

# Optimizing Solar Streetlight Systems for Sustainable Urban and Community Development

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## ABSTRACT

Solar streetlight systems, powered by photovoltaic panels, are increasingly adopted as sustainable alternatives to conventional streetlights due to their environmental, economic, and operational advantages. They reduce dependency on non-renewable energy, lower electricity costs, and extend system lifespan, making them highly relevant for urban and community development. Despite these benefits, their efficiency and feasibility are often constrained by battery size and weight. Large batteries not only increase material and installation costs but also demand specialized handling equipment, which complicates deployment and maintenance. Addressing this challenge requires an optimized approach that balances performance with cost-effectiveness. This study presents the design and evaluation of a solar streetlight system incorporating an optimized battery size supported by improved energy management strategies. The research involved determining the optimal tilt angle of the solar panel to maximize power generation under varying environmental conditions. Additionally, a smart LED control algorithm was developed to minimize energy consumption by dynamically adjusting light output based on demand and availability of stored energy. Through these enhancements, the system effectively reduced energy wastage, leading to the identification of the most efficient and practical battery capacity. The findings demonstrate that optimizing both energy generation and consumption not only reduces reliance on oversized batteries but also lowers installation complexity and costs. Such advancements highlight the potential of solar streetlight systems as scalable, sustainable solutions for urban and community development. Ultimately, the proposed approach contributes to promoting greener infrastructure while ensuring long-term reliability and affordability of public lighting systems.

**Keywords:** Solar streetlights, Battery optimization, Sustainable urban infrastructure, Energy efficiency, Community development

## INTRODUCTION

Street lighting is a crucial public service that enhances safety for pedestrians and road users (Elakya et al., 2018). With the global shift towards renewable energy sources, there is a growing demand for efficient and reliable lighting solutions. Consequently, solar streetlights are gaining popularity due to their ability to reduce energy costs and lower carbon footprints. Advances in the design and technology of solar streetlights have further improved their efficiency and effectiveness. Current solar streetlight systems offer numerous benefits, including positive environmental impact, lower electrical and installation costs, and extended lifespan (Zahari et al., 2020; Abed et al., 2020; Ambhore et al., 2020). However, many contemporary solar streetlights are equipped with oversized backup storage to enhance reliability, ensuring continued operation despite insufficient solar input. This oversizing, however, can lead to unnecessary costs and energy wastage. Additionally, energy waste is prevalent in current streetlight systems due to the lack of smart LED control algorithms (P. H. Liew and Z. A.

Akasah, 2019; D'souza et al., 2018; Sharma et al., 2014), resulting in lights operating at full intensity even when not needed, such as during low-traffic periods at midnight.

An auto-intensity streetlight system, which adjusts lighting based on real-time conditions, offers a solution to reduce electrical wastage and costs. Solar panels are the sole source of electrical energy for solar streetlights. Therefore, optimizing the placement of these panels is crucial for maximizing energy generation and system efficiency (Wong Tsun Kiong, 2014; Dandu and Sarla, 2022; Mumtaz et al., 2018). According to Shams et.al. (2020), incorporating a Maximum Power Point Tracking (MPPT) system can maximize solar power utilization. A project introduced by Kuamthab and Mustafa (2021) minimizes energy loss by using Light Dependent Resistor (LDR) and Infrared (IR) sensors to control LEDs, increasing lighting intensity only when vehicles are present. Yahya and Aziz (2021) proposed a smart street lighting system with Passive Infrared (PIR) and LDR sensors was proposed, resulting in a 44% reduction in power consumption, while Kiwan et.al. (2018) developed a smart control mechanism to extend battery life by preventing over-discharge. An IoT-based solar system was also presented to monitor various system parameters, perform data logging, and enable remote monitoring (Shivaleelavathi et al., 2018).

Most existing studies have not focused on optimizing battery size within the system. Therefore, this paper proposes a smart solar streetlight system featuring an optimized solar panel tilt angle to enhance efficiency and a smart LED control algorithm to reduce power consumption. Additionally, various system parameters are transmitted to the ThingSpeak platform for data storage and analysis.

