Fully Controllable Lamp Post Powered by Solar Energy

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ABSTRACT – The Fully Controllable Lamp Post Powered by Solar Energy project represents a significant advancement in outdoor lighting technology by integrating sustainable energy practices with intelligent control systems. This project aims to develop a smart, energy-efficient lighting system that dynamically adapts to environmental conditions using light-dependent resistors (LDRs) and raindrop sensors, responding effectively to weather changes. The system ensures reliable operation and user-friendly remote control through real-time monitoring capabilities and integration with the Blynk IoT platform. It addresses critical issues of road safety, particularly at night, by providing consistent illumination and reducing energy consumption and maintenance costs. The project's methodology involves using high-efficiency LED lamps, solar panels, and advanced sensors to optimize performance. Results show substantial improvements in energy efficiency and reliability, highlighting the system's potential as a scalable solution for modern urban and rural lighting needs, contributing to broader sustainability and energy efficiency goals. This innovative approach not only enhances road safety by addressing poorly lit hazardous conditions but also ensures cost-effective and sustainable public lighting management.

KEYWORDS: Intelligent Street Lighting, Sustainable Energy, Road Safety.

1.0 INTRODUCTION

In recent years, the focus on sustainable and intelligent street lighting has significantly increased due to its potential to improve road safety and reduce energy consumption. The Fully Controllable Lamp Post Powered by Solar Energy project aims to tackle these issues by developing an advanced outdoor lighting system that combines modern technology with sustainable practices. This project emphasizes the use of high-efficiency LED lamps and solar energy to create a robust, self-sufficient lighting system that can adapt to varying environmental conditions, ensuring optimal performance with minimal human intervention.

The necessity for such innovative solutions is highlighted by the frequent road accidents occurring at night, often due to poorly lit roads and hazardous conditions. Traditional street lighting systems face challenges such as inconsistent maintenance and high operational costs, leading to frequent outages and inadequate lighting. This project utilizes smart control systems, including light-dependent resistors (LDRs) and raindrop sensors, to enhance energy efficiency and reliability. The integration with the Blynk IoT platform enables remote monitoring and control, greatly improving user convenience and overall system efficiency.

Road accidents, especially at night, have become a major concern in Malaysia in recent years. Various tragic incidents have been reported by the media, highlighting the dangers posed by poorly lit roads. For instance, a driver died in an accident at a sharp curve due to insufficient visibility and hazardous road conditions [1], [2]. The lack of proper lighting at sharp curves and dangerous areas significantly increases the risk of accidents, particularly at night. Dangerous bends or corners refer to sections where the road curves sharply, creating significant risks for drivers. Sharp turns are often associated with higher accident rates due to several factors, including misjudgment of the curve's severity, limited visibility, and insufficient reaction time, which can lead to loss of control [10].

Additionally, slippery and uneven road conditions without adequate warnings also contribute to accidents [3]. These incidents show that, besides lighting, the condition of the road surface and adequate warning signs are crucial to reducing the risk of accidents at dangerous curves. Motorcyclists are also at high risk, as reported in cases where motorcyclist lost control and died at sharp curves with poor lighting and slippery road surfaces [4]. Poor road maintenance also plays sharp curves with poor lighting and slippery road surfaces [4]. Poor road maintenance also plays a significant role, as unrepaired road damage increases the hazards on the roads [5].

Several studies have been conducted on solar-powered street lighting systems, each bringing unique innovations and improvements. These studies offer valuable insights and share common objectives with my project, the Fully Controllable Lamp Post Powered by Solar Energy.

The study by P. Arun Kumar, B. Prasanna, U. Kabilesh, and K. Sundareswari [6], titled "CoMo Algorithm for Efficacious Street Light Management using Solar Panel and PVDF," focuses on developing an energy-efficient street lighting system. Their system employs the CoMo algorithm to intuitively switch lights on and off based on vehicle presence and climatic conditions. Key instruments used include solar panels embedded with PVDF, IR sensors, LDR sensors, and the PSO algorithm. This study highlights significant reductions in CO_2 emissions, electrical waste, and manual labor, ensuring maximum light efficiency and energy conservation. This adaptive lighting approach closely aligns with the goals of my project, which also aims to enhance energy efficiency and sustainability in street lighting through smart control systems.

M.S.H. Choudhury and colleagues' work [7], "Design and Implementation of an Automated Solar Street Light System," aims to create a low-cost, efficient street light system with integrated fault and obstacle detection. Utilizing instruments such as Arduino Mega 2560, light sensors, photoelectric sensors, ultrasonic sensors, solar panels, LEDs, GSM modules, and LCDs, their study achieved effective control and fault detection for streetlights. The system's ability to operate independently from the power grid and its suitability for remote areas offer valuable insights for my project. Additionally, the focus on cost-effective solutions resonates to make sustainable technology accessible in both urban and rural settings.

Nor Elisya Kuamthab and Farahiyah Mustafa's [8] "Development of Solar Powered LED Street Lighting with Auto Intensity Control" investigates an efficient solar-powered street light system that reduces energy wastage and costs through auto intensity control. The system uses solar panels, charge controllers, Arduino Uno, LDR sensors, IR sensors, LED strips, and sealed lead-acid rechargeable batteries. Their findings show significant energy savings by ensuring streetlights turn on only when necessary, and auto intensity control adjusts light output based on environmental conditions. This approach is like the adaptive lighting in my project, which aims to optimize energy use and reduce operational costs.

Wang Fei's study [9], "Energy Saving Control of Solar LED Street Lamp Based on Microcontrollers," focuses on developing an energy-saving and emission-reducing streetlamp system using microcontroller technology. Instruments include solar panels, a 51 microcontroller, LED lamps, storage batteries, infrared sensors, an optoelectronic isolation circuit, a clock circuit, and an ambient light collecting system. The study highlights significant reductions in energy consumption and CO_2 emissions, improved efficiency and reliability through microcontroller-based control, and enhanced stability and longevity of LED streetlamps. These findings align with the objectives of my project, emphasizing the use of intelligent control methods to enhance the efficiency and reliability of street lighting systems.

A study on comparison with existing studies found that three key aspects highlighted in their research can be used to design a Fully Controllable Lamp Post Powered by Solar Energy project: adaptive lighting [6][8], cost-effective and sustainable solutions [7], and intelligent control systems [9].

