623–202638, 2020, https://doi.org/10.1109/ACCESS.2020.3035702.

[28] M. Aghaei *et al.*, "Autonomous Intelligent Monitoring of Photovoltaic Systems: An In-Depth Multidisciplinary Review," *Progress in Photovoltaics: Research and Applications*, vol. 33, no. 3, pp. 381–409, Mar. 2025, https://doi.org/10.1002/pip.3859.

[29] A. Mimouni, Y. Chahet, A. El Amrani, M. El Amraoui, and L. Bejjit, "Internet of Things Technology for an Autonomous Photovoltaic Solar Energy System Monitoring," *E3S Web of Conferences*, vol. 601, Jan. 2025, Art. no. 00056, https://doi.org/10.1051/e3sconf/202560100056.