## METHODS

In this section, we present the initial conceptual framework for the proposed system, detailing the core components, design principles, and methodologies employed. This preliminary design serves as the foundational blueprint, guiding the subsequent development phases and ensuring alignment with the project's objectives and specifications. This section explores both simulated and practical methodologies in hardware design. We examine the theoretical models and simulation techniques used to predict system performance and identify potential issues before implementation. Additionally, we discuss hands-on approaches and experimental practices that validate these simulations, providing a robust framework for developing reliable and efficient hardware solutions.

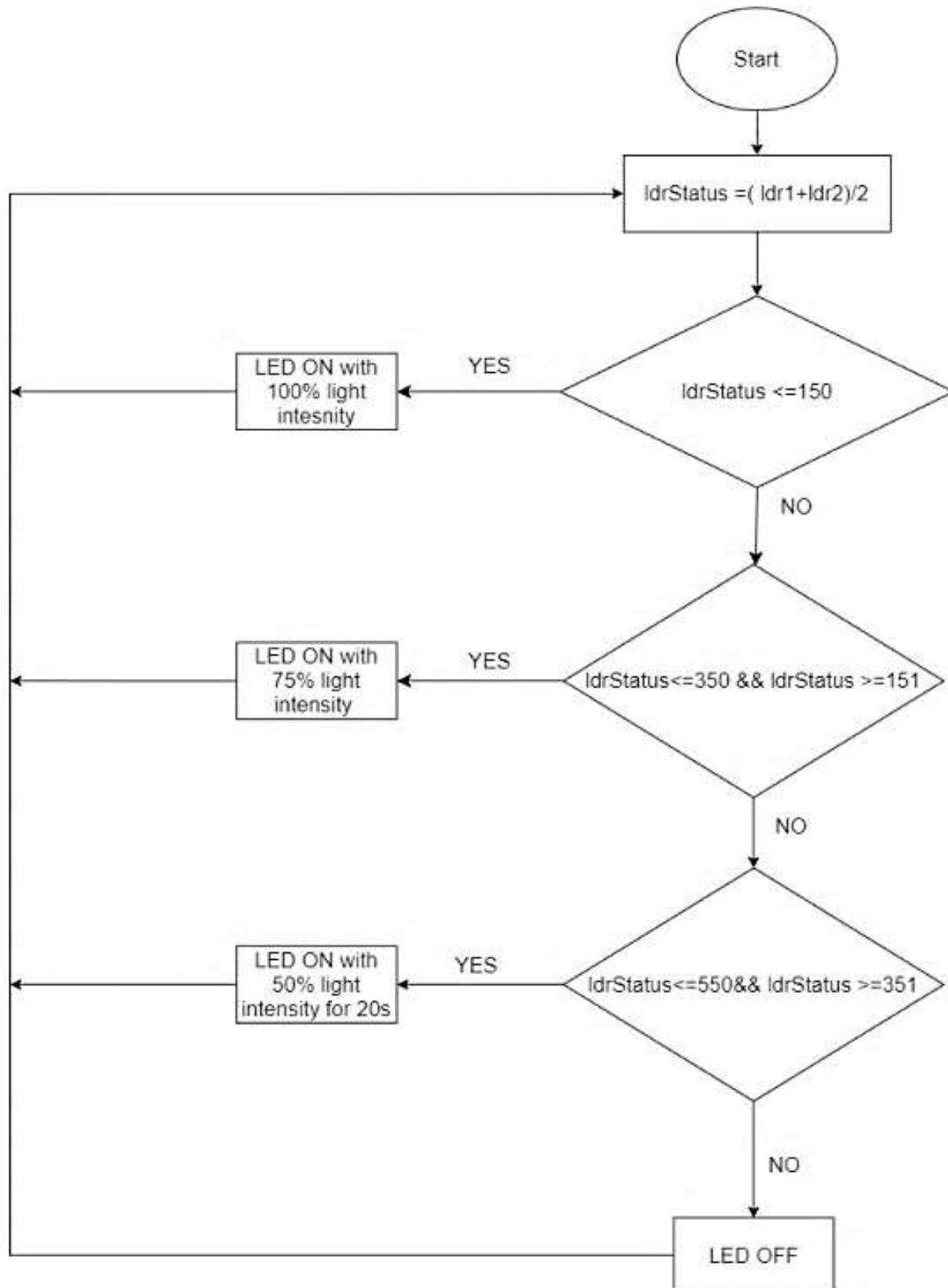
### Preliminary Design of the Proposed System

Determining the appropriate size for a solar system requires balancing the array size and storage capacity to meet the expected energy demand cost-effectively while ensuring system reliability. Reliability, in this context, refers to the probability that the system will consistently meet the load requirements. A solar streetlight system consists of a solar panel to harvest solar energy and a battery to store the collected energy, which is then used to power the lighting fixture during the night. Oversizing the system results in wasted energy and economic resources, while undersizing it may lead to insufficient energy collection to meet the system's needs. Therefore, optimizing the size and parameters of the solar streetlight system is crucial to achieve maximum utilization and efficiency.