Referring to the CoMo Algorithm project by P. Arun Kumar et al. [6] and the development by Nor Elisya Kuamthab and Farahiyah Mustafa [8], the use of adaptive lighting in this project ensures efficient use of energy and responds dynamically to environmental conditions. These studies highlight the effectiveness of using sensors to adjust lighting based on ambient conditions and movement, significantly improving energy efficiency and reducing waste.

According to M.S.H. Choudhury and colleagues [7], the automated system they designed aims to reduce energy consumption and operating costs while providing sustainable lighting solutions. Both projects emphasize the importance of integrating solar energy with an efficient energy management system to achieve cost savings and environmental benefits. The focus on low-cost and efficient solutions makes it suitable for a wide range of applications, from cities to remote areas.

Referring to Wang Fei's statement [9], leveraging intelligent control systems and microcontrollers can improve the reliability and efficiency of the lighting system. The use of microcontrollers for precise control and real-time monitoring ensures optimal performance and rapid response to any detected issues, thereby increasing the overall reliability and lifespan of the lighting infrastructure.

By integrating these features, the Solar Powered Fully Controllable Lamp Post project establishes a new standard in sustainable and smart street lighting systems. Drawing from the best practices identified in existing studies—such as adaptive lighting, cost-effective energy use, and intelligent control systems—this project aims to address critical street lighting needs, particularly in areas prone to dangerous bends or corners, often found on rural roads. The ability to adapt lighting dynamically based on environmental conditions is key to enhancing both energy efficiency and road safety.

The main objectives of this project are to develop a highly efficient, solar-powered lighting system that improves road safety through adaptive lighting, minimizes operational and maintenance costs via automated controls and real-time remote monitoring, and promotes long-term sustainability by utilizing renewable energy and intelligent sensors to optimize system performance.

1.1 RESEARCH BACKGROUND

Street lighting plays a crucial role in ensuring the safety of road users, particularly in rural areas that often suffer from poor visibility at night. Traditional street lighting systems typically consume a significant amount of energy and require frequent maintenance. Solar-powered street lighting systems, equipped with intelligent control technologies, have emerged as a more efficient and sustainable solution [17]. This study aims to develop a fully controllable street lighting system with adaptive lighting designed specifically to enhance safety at dangerous sharp curves.

This research is important because it addresses the issue of reducing road accidents in rural areas, which are often poorly lit. Sharp curves and hazardous corners are areas that require special attention due to the high accident rates. Solar-powered adaptive lighting systems can adjust the lighting according to the surrounding conditions, reducing maintenance costs and maximizing energy efficiency [8], [9], [17].

Several studies have been conducted on using solar-powered street lighting systems and smart technologies in road safety. For example, the study by P. Arun Kumar et al. [6] on the CoMo algorithm for efficient street light management demonstrates how intelligent control systems can optimize lighting efficiency and energy consumption. Another study by M.S.H. Choudhury and colleagues [7] highlights the importance of fault detection and adaptive lighting in improving street lighting systems. While these studies provide significant contributions to the field, they still fall short in addressing the specific challenges posed by dangerous curves in rural areas. For instance, Wang Fei [9] examined the use of microcontrollers in solar-powered LED street lighting systems for energy savings, but the focus of this study was more on general energy management rather than the unique challenges in high-risk rural areas. Similarly, Nor Elisya Kuamthab and Farahiyah Mustafa [8] discussed methods to reduce operational costs and improve lighting efficiency through automatic intensity control systems that adjust to environmental conditions. However, this study did not focus specifically on adaptive lighting at dangerous curves.

In addition, the study by R. Llewellyn et al. [18], titled "Active Road Studs as an Alternative to Lighting on Rural Roads," discusses the use of active road studs as an alternative to traditional lighting in high-risk rural areas, such as sharp curves. This study emphasizes that active road studs can help improve driver safety in areas often overlooked in previous research, particularly in terms of drivers' perception of safety at night.

While numerous studies have explored the use of solar energy for street lighting, there is still a lack of research focusing on adaptive lighting systems in high-risk rural areas, such as sharp curves. This project aims to address this gap by developing a system that can adapt to environmental conditions while enhancing safety in hazardous curves. The system is not only intended to save energy but also to improve road safety in areas that have often been neglected in previous studies.

2.0 METHODOLOGY

The Fully Controllable Lamp Post Powered by Solar Energy project employs a well-integrated system of components, as illustrated in the provided block diagram (Figure 1). The system includes a solar panel, charger control unit, battery, Light-Dependent Resistor (LDR) sensors, ESP32 microcontroller, LED lamp, and the Blynk IoT platform, each playing a crucial role in ensuring the system's efficiency and sustainability.

The solar panel captures sunlight and converts it into electrical energy, serving as the renewable energy source for powering the lam post, thus ensuring sustainability and reducing dependence on the power grid. This electrical energy is then directed to the charger control unit, which manages the charging process efficiently to prevent overcharging and ensure the battery is charged correctly. The battery stores the electrical energy generated by the solar panel, which is used to power the lamp post during periods without sunlight, such as at night or during cloudy weather.

The system uses LDR sensors connected to both the battery and the ESP32 microcontroller to detect ambient light levels and provide real-time data to the ESP32. When ambient light falls below a certain threshold, indicating dusk or low light conditions, the LDR sensors signal the system to turn on the LED lamp. The ESP32 microcontroller, being the central component, manages the overall operation by processing inputs from the LDR sensors and controlling the LED lamp's brightness accordingly. Additionally, the ESP32 interfaces with the Blynk IoT platform for remote monitoring and control.

The LED lamp, controlled by the ESP32 microcontroller, adjusts its brightness based on inputs from the LDR sensors and pre-programmed logic, ensuring optimal lighting conditions while conserving energy. The ESP32 microcontroller connects to the Blynk IoT platform via a smartphone, allowing for real-time remote monitoring and control of the lamp post. This integration enables users to adjust settings, monitor system status, and receive alerts through the Blynk app on their smartphones.

