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Prototype Smart Street Light System with PV Source

Asnal Effendi[1], Arfita Yuana Dewi[2], Rezi Satiawan[1]
[1] Department of Electrical Installation Engineering Technology, Institut Teknologi Padang, Indonesia
[2] Department of Electrical Engineering, Institut Teknologi Padang, Indonesia

Corresponding Author:

Arfita Yuana Dewi

Department of Electrical Engineering
Institut Teknologi Padang
Padang, West Sumatra Barat

E-mail:
arfitarachman.itp@gmail.com

ABSTRACT

This study presents the design and development of a photovoltaic (PV)-based smart public street lighting system integrated with Internet of Things (IoT) technology for real-time monitoring and adaptive energy management. The system utilizes solar panels as the primary energy source, with energy stored in a $LiFePO_4$ battery and monitored using a PZEM-017 sensor via RS485 communication. An ESP8266 microcontroller serves as the main control and communication unit, enabling remote monitoring and control through the Blynk application. Key operational parameters, including PV voltage, battery voltage, state of charge (SOC), and lamp power consumption, are continuously monitored in real time. To improve energy efficiency, a passive infrared (PIR) sensor is implemented to enable adaptive lighting, allowing the lamp to operate in dim mode under no-motion conditions and switch to full brightness when movement is detected. Experimental results show that during daytime operation the PV voltage reached up to 4 V with a battery SOC of approximately 66%, while at night the lamp consumed 8–9 W during motion detection and only 0.8–0.9 W in dim mode. These results demonstrate that the proposed system effectively reduces energy consumption while maintaining adequate lighting performance. The developed prototype provides an efficient, reliable, and integrated solution for smart street lighting, particularly suitable for energy-saving applications in resource-constrained environments.

Keywords: Smart street lighting, Photovoltaic system, Internet of Things, Energy monitoring, PIR-based dimming

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1. Introduction

Public street lighting (PJU) plays a vital role in supporting nighttime activities and ensuring safety in public road environments [1], [2], [3]. However, conventional street lighting systems that rely on manual switches are inefficient in terms of energy consumption, operational management, and human resources [4], [5]. Manual operation makes it difficult to ensure timely switching of lamps and often leads to unnecessary energy use, especially when lighting operates at full intensity regardless of actual needs or environmental conditions [6], [7]. As a result, electricity consumption and operational costs tend to increase, while system monitoring and maintenance remain limited [1], [2], [3], [4], [8].

To address these issues, various control methods have been developed. Time-based control systems allow streetlights to turn on and off at predetermined schedules, while light-intensity-based systems use sensors to respond to ambient lighting conditions [5], [6], [7], [9], [10]. Other studies have incorporated solar energy as an alternative power source to reduce dependence on the grid and lower operational costs [8], [9], [10], [11], [16]. In addition, sensor-based approaches using PIR, ultrasonic, or LDR sensors have been applied to adjust lamp brightness based on motion or environmental conditions [12], [13], [14], [17], [18]. Despite these advancements, most existing systems focus primarily on basic automation and lack integrated real-time monitoring of energy performance, battery condition, and system efficiency, which are crucial for effective maintenance and long-term operation [19], [20], [21].

This research proposes an IoT-based smart street lighting system powered by photovoltaic energy, integrating real-time energy monitoring and adaptive lighting control within a single platform [22], [23]. Unlike previous works, this study combines PV performance monitoring (voltage, current, and power), battery condition monitoring (state of charge and voltage), and lamp power consumption analysis using a PZEM-017 sensor and ESP8266 microcontroller [24], [25], [26]. The integration with a cloud-based monitoring application enables real-time data visualization and remote supervision [27], [28]. The novelty of this research lies in the comprehensive integration of energy monitoring and PIR-based dimming control, providing quantitative data that supports data-driven evaluation and maintenance decisions—an aspect that has not been widely implemented in conventional smart street lighting systems [15], [29], [30].

The objective of this research is to design and develop a prototype of a photovoltaic-based smart public street lighting system that is capable of adaptive lighting control and real-time energy monitoring through IoT technology [22], [23]. Specifically, this study aims to improve energy efficiency, reduce power consumption, and enhance system reliability by utilizing PIR-based dimming and continuous monitoring of PV and battery performance [18], [24], [25]. The proposed system is expected to offer an efficient and practical solution for sustainable street lighting applications, particularly in areas with limited energy resources [16], [20].

2. Research method

This research employs an engineering-based experimental method to design, develop, and evaluate a photovoltaic (PV)-based smart public street lighting system integrated with Internet of Things (IoT) technology [1], [4]. The research procedure consists of several systematic stages, including literature review, system design, prototype development, testing, data collection, analysis, and conclusion [5], [15], [22]. This structured approach ensures that the developed system meets functional requirements and performance objectives effectively [1], [4], [5], [15], [23].