### Smart LED control algorithm

A smart LED control algorithm has been designed to reduce the power consumption of the lighting fixture during the night, utilizing an LDR sensor for functionality. Figure 1 illustrates the flowchart of this smart LED control algorithm. During each iteration, the 'ldrStatus' is determined by averaging the values from 'ldr1' and 'ldr2'. The LED operates at different light intensities based on the 'ldrStatus' values:

1. When 'ldrStatus' is less than or equal to 150, the LED operates at 100% light intensity.
2. When 'ldrStatus' is between 151 and 350, the LED operates at 75% light intensity.
3. When 'ldrStatus' is between 351 and 550, the LED operates at 50% light intensity.
4. The LED remains off if none of these conditions are met.



**Figure 1.** The proposed algorithm for smart LED lighting algorithm

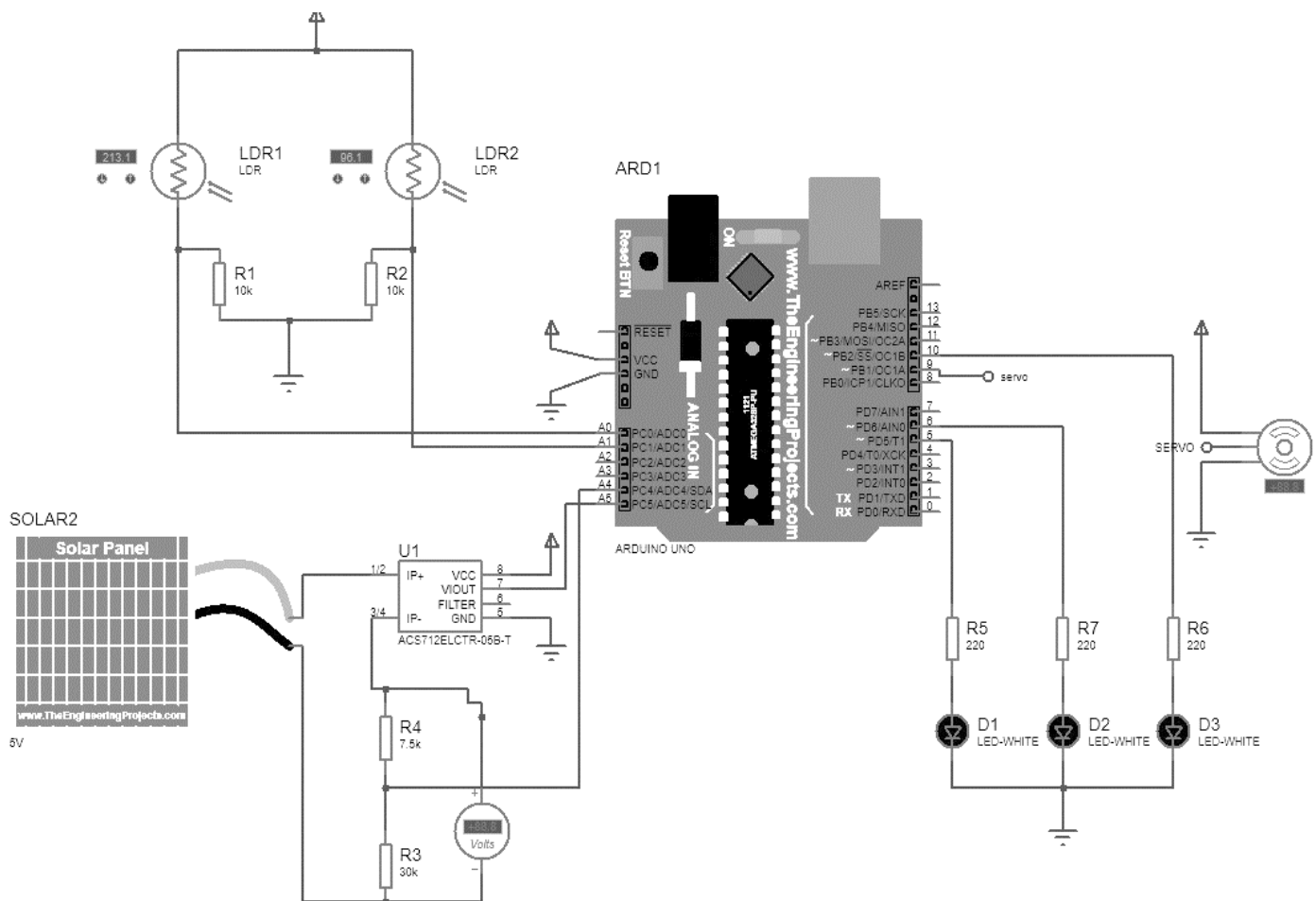
### Simulated and Practical Approaches to Hardware Design