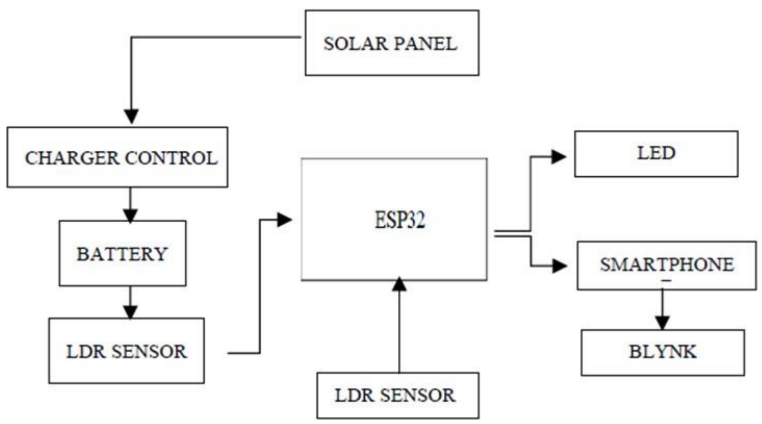

Figure 1. Block Diagram of the Fully Controllable Lamp Post Powered by Solar Energy

The methodology for the Fully Controllable Lamp Post Powered by Solar Energy project involves the seamless integration of solar energy with intelligent sensors and a microcontroller to create a self-sufficient, smart lighting system. The solar panel charges a battery through a charger control unit, providing a reliable energy source. The LDR sensors provide real-time data to the ESP32 microcontroller, which adjusts the LED lamp's brightness accordingly. Remote monitoring and control through the Blynk IoT platform enhance user convenience and system efficiency. This innovative approach ensures reliable, energy-efficient lighting, particularly in remote and rural areas with challenging conditions.

2.1 Flow Chart of Project

Figure 2 shows a flowchart describing the automated control process for a lamp post powered by solar energy. The process begins with the system determining whether it is in day mode or night mode.In day mode, the system activates a rain sensor. If rain is detected, the lamp post will turn on at 100% brightness. If no rain is detected, the lamp post will remain off. In night mode, the lamp post enters standby mode with the light at 25% brightness. If rain is detected during the night, the lamp post will turn on at 100% brightness. If no rain is detected, the system will check for vehicle lights detected by a roadside LDR (Light Dependent Resistor). If vehicle lights are detected, the lamp post will turn on at 100% brightness. If no vehicle lights are detected, the lamp post will remain in standby mode at 25% brightness.

Next, the system checks for any malfunctions in the lamp post. If a malfunction is detected, the system sends a notification to maintenance via the Blynk application. Regardless of whether a malfunction is detected, the system continues to monitor the lamp post.

Overall, this flowchart illustrates a fully automated solar-powered lamp post control system. The system adjusts the lamp post's lighting based on the time of day, weather conditions, and the presence of vehicle lights, ensuring efficient operation and timely maintenance

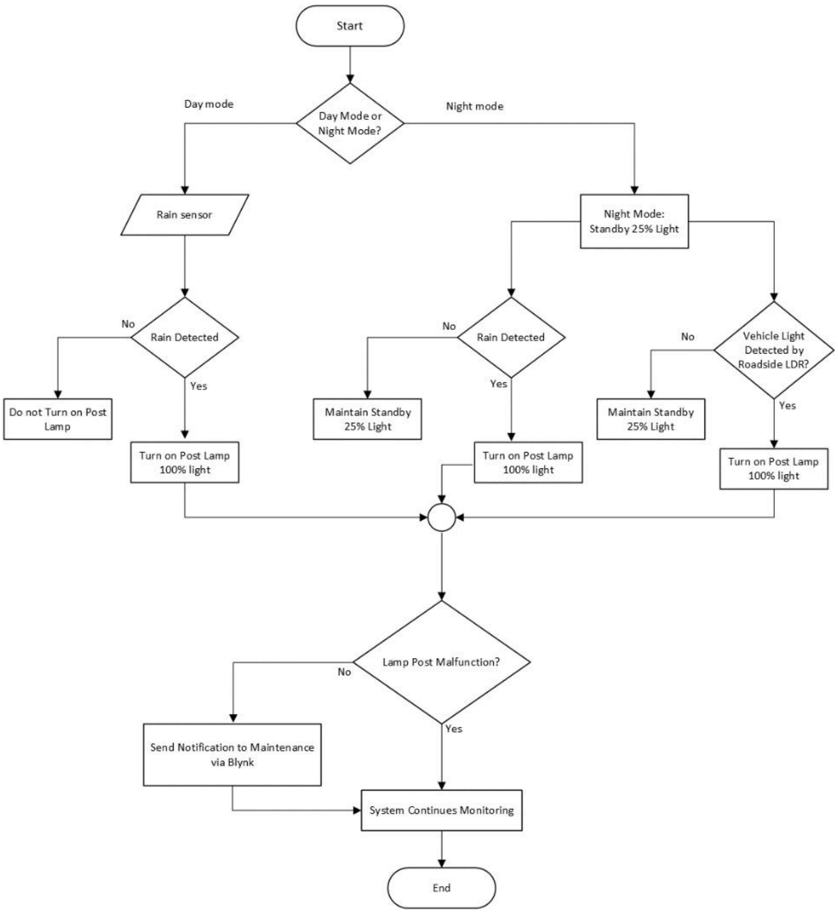

Figure 2. Flowchart Fully Controllable Lamp Post Powered By Solar Energy

2.2 Circuit Layout

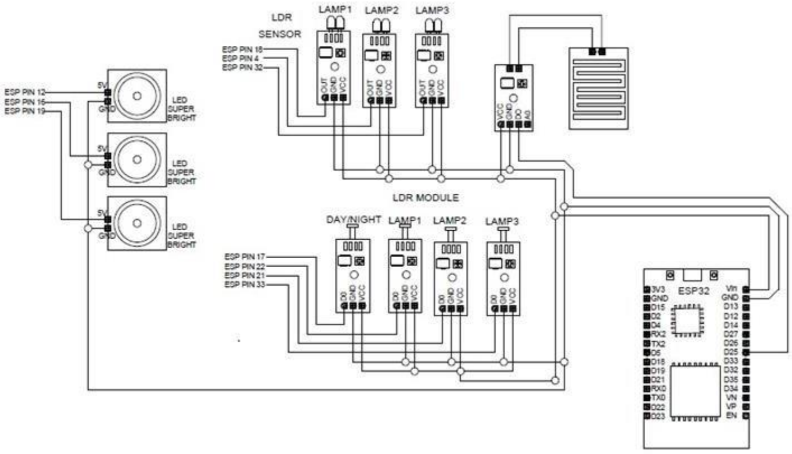

Figure 3; Circuit Layout for Fully Controllable Lamp Post Powered by Solar Energy with Adaptive Lighting and Environmental Sensing

The diagram (Figure 3) clearly illustrates the core elements of the Fully Controllable Lamp Post Powered by Solar Energy project, aligning well with the project's objectives described in the text. At the heart of this system is the ESP32 microcontroller, which manages various components such as LED lamps, LDR sensors, and other modules. The microcontroller ensures that the lamp post adapts dynamically to environmental conditions, enabling energy-efficient and sustainable operation.