The literature review stage was conducted to identify existing problems in conventional and smart street lighting systems, as well as to examine previously proposed solutions related to PV-based lighting, sensor-based control, and IoT monitoring [6], [8], [9], [10], [11], [16]. Based on this review, a needs analysis was performed to determine the required hardware and software components [19], [20]. The system design phase involved the development of block diagrams and flowcharts that describe the operational logic and interaction between system components [21], [22]. These designs were then implemented during the prototype construction stage, where all components were assembled and integrated into a functional system, as illustrated in Figure 1 [23], [24].

The proposed smart street lighting system operates by utilizing solar energy as the primary power source [8], [9], [16]. During daytime operation, energy generated by the photovoltaic panel is used to charge a $LiFePO_4$ battery through a charge control mechanism, while key electrical parameters such as voltage and current are monitored using a PZEM-017 sensor [24], [25], [26]. At night, the system switches to lighting mode, where a DC lamp operates under adaptive control [12], [13]. A passive infrared (PIR) sensor detects the presence of moving objects, allowing the system to dynamically adjust lamp brightness between dim mode and full illumination [14], [17], [18]. An ESP8266 microcontroller functions as the central control unit, processing sensor data and managing system operation while transmitting monitoring data to the Blynk application via Wi-Fi [27], [28], [29].

The testing and data collection stage was carried out to evaluate system performance under real operating conditions [19], [20]. Measurements included PV voltage and current, battery voltage, state of charge (SOC), and lamp power consumption during both motion-detected and no-motion conditions [24], [25], [26], [30]. Data were collected hourly during daytime and nighttime operation to observe system behavior under varying environmental conditions, particularly changes in solar irradiance [16], [20]. The collected data were then analyzed to assess energy efficiency, system reliability, and the effectiveness of PIR-based dimming control [18], [21], [23]. The results of this analysis form the basis for evaluating the feasibility and performance of the proposed smart street lighting system.

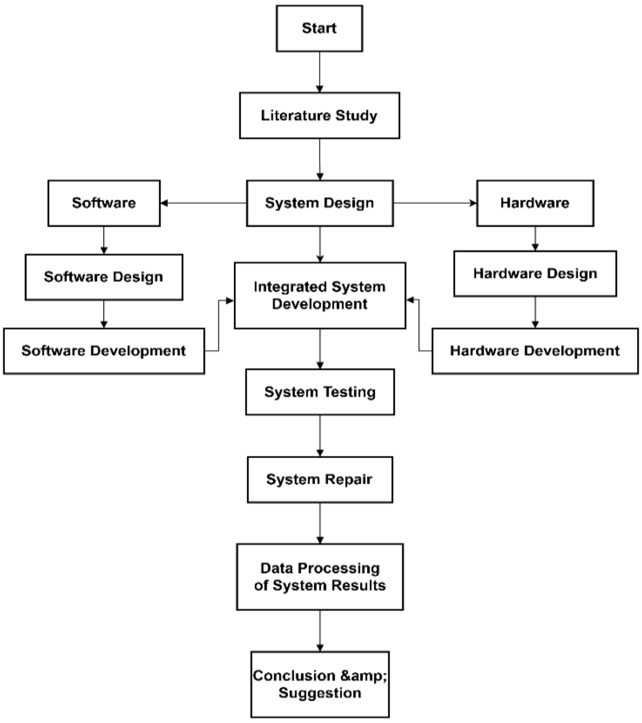


Figure 1. Research flowchart of the proposed smart street lighting system

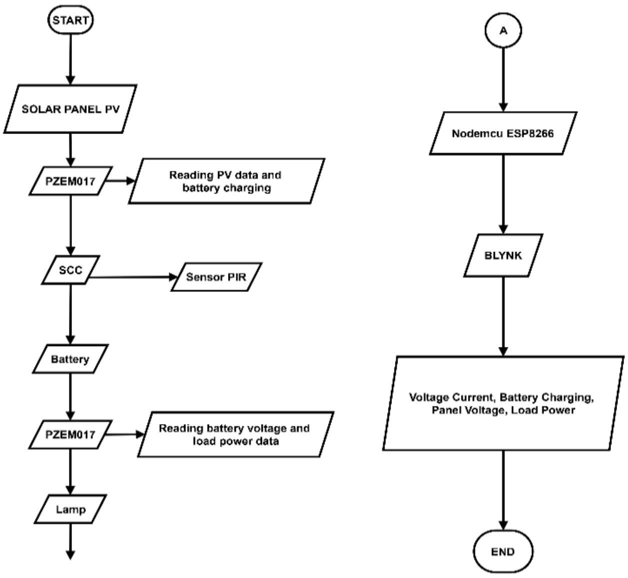


Figure 2. Research flowchart of the proposed smart street lighting system

3. Results and discussion

The developed PV-based smart street lighting prototype integrates solar energy generation, energy storage, adaptive lighting control, and IoT-based monitoring into a single system, as illustrated in Figure 2. The monitoring system enables real-time observation of key electrical parameters, including PV voltage and current, battery voltage, state of charge (SOC), and lamp power consumption through the Blynk application. This integration allows the system to not only operate autonomously but also provide continuous feedback regarding energy flow and system performance.