The design of the solar streetlight system in Proteus software focuses on optimizing the tilt angle of the solar panel and implementing a smart LED control algorithm. In Proteus, an Arduino Uno R3 serves as the main microcontroller to execute instructions. A voltage sensor is constructed using a voltmeter and a voltage divider

composed of two resistors (7500 ohms and 30000 ohms). Additionally, an ACS712 current sensor from the Proteus library captures the voltage and current values from the solar panel. Due to the absence of a solar panel library in Proteus, a third-party solar panel is used, though it is limited to consistently providing 5V and lacks current information.

Two LDR sensors are employed to detect sunlight, enabling the LEDs to light up at night. The system includes three white LEDs controlled via PWM pins, with brightness levels adjusted based on LDR values. A motor is used to adjust the solar panel's tilt angle to the desired degree. Once the optimized design is achieved, the solar streetlight is practically set up. The schematic diagram of the designed solar streetlight is shown in Figure 2. Initially, a pan-tilt bracket for the solar panel, using a servo motor, is assembled. The bracket set is secured with screws for stability. Two LDR sensors are soldered onto a PCB board and attached to the back of the 5V/1W solar panel, which is then mounted on the pan-tilt bracket. Due to limitations, the servo motor cannot rotate a full 180 degrees.

A 5V Power Solar Manager, featuring MPPT functionality and capable of providing a charging current up to 900mA to a 3.7V Li battery, is used in the system. It also includes a 5V 1A USB output suitable for the Arduino Uno R3. The ACS712 5A current sensor is connected in series, while the 5V voltage sensor is connected in parallel to the solar panel and the 5V Power Solar Manager. An ESP8266 WIFI module is connected to the Arduino Uno R3 to transmit the captured data to the ThingSpeak platform.



**Figure 2.** The schematic diagram of a solar streetlight in Proteus Simulation

### Measurement of The Solar Panel Efficiency

The efficiency of solar panels is typically determined through measurements using current and voltage sensors integrated within the system. In this study, an ESP 826 WiFi module paired with an Arduino microcontroller is

employed to transmit data to the Thingspeak platform, where it is stored for comprehensive analysis. To evaluate the efficiency of the solar panels, two primary conditions were examined: the implementation of Maximum Power Point Tracking (MPPT) and the tilt angle of the solar panel.

Under the first condition, a solar streetlight system equipped with MPPT was exposed to sunlight, and data was collected continuously over a full day. Subsequently, the same procedure was repeated with a solar streetlight system lacking MPPT. Both tests were conducted at the same location to ensure consistent environmental conditions and enhance data reliability. Under the second condition, the solar streetlight system was tested with varying tilt angles of the solar panel. Tilt angles of 55°, 90°, and 180° were chosen due to constraints imposed by the tilt and pan bracket set. Similar to the first condition, all tests with different tilt angles were conducted at the same location to ensure accuracy and reliability in measurements.

The evaluation of the designed solar streetlight system included verifying its ability to meet power consumption requirements and confirming adherence to the system's intended operational parameters. Solar panel efficiency was assessed by calculating the total power output, and the systems with different tilt angles were compared based on the total power generated and their respective efficiencies. This methodological approach ensures a systematic and rigorous assessment of the solar panel efficiency under varying operational conditions, thereby providing comprehensive insights into the performance of the solar streetlight system.