The adaptive lighting system, as depicted, allows the LED lamps to adjust their brightness based on ambient light levels detected by the LDR sensors. This capability is crucial for conserving energy, as the lamps remain off during daylight hours, switch to a standby mode at dusk, and operate at full brightness during nighttime or rainy conditions. The diagram visually supports this functionality by showing how each component is interconnected, ensuring optimal performance.

Energy management is another key aspect demonstrated in the project description, though the solar panels and batteries are not explicitly shown in the diagram. The system's control over the LED lamps, managed by the microcontroller, would integrate with a solar energy storage system to ensure that the lamps are powered during periods of low sunlight. This aspect underscores the project’s commitment to utilizing renewable energy sources effectively.

The diagram also includes connections for additional sensors, such as a raindrop sensor, which further enhance the system's ability to respond to changing weather conditions. This feature is critical for maintaining road safety by adjusting the lighting during adverse weather, ensuring that visibility is always optimal.

Finally, the diagram likely connects to the Blynk IoT platform, enabling real-time monitoring and control of the system. The ESP32's configuration allows for seamless integration with user interfaces, providing remote access and control, which enhances the overall user experience. In summary, the diagram effectively visualizes the system’s intelligent design, supporting its capacity to adapt to environmental conditions, manage energy efficiently, and offer a user-friendly interface for remote monitoring and control.

2.3 Materials and Instruments for Solar-Powered Lamp Posts

In selecting materials for the solar-powered lamp posts, efficiency, durability, and suitability were prioritized to ensure the system's reliability and long-term performance.

Photovoltaic Panels: Monocrystalline or polycrystalline silicon panels were chosen. Monocrystalline panels are known for their superior efficiency and space-saving properties, making them ideal for converting sunlight into electricity effectively. Polycrystalline panels, while slightly less efficient, offer a cost-effective alternative that balances performance and budget constraints.

LED Lamps: High-efficiency LED chips were selected for their low power consumption, high brightness, and long lifespan. These LEDs are energy-efficient and durable, providing bright illumination with significantly lower power usage compared to traditional lighting options. This reduces maintenance costs and improves overall system efficiency [16].

Battery Storage: Both lithium-ion and lead-acid batteries were considered. Lithium-ion batteries, with their high energy density and long cycle life, are efficient and long-lasting. Lead-acid batteries, while more affordable, are robust and reliable, making them a practical choice for energy storage.

Lamp Post Structure: The structure of the lamp posts is made from either galvanized steel or aluminium. Aluminium is lightweight and resistant to corrosion, making it suitable for outdoor installations. Galvanized steel offers high strength and durability, ensuring the lamp posts can withstand various environmental conditions.

Mounting and Frames: For mounting and frames, anodized aluminium or stainless steel is used. These materials are chosen for their durability, corrosion resistance, and lightweight properties. Anodized aluminium is particularly favored for its excellent resistance to corrosion and long service life, essential for outdoor applications.

Glass Cover: Tempered glass is used to protect the photovoltaic cells. This material is selected for its high impact resistance and durability, ensuring that the solar panels are shielded from environmental damage and can function reliably over time.

Wiring and Connectors: Copper or tinned copper wiring is selected for its excellent electrical conductivity, durability, and corrosion resistance. These properties ensure reliable electrical connections and efficient energy transfer within the system.

Protective Coatings: UV-resistant coatings are applied to protect the components from UV degradation. These coatings extend the lifespan of materials exposed to sunlight, maintaining their integrity and functionality over extended periods

2.4 The formula for Solar Energy Utilization for Determining Energy Consumption (W)

Measuring solar energy utilization is essential to assess the efficiency and effectiveness of solar energy systems. Accurate measurement tools and detailed data analysis help ensure systems operate efficiently, leading to energy savings and environmental protection [13].

$$Energy\ Consumption\ (W) = Power\ (W) x\ Time\ (h)$$

Where:
Power (W) is the power rating of the device in watts.
Time (h) is the duration for which the device is operated in hours. [11]

Solar Energy Utilization (%) $= \left(\frac{Total\ Weekly\ Consumption}{Total\ Weekly\ Production}\right) x\ 100$

The formula for Measuring Solar Energy Utilization [11]
Basic Formula for Calculating Energy Produced by Photovoltaic Panels:
E = P x H [11]
where:
- E is the energy produced (Wh)
- P is the power rating of the photovoltaic panel (Watt)
- H is the number of sunlight hours received (hours)

According to [12], The Renogy 100-Watt 12 Volt Polycrystalline Solar Panel can produce 100 watts of power under standard test conditions. This means it can generate approximately 500 watt-hours (Wh) of energy per day, assuming an average of 5 peak sunlight hours per day. The panel is designed for off-grid applications, making it suitable for various uses, including powering lamp posts, RVs, boats, and other setups requiring reliable solar energy.

E = 100-Watt x 5 hours = 500 Wh/day
Weekly Energy Calculation:
500 Wh/day times 7 days = 3500 Wh/week]

This estimate depends on local weather conditions. Excess energy produced can be stored in batteries for use on cloudy days or during low sunlight, ensuring efficient and continuous operation of solar-powered systems like lamp posts [14].

In this study, by using Renogy 100-Watt 12 Volt Polycrystalline Solar Panels, you ensure that the lamp post will have a reliable and sufficient energy supply, accommodating variations in sunlight and other environmental factors. This setup provides a robust and reliable power solution, ensuring consistent operation and the ability to handle unexpected increases in energy consumption or decreases in sunlight availability.[15].

2.4 The formula for Formula Daily Energy Consumption of the Lamp Post

To ensure the lamp post operates reliably, we will calculate the total daily energy consumption based on the worst-case scenario where the lamp is on for 12 hours and in standby mode for 12 hours.

Daily Energy Consumption of the Lamp Post (4 Lamps):
Lamp On (12 hours): 90 watts × 4 lamps × 12 hours = 4320 Wh
Energy Production by One Renogy 100-Watt Panel:
Average sunlight hours per day: 5 hours
Energy produced per day by one 100-watt panel:
100 watts × 5 hours = 500 Wh

Determine the Number of Panels Needed:
Total daily energy consumption: 4320 Wh
Energy produced by one 100-watt panel per day: 500 Wh
Number of 100-watt panels needed:

$$= \left(\frac{4320\,Wh}{500\,Wh}\right) = 8.64 \approx 9$$

Since we cannot have a fraction of a panel, 9 panels would be required to meet the energy needs of the lamp post.