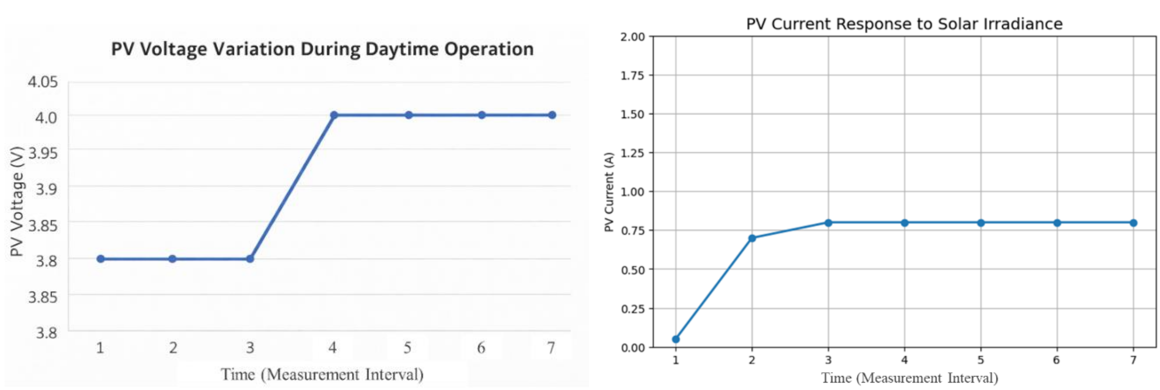
During daytime operation, the photovoltaic panel acts as the primary energy source, charging the $LiFePO_4$ battery while system parameters are monitored using the PZEM-017 sensor. At night, the system transitions to lighting mode, where the lamp operation is controlled adaptively based on motion detection using the PIR sensor. This operational scheme ensures that energy usage is aligned with actual lighting demand, which is essential for improving efficiency and extending battery lifespan.

Table 1. Six-Step PWM Simulation Efficiency Results

Measurement time	PV-Voltage (V)	PV Current (A)	Soc battery (%)	Lamp (W)	Battery Voltage (V)
09.30 - 10.30	3,7	0,7	40	0	3,0
10.30 - 11.30	3,8	0,7	42	0	3,0
11.30 - 12.30	3,7	0,7	42	0	3,1
12.30 - 13.30	4	0,8	43	0	3,1
13.30 - 14.30	4	0,8	44	0	3,1
14.30 - 15.30	3,7	0,7	45	0	3,1
15.30 - 16.30	3,6	0,7	44	0	3,1
19.00 – 20.00	0	0	44	9 (people)	3,1
Total	3,8	0.7	43	0.9 (no people)	3,0

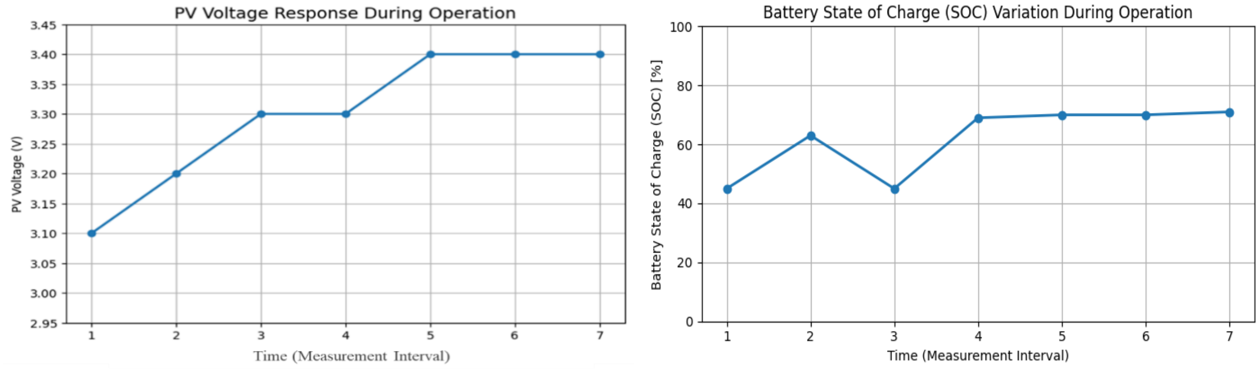
Table 1 presents the monitoring results obtained during system testing under varying environmental conditions. The PV voltage ranged from 3.6 V to 4.0 V during daylight hours, with the highest values occurring between 12.30 and 14.30 WIB. This trend indicates optimal solar irradiance during midday, which directly contributes to improved battery charging performance. Correspondingly, the PV current increased from 0.7 A to a peak of 0.8 A during the same period, demonstrating a positive correlation between solar intensity and energy generation. The battery SOC gradually increased from 40% in the morning to approximately 45% in the afternoon, confirming that the charging process operated effectively throughout the day. Battery voltage remained relatively stable around 3.0–3.1 V during charging, indicating proper battery regulation and the absence of overcharging or excessive voltage fluctuation. These results confirm that the PV charging subsystem and battery management performed reliably under real operating conditions.