### **Comparative Analysis of Battery Lifespan with Varied Lighting Algorithm**

The study involved measuring the operational duration of batteries of varying capacities under two distinct lighting algorithms: the smart LED control algorithm and the conventional streetlight algorithm. Testing was conducted using different battery capacities in solar streetlights, with the normal streetlight algorithm applied during nighttime operations to record the time required for complete battery discharge. Similarly, tests were performed using the smart LED control algorithm. Subsequently, comparisons were drawn between the operational hours achieved by solar streetlight systems employing the lighting fixture controller algorithm and those utilizing the conventional solar streetlight system.

### **Construction And Experimental Results**

In this section, we present the detailed process of constructing the proposed system and the experimental results obtained through testing. The design and implementation phases are carefully described, followed by the evaluation of the system's performance under various conditions.

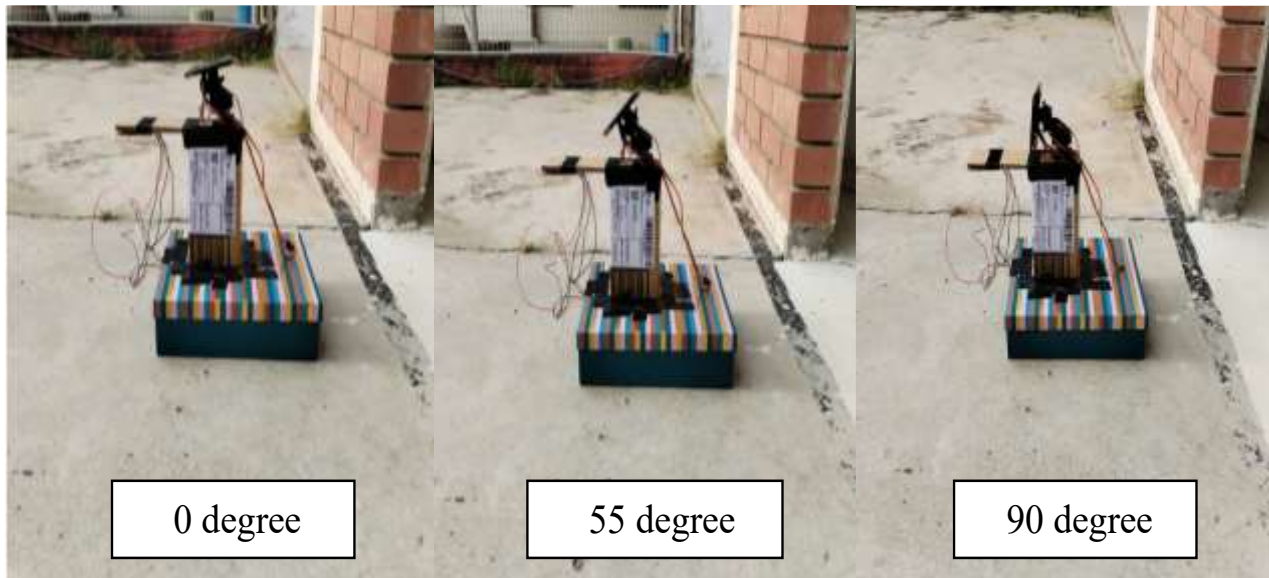
#### **Impact of Tilt Angles on Solar Panel Voltage, Current, and Power Generation**

The project prototype was assembled and measured to experimentally validate the design methodology and simulation presented in the previous section. The prototype includes connections between sensors and an Arduino Uno R3 enclosed within a housing. Atop the pole, a solar panel is mounted alongside a lighting fixture equipped with three white LEDs. Additionally, a printed circuit board (PCB)-mounted LDR sensor is securely attached to the solar panel assembly.

The experiment involved evaluating the operational performance of the solar streetlight system under varying conditions, such as changes in light levels throughout the day. This comprehensive assessment aimed to validate the system's capability to effectively harness solar energy and provide reliable lighting functionality, contributing to the overall understanding and optimization of solar-powered lighting solutions.