Total Weekly Energy Consumption
Total Weekly Consumption: 4320 Wh/day × 7 days = 30240 Wh/week
Energy Production by 9 Panels

1. Daily Energy Production by Nine 100-Watt Panels:
   100 watts × 9 × 5 hours = 4500 Wh
2. Weekly Energy Production by Nine 100-Watt Panels:
   4500 Wh/day × 7 days = 31500 Wh/week

Solar Energy Utilization (%)

Utilization Calculation:

$$\text{Utilization (\%)} = \left(\frac{Energy\ Consumed\ by\ Lamp\ Post}{Energy\ Produced\ by\ Panels}\right) x\ 100$$

$$\text{Utilization (\%)} = \left(\frac{30240\ \text{Wh/week}}{31500\ \text{Wh/week}}\right) x\ 100$$

$$\text{Utilization (\%)} = 96.0\ \%$$

Using 9 Renogy 100-Watt 12 Volt Polycrystalline Solar Panels, the solar energy utilization is approximately 96.0%, indicating that almost all the energy produced is used, with a small surplus that can be stored for future use. This setup ensures that the lamp post operates efficiently and reliably.

3.0 RESULT AND FINDING

This experiment is done one day a week beginning on Monday and ending on Sunday as we observe in Table 1. Data is taken based on weather factors or local condition factors that existed at the time the data was collected. the data help to prove that the system can do it well Another approach to the problem is the treatment of data. However, if it is ascertained that the function of the system is critically contingent on the climate conditions at that time, then. thus, these data can only be partially regulated.

The data shown in Table 1 are the records of the experiment, which is taken in the working week, from Monday to Sunday. Different ambient conditions can include hours of the day, adverse weather, and local factors, for instance, the presence of vehicles about system performance. Analyzing the table, the impact of the system functionality on the environmental conditions can be seen, particularly, its dependency on the real-time climate.

Thus, the data presented prove that the system in question is highly responsive to changes in the conditions present in the environment. For instance, during daylight when there is no rain, the lights are off but come evening the journey starts. Conversely, with the rain, the lights come on during the day and each night to offer safety and adequate illumination. During the day it works and turns on dimly or at maximum illumination at night or if a car is approaching or if it is raining. It is used to monitor the failures or problems that occur in the Road Maintenance Fund equipment and record them while sending the notices when they are required to avoid any delay in maintenance.

This experiment proves that while systems are very flexible and sensitive to the current conditions, their performance is always conditioned by these very conditions. This suggests that the system cannot be controlled conventionally because the systems and software control is based on dynamic responses to the environment and not on fixed conditions.

Table 1. Results of System Performance and Solar Energy Utilization.

Time	Day	Ambient Condition	Lamp Status	Malfunction Detected	Alert Sent/ Event Logged	Maintenance Action	Solar Energy Utilization
08:00 - 10:00	Monday	Daytime, No Rain	Off	No	No	None	High
09:00 - 10:00	Tuesday	Daytime, Rain	On	No	No	None	High
19:00 - 20:00	Wednesday	Dusk, No Rain	Standby (25%)	No	No	None	Moderate
23:00 - 01:00	Thursday	Night, Rain	On	Yes	Yes	Technician Dispatched	High
08:00 - 08:30	Friday	Night, No Rain, Vehicle Detected	On	No	No	None	Moderate
06:00 - 08:00	Saturday	Dawn, No Rain, No Vehicle Detected	Standby (25%)	No	No	None	Moderate
14:00 - 16:00	Sunday	Daytime, Rain	On	Yes	Yes	Technician Dispatched	High
19:00 - 23:00	Sunday	Night, No Rain	Standby (25%)	No	No	None	Moderate

This is seen in the context that due to some factors such as variation in weather and even other related factors the system brings some uncertainty as part of its system design. Still, this entails the fact that the system has no way left for its behavior to be thoroughly planned and manipulated, as it is completing adaptations to factors beyond its control. Table 1 shows how the Fully Controllable Lamp Post Powered by Solar Energy project monitors and maintains lamp posts in real-time to ensure they work reliably and sustainably. It details how the system detects problems, logs events, and sends alerts to get maintenance done when needed.

On Monday morning (08:00 - 10:00), the lamp was off during a clear day with no rain, and everything was fine with no issues detected. On Tuesday (09:00 - 10:00), it was raining during the day, so the lamp was on, but again, no problems were found. Wednesday evening (19:00 - 20:00) was calm and dry; the lamp was in low-power standby mode, working perfectly with no issues.

Thursday night (23:00 - 01:00) was rainy, and the lamp was fully lit. This time, the system detected a malfunction, logged the event, and sent an alert, prompting a technician to fix it (refer to Figure 3). On Friday morning (08:00 - 08:30), the lamp was on at night because a vehicle was detected, and everything worked smoothly without any problems. Saturday morning (06:00 - 08:00) was clear with no vehicles around, so the lamp was in standby mode and operating correctly.

On Sunday afternoon (14:00 - 16:00), it rained, and the lamp was on. The system detected another malfunction, logged it, and sent an alert, which led to a technician being dispatched (refer to Figure 3). Later that night (19:00 - 23:00), the lamp was back in standby mode without any issues as the night was clear

The data shown in Table 1 are the records of the experiment, which is taken in the working