The photovoltaic electrical characteristics during daytime operation are illustrated in Figure 3. As shown in Figure 3(a), the PV voltage exhibits an increase during peak sunlight hours, reaching a maximum value of 4 V. Meanwhile, Figure 3(b) shows that the PV current follows a similar trend, increasing from 0.7 A to 0.8 A during periods of higher solar intensity. The simultaneous increase in PV voltage and current indicates effective energy harvesting under real outdoor conditions and supports the battery charging process. The battery charging behavior during daytime operation is presented in Figure 4. As shown in Figure 4(a), the battery voltage remains relatively stable during the charging process, indicating proper voltage regulation and safe charging conditions. In addition, Figure 4(b) shows a gradual increase in battery SOC from 40% to approximately 45%, confirming balanced energy storage and effective utilization of the harvested solar energy.



(a) (b)

Figure 3. Photovoltaic electrical characteristics during daytime operation: (a) PV voltage and (b) PV current



(a) (b)

Figure 4. Battery charging characteristics during daytime operation: (a) battery voltage and (b) battery state of charge (SOC)

At night (19.00–20.00 WIB), the PV output dropped to zero as expected, and the system relied entirely on battery energy. Under these conditions, the lamp power consumption varied depending on PIR sensor activation. When motion was detected, the lamp operated at full brightness with a power consumption of approximately 8–9 W, while in the absence of motion the lamp remained in dim mode, consuming only 0.8–0.9 W. This significant reduction in power consumption highlights the effectiveness of PIR-based dimming in conserving energy. Table 2 further illustrates battery voltage behavior during nighttime operation with DC lamp loading. The battery voltage decreased slightly from 3.4 V at 18.00 WIB to 3.3 V at 21.00 WIB, indicating a controlled and gradual discharge process. This behavior confirms that adaptive lighting control contributes to reducing battery discharge rates, thereby extending operational duration during nighttime hours.

Table 2. Six-Step PWM Simulation Efficiency Results

Time	Battery Voltage (V)
18.00	3,4
19.00	3,4
20.00	3,4
21.00	3,3

Figure 5(a) and Figure 5(b) illustrate lamp operation under PIR-based adaptive control. As shown in Fig. 5(a), when motion is detected by the PIR sensor, the lamp operates in full-brightness mode, consuming approximately 8 W and providing adequate illumination within a detection range of up to 8 meters in front and 7 meters on the sides. In contrast, as shown in Fig. 5(b), when no motion is detected, the lamp operates in dim mode with power consumption reduced to approximately 0.8 W. Despite the reduced brightness, the lamp remains sufficiently visible for basic illumination while significantly lowering energy usage. This adaptive lighting strategy demonstrates the effectiveness of PIR-based control in reducing energy consumption while maintaining reliable street lighting performance.

(a) (b)

Figure 5. Lamp operation under PIR-based adaptive control: (a) full-brightness mode with motion detection and (b) dim mode without motion detection

4. Conclusions

This study has successfully developed a photovoltaic (PV)-based smart public street lighting system integrated with Internet of Things (IoT) technology for real-time monitoring and adaptive control. The proposed system enables continuous monitoring of PV voltage and current, battery voltage, state of charge (SOC), and lamp power consumption through a cloud-based application. Experimental results show that the PV subsystem can deliver up to 4 V and 0.8 A under optimal sunlight conditions, allowing effective battery charging with stable battery voltage in the range of 3.0–3.4 V during charging and discharging cycles, which confirms reliable energy management and system stability.

Furthermore, the implementation of PIR-based adaptive dimming significantly improves energy efficiency during nighttime operation. The streetlamp operates at full brightness with a power consumption of approximately 8–9 W when motion is detected, and automatically switches to dim mode with a reduced power consumption of approximately 0.8–0.9 W in the absence of motion. This adaptive lighting strategy effectively reduces overall energy consumption while maintaining adequate illumination for safety. The results indicate that the proposed system is suitable for sustainable and energy-efficient public street lighting applications, particularly in tropical and resource-constrained environments.

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