The voltage, current, and power generated by the proposed solar streetlight system were assessed at tilt angles of 0°, 55°, and 90°. All data were transmitted to the Thingspeak platform for analysis. Voltage and current readings of the solar streetlight were obtained using dedicated sensors, while power was calculated as the product of voltage and current values. The solar panel utilized in the study is a 1W/5V polycrystalline module. A photograph of the setup used to measure these parameters is shown in Figure 3, illustrating the experimental configuration for comprehensive analysis and validation.

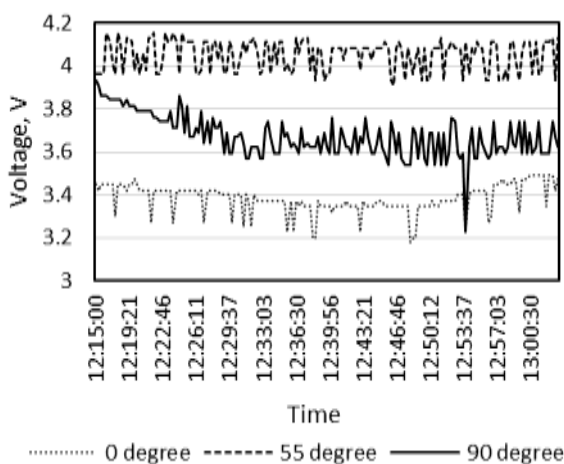
Figure 4 illustrates the comparative analysis of solar panel efficiency under varying tilt angles. The experiment involved evaluating the voltage output of the solar panel at the specified tilt angles ( $0^\circ$ ,  $55^\circ$ , and  $90^\circ$ ). The panel was mounted on a pan and tilt bracket set, with positioning controlled by a 180-degree servo motor. Results show that the average voltage produced by the solar panel is highest at  $55^\circ$ , exceeding 4 V, and lowest at  $0^\circ$ , falling below 3.5 V. These results suggest that a tilt angle of  $55^\circ$  yields optimal voltage production.



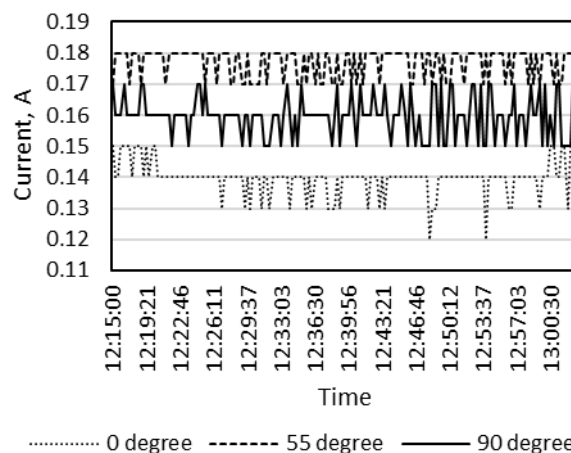
**Figure 1.** The solar panel at tilt angles of  $0^\circ$ ,  $55^\circ$ , and  $90^\circ$ .

Similarly, current measurements revealed that the average current output was highest at  $55^\circ$ , nearing 0.18 A, and lowest at  $0^\circ$ , averaging 0.14 A. Consequently, the solar panel demonstrated superior current production at a  $55^\circ$  tilt angle. Given the highest voltage and current outputs observed at  $55^\circ$ , the corresponding power generated also peaked, ranging approximately between 0.8 W and 0.7 W. In contrast, the lowest power outputs were recorded at  $0^\circ$ , ranging from 0.4 W to 0.5 W, and at  $90^\circ$ , between 0.7 W and 0.5 W.