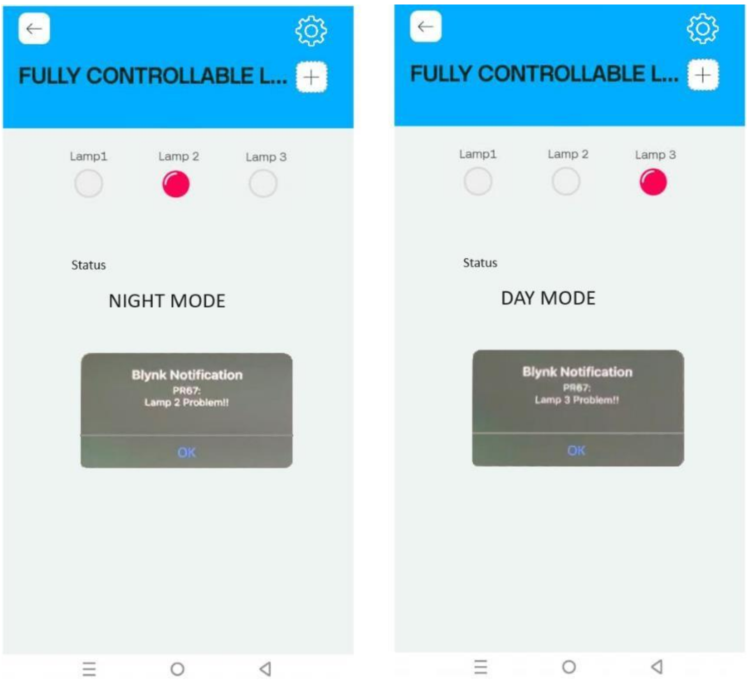

Figure 3; Blynk notification

Event Logged refers to recording incidents detected by the system, such as malfunctions, anomalies, or significant changes in the lamp post's status. This creates a record that can be reviewed for maintenance and performance analysis. For example, the record might show a lamp failing to turn on, incorrect brightness adjustments, or the lamp shutting down unexpectedly. It also includes environmental changes, such as weather shifts that require immediate adjustments to the lamp's settings or vehicle detection at night that necessitates full brightness. Additionally, any alerts generated by the system about potential issues or maintenance needs are also logged. By recording these events, the system ensures efficient troubleshooting, and continuous performance monitoring, and maintains the reliability of the lighting infrastructure.

Table 1 highlights how the system carefully monitors the lampposts, ensuring they always function properly. The system detects any issues, logs them, and quickly alerts the maintenance team, thereby maintaining the reliability and effectiveness of the lighting infrastructure. To better understand how the findings meet the study's objectives, let's examine the corresponding graph plots, which provide valuable insights into the system's performance and solar energy consumption.

3.1 Energy Efficiency and Adaptive Lighting

One of the primary objectives is to develop a Smart Outdoor Lighting System. The lamp's status adapts dynamically to ambient conditions, showcasing energy efficiency and responsiveness. For example, the lamp remains off during the daytime with no rain and switches to standby mode at dusk. During nighttime or rainy conditions, the lamp is fully on, ensuring safety and visibility. The graph "Lamp Status vs. Ambient Conditions" illustrates how the lamp adjusts its brightness based on ambient light and weather conditions. For instance, the lamp is off during the day on Monday and Tuesday, in standby mode during dusk on Wednesday, and fully on during the night with rain on Thursday (refer to figure 4).

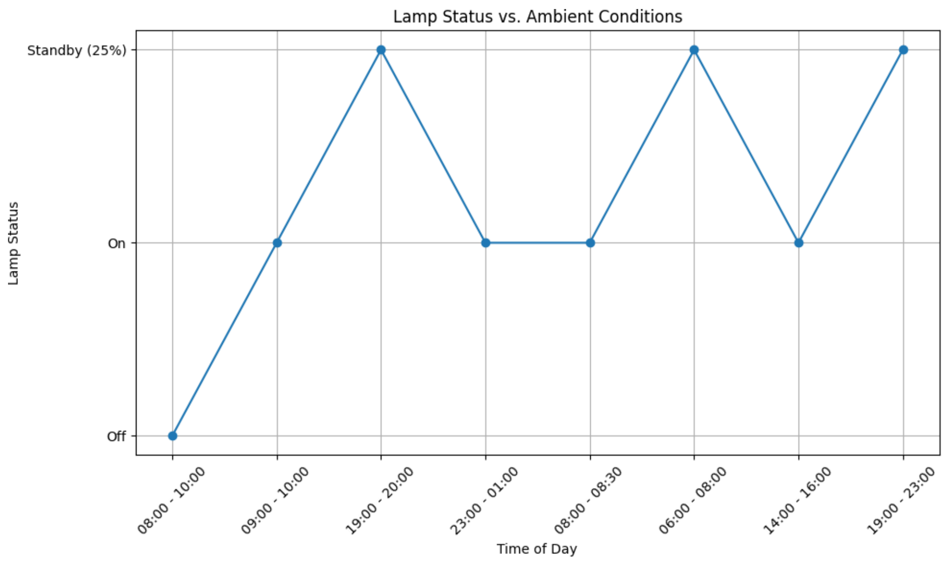

Figure 4; Lamp status vs. Ambient Conditions

Figure 4; Lamp status vs. Ambient Conditions

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3.2 Weather Response and Safety

Implementing a Raindrop Sensor is another crucial objective. The system responds to rainy conditions by turning the lamp on, as seen on Tuesday and Sunday afternoons. The graph "Lamp Status vs. Weather Conditions" highlights the system's responsiveness to weather changes. The lamp remains consistently on during rainy conditions (Tuesday, Thursday night, and Sunday afternoon), ensuring adequate lighting during adverse weather, thus enhancing road safety (refer to Figure 5).

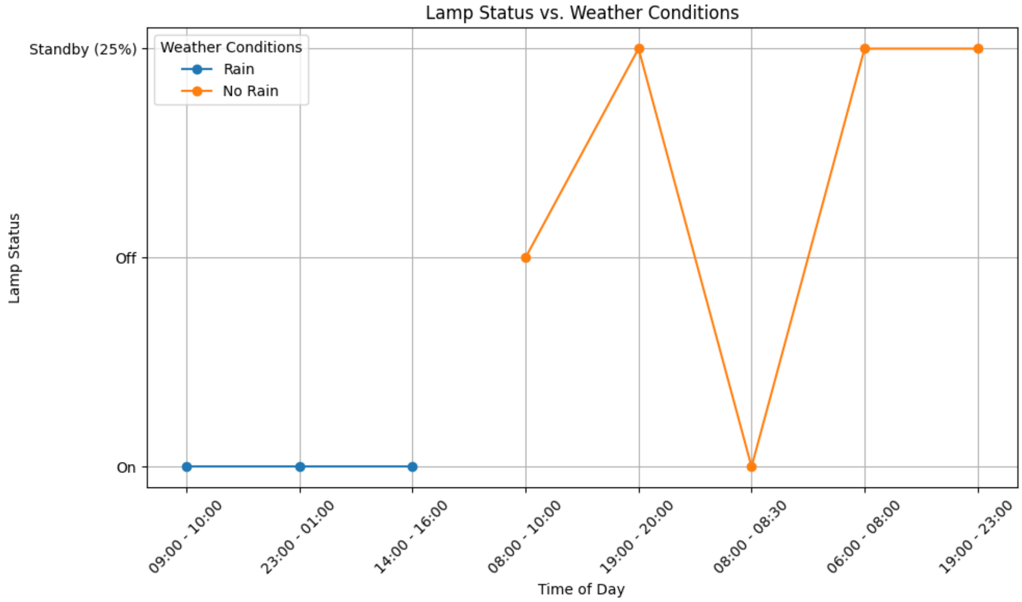

Figure 5; Lamp status vs. Weather Conditions

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3.3 Continuous Monitoring and Maintenance

A key objective is to integrate Light-Dependent Resistors (LDR). The system logs events and detects malfunctions, triggering necessary maintenance actions. For example, malfunctions detected on Thursday night and Sunday afternoon were logged, and alerts were sent, prompting technician dispatch. The graph "Lamp Status and Events Logged vs. Time" demonstrates how the system continuously monitors lamp status and logs events, facilitating timely maintenance and ensuring system reliability (refer to Figure 6).