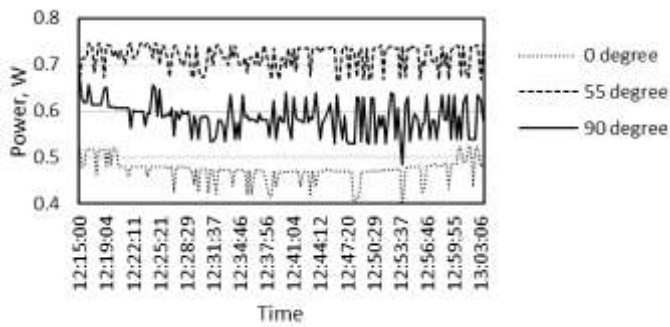
The efficiency of the solar panel was evaluated, yielding average power outputs of 0.72 W at a  $55^\circ$  tilt angle, 0.59 W at a  $90^\circ$  tilt angle, and 0.47 W at a  $0^\circ$  tilt angle. The most substantial improvement in efficiency was observed at the  $55^\circ$  tilt angle, representing a 53% increase over the initial power output. These findings are detailed in Table 1, which outlines the percentage improvements for the different tilt angles. Additionally, the assessment underscores the importance of optimizing the tilt angle to maximize solar energy harvest. Such optimization can significantly enhance the performance of solar streetlight systems, contributing to more efficient and sustainable energy use. These results suggest that careful consideration of the solar panel's tilt angle is crucial for achieving optimal performance in solar energy applications.



(a)



(b)



(c)

**Figure 2.** Effect of tilt angle variation on solar panel: (a) voltage, (b) current, and (c) power

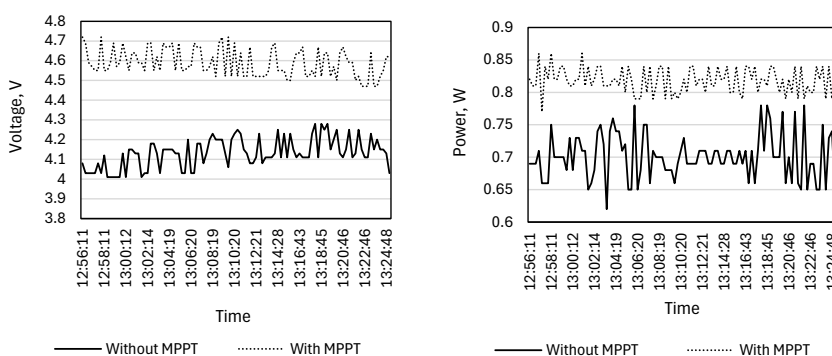
**Table 1.** The efficiency improvement of angle of solar panel

| Angle of Solar Panel | Improvement (%) |
|----------------------|-----------------|
| 0                    | 25              |
| 55                   | 53              |
| 90                   | 0               |

### Impact of MPPT Implementation on Solar Panel Efficiency

Figure 5 illustrates the effect of Maximum Power Point Tracking (MPPT) implementation on solar panel efficiency, emphasizing how MPPT technology substantially increases power output across variable environmental conditions. The results indicate that, during peak sunlight hours, a solar panel connected directly to a battery without MPPT registers voltage values between 4 V and 4.3 V, as measured by the voltage sensor. In contrast, the integration of an MPPT results in voltage readings around 4.8 V, demonstrating enhanced power regulation and current optimization. This observed difference is primarily due to the MPPT controller's capacity to dynamically adjust the operating point of the solar panel to align with its maximum power output potential, as opposed to fixed voltage levels set by battery constraints in non-MPPT systems.

The MPPT controller in the 5 V Solar Power Manager continuously calibrates the panel's voltage around the 5 V range, ensuring that the solar module operates at its peak efficiency. As shown in Figure 5(b), the deployment of MPPT technology significantly amplifies power generation, leading to notably higher power levels compared to systems lacking this feature. This improvement arises because MPPT sustains optimal electrical conditions, allowing the system to capture maximum power under changing sunlight levels. The study finds that employing MPPT in solar streetlight configurations improves power output by an average of 16.78%, thus underscoring its efficacy in enhancing the overall performance and sustainability of solar-based systems.



(a)

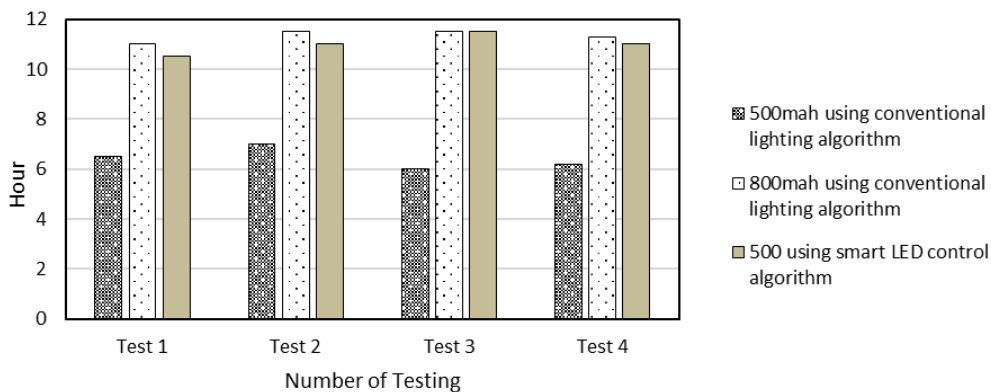
(b)

**Figure 3.** Impact of MPPT implementation on solar panel efficiency (a) voltage and (b) power

## Impact of Lighting Algorithms on LED Streetlight Operational Duration

Figure 6 presents a comparison of battery lifespan across different sizes and lighting algorithms, highlighting variations in operational duration based on battery capacity and lighting control strategies. Based on the methodology employed, an 800 mAh battery was utilized in the solar streetlight system to store energy generated by the solar panel and supply it to the lighting fixture during nighttime operations. It can be observed that the 800 mAh battery can sustain the solar streetlight system's lighting fixture for up to 11.5 hours when operating with a conventional lighting algorithm. In contrast, testing with a 500mAh battery under the same conventional lighting algorithm indicated an average support time of approximately 6 hours.

However, with the implementation of the smart LED control algorithm, the 500mAh battery demonstrated an average lighting fixture support time of about 11 hours. This performance is comparable to that of the 800 mAh battery operating under the conventional lighting algorithm. This equivalence is achieved through PWM-controlled dimming of the LEDs, which reduces overall power consumption during periods when full brightness is unnecessary. For instance, reducing brightness by 50% via PWM can achieve nearly 50% energy savings compared to operating LEDs continuously at full brightness. In PWM terms, **analogWrite**(255) corresponds to 100% duty cycle (constant on), while **analogWrite**(127) represents a 50% duty cycle (half on). Thus, the reduced power consumption extends the service life of the 500 mAh battery, enabling it to perform similarly to the 800 mAh battery in terms of supporting the lighting fixture.



**Figure 4.** Comparison of Battery Lifespan Across Varying Sizes and Lighting Algorithms

## Impact of Soar Panel Efficiency and Smart LED Control on Battery Optimization

In accordance with the calculations detailed in Section 2.1, an 800 mAh battery was initially deployed to power the solar streetlight system, providing LED illumination for a continuous duration of 12 hours. Through the integration of a smart LED control algorithm and improvements in solar panel efficiency, the required battery capacity was successfully reduced to 500 mAh, achieving performance comparable to that of the original 800 mAh setup. This enhancement was made possible by the optimized energy conversion of the solar panel, which allowed for faster battery recharge cycles, in conjunction with the smart LED control algorithm that effectively curtailed overall power consumption.

Consequently, the storage capacity needed for backup batteries was minimized, resulting in a more efficient battery size. This study identifies the optimal battery capacity as 500 mAh, reflecting a 300 mAh reduction from the initial setup. Due to budget limitations, the project was executed on a reduced scale, with the prototype dimensioned at a 1:400 ratio relative to its intended real-world application. This smaller scale facilitated the experimental validation of the proposed design without compromising the reliability of the results.

## CONCLUSION

This paper presents a comprehensive analysis and design of a solar streetlight system utilizing Arduino Uno R3 and sensors to determine the optimal battery size. The optimal battery capacity is identified through evaluating

the solar panel efficiency at different angles, the integration of MPPT controllers, and the implementation of a smart LED control system. The tilt angle of  $55^\circ$  for the solar panel proves to be optimal, delivering maximum power and energy to the battery. Additionally, the MPPT controller plays a crucial role in preventing battery overcharge and overdischarge while optimizing solar panel power output, ensuring efficient charging even in fluctuating sunlight conditions. The smart LED control algorithm further enhances system efficiency by regulating the lighting fixture's power consumption via PWM signals from the Arduino. This algorithm adjusts brightness according to ambient light levels, thereby minimizing energy usage. Ultimately, through the proposed system, an optimized battery configuration is achieved to sustain the solar streetlight effectively. In addition to its technical contributions, this research demonstrates that engineering optimization not only advances system performance but also provides pathways for addressing community needs, reducing public expenditure, and supporting inclusive, sustainable infrastructure planning.

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