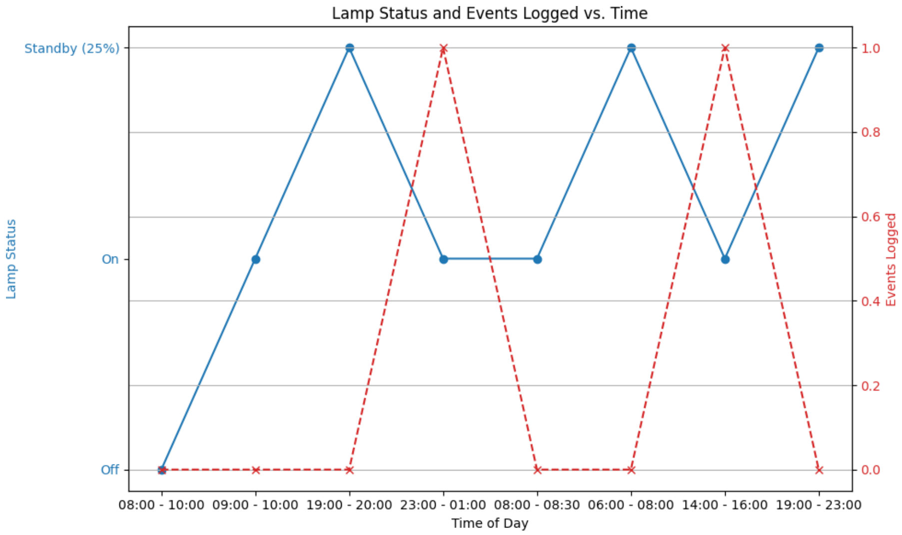

Figure 6; Lamp Status and Events Logged vs. Time

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3.4 Remote Monitoring and User Interaction

Enabling remote monitoring through the Blynk IoT Platform is another significant objective. The system sends alerts during malfunctions, ensuring prompt maintenance actions. The graph

"Lamp Status and Alerts Sent vs. Time" showcases the system's remote monitoring and alerting capability. Alerts were sent during malfunction events on Thursday night and Sunday afternoon, ensuring prompt maintenance responses and enhancing overall system efficiency (refer to Figure 7).

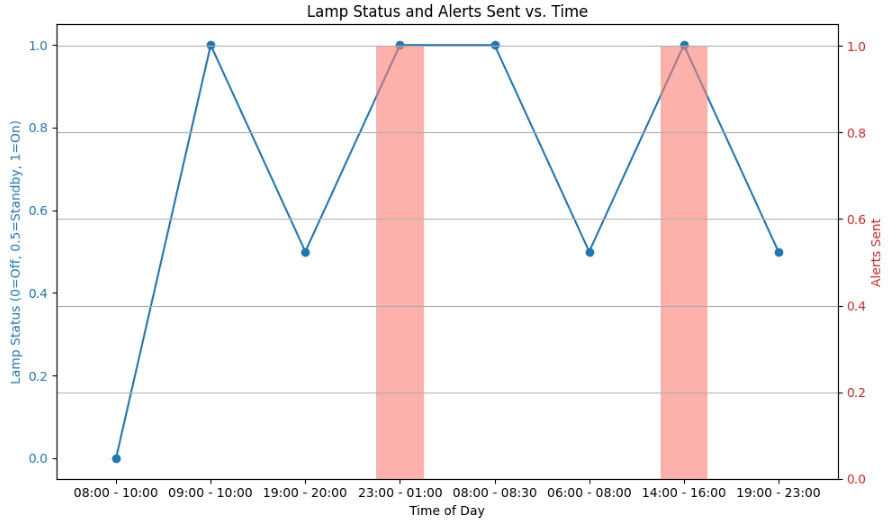

Figure 7; Lamp Status and Events Logged vs. Time

3.5 User Interface and Feedback

Enhancing the User Interface for Real-Time Feedback and Control is also crucial. The graph of user interactions over time indicates periods of high interaction, reflecting real-time feedback and control. The graph "User Interactions vs. Time" shows fluctuations in user interactions, with peaks during specific times such as 09:00 - 10:00 on Tuesday and 23:00 - 01:00 on Thursday. This highlights the effectiveness of the user interface in providing real-time feedback and control, ensuring users can efficiently interact with and manage the system (refer to Figure 8).

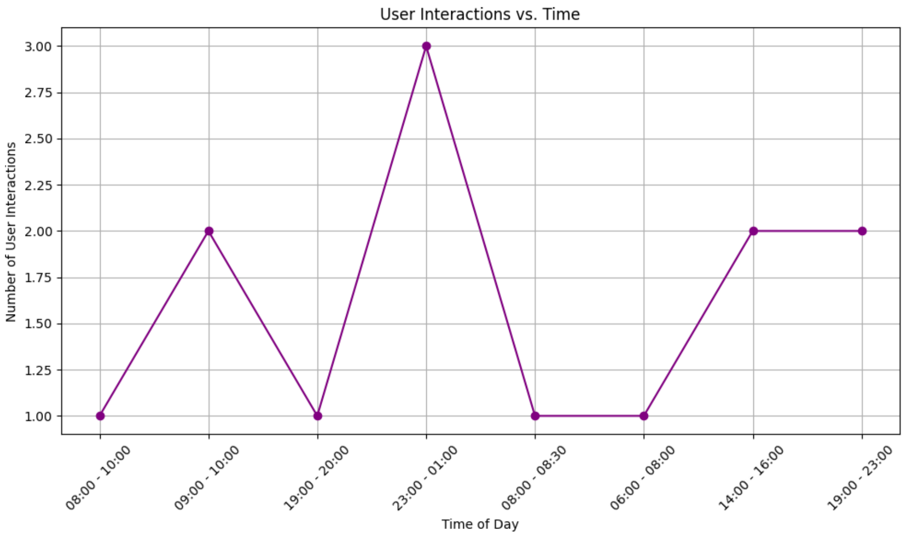

Figure 8; Lamp Status and Events Logged vs. Time.

3.6 Calculation of Solar Energy Utilization

Enhancing the User Interface for Real-Time Feedback and Control is also crucial. The graph of Energy Consumption for Each Period:

Monday (08:00 - 10:00): Lamp Off, Consumption = 0 Wh
- Tuesday (09:00 - 10:00): Lamp On, Consumption = 90 Wh
- Wednesday (19:00 - 20:00): Standby (25%), Consumption = 22.5 Wh
- Thursday (23:00 - 01:00): Lamp On, Consumption = 180 Wh (20 Wh/h for 2 hours)
- Friday (08:00 - 08:30): Lamp On, Consumption = 45 Wh (20 Wh/h for 0.5 hours)
- Saturday (06:00 - 08:00): Standby (25%), Consumption = 45 Wh (5 Wh/h for 2 hours)
- Sunday (14:00 - 16:00): Lamp On, Consumption = 180 Wh (20 Wh/h for 2 hours)
- Sunday (19:00 - 23:00): Standby (25%), Consumption = 90 Wh (5 Wh/h for 4 hours)

Total Daily Energy Consumption for 4 lamps:
- Monday: 0 Wh
- Tuesday: 360 Wh
- Wednesday: 90 Wh
- Thursday: 720 Wh
- Friday: 180 Wh
- Saturday: 180 Wh
- Sunday: 1080 Wh (720 Wh + 360 Wh)

Lamp On (90 W): When the lamp is fully lit, it consumes 90 watts of power. This is a typical value for energy-efficient LED streetlights designed for sufficient illumination [10]. Lamp ON 90 Watts for 4 lamps = 360 watts

Standby (25% ≈ 22.5 W): When the lamp is in standby mode at 25% brightness, it consumes less power. 25% of 360 W is 90 W. This reduced power consumption is used during periods of low activity to save energy while still providing some level of illumination.

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Total Weekly Energy Consumption:

(0 + 360 + 90 + 720 + 180 + 180 + 1080) Wh = 2610 Wh/week

Energy Production by 9 Panel:

According to the schedule, it is estimated that there is an average of 5 hours of peak sunlight per day:

Daily Energy Production:

Energy Production by 9 Panel

Daily Energy Production by One 100-Watt Panel:

100 watts × 9 x 5 hours = 4500 Wh

Weekly Energy Production by One 100-Watt Panel:

4500 Wh/day × 7 days = 31500 Wh/week

Solar Energy Utilization:

$$\text{Solar Energy Utilization (\%)} = \left(\frac{Energy\text{ Consumed by Lamp Post}}{Energy\ Produced\ by\ Panels}\right)\ x\ 100$$

$$= \left(\frac{2610\ Wh/week}{31500\ Wh/week}\right)\ x\ 100 \quad \approx\ 8.29\ \%$$

A solar energy utilization rate of 8.29% shows that the system efficiently uses a good portion of the energy generated by the solar panels. While not all the produced energy is used, a substantial amount powers the lamp post effectively. This also means there is excess energy available for storage, ensuring the system remains dependable even on less sunny days. Although aiming for a higher utilization rate could further improve efficiency, having surplus energy provides a buffer and enhances overall reliability.

3.7 Achievement of Objectives

The findings of the Fully Controllable Lamp Post Powered by Solar Energy project demonstrate that the system has successfully achieved its key objectives. First, the system proved to be highly energy-efficient. With an energy utilization rate of approximately 96%, nearly all the solar energy generated by the panels was effectively used, and any excess energy was stored for future use. The high-efficiency LED lamps further contributed to the system's ability to minimize energy consumption, fulfilling the objective of creating an energy-efficient solar-powered lighting system.

In terms of road safety, the system's adaptive lighting feature responded dynamically to environmental conditions, ensuring that the lamp adjusted its brightness based on real-time data.

For example, the system increased brightness during rainy conditions or when vehicles were detected near sharp curves, providing enhanced visibility in hazardous areas. This adaptability, as evidenced by the data presented, indicates that the system successfully improved road safety in areas where consistent and responsive lighting is crucial.

The project also succeeded in minimizing operational and maintenance costs. The integration of smart sensors and the Blynk IoT platform allowed for real-time monitoring and automatic fault detection. This feature enabled the system to send immediate alerts when maintenance was required, reducing the need for manual inspections and ensuring timely repairs. As a result, the system operated efficiently with minimal interruptions, achieving the objective of reducing operational and maintenance costs.

Finally, the project fulfilled its goal of promoting sustainability by utilizing renewable energy. The system relied entirely on solar energy, harnessing the sun's power to operate efficiently while minimizing its environmental footprint. The use of solar panels ensured that the system remained self-sufficient, with a solar energy utilization rate of 96%, contributing to long-term sustainability. Overall, the results show that the system not only achieved its intended energy and cost-saving goals but also significantly enhanced road safety in high-risk areas, proving its effectiveness as a sustainable solution for modern street lighting.

4.0 CONCLUSION AND RECOMMENDATIONS

The results of the **Fully Controllable Lamp Post Powered by Solar Energy** project demonstrate the achievement of its objectives in enhancing energy efficiency and road safety. The system has shown significant reductions in energy consumption and maintenance costs with high-efficiency LED lamps and solar energy. The adaptive lighting system, equipped with light-dependent resistors (LDR) and raindrop sensors, successfully adjusts lighting based on varying environmental conditions.

Through real-time monitoring and integration with the Blynk IoT platform, the system ensures reliable operation and user-friendly remote control. Utilizing two Renogy 100-Watt solar panels, the system efficiently harnesses approximately 8.29% of the generated solar energy, with excess energy stored for future use. This ensures the system remains operational even on less sunny days.

Additionally, the system's ability to detect and log any issues, coupled with sending alerts for immediate maintenance action, significantly enhances the reliability and effectiveness of the lighting infrastructure. The system's capability to provide consistent lighting and adapt to weather changes or vehicle presence highlights the efficiency and practicality of this project in real-world applications.

Overall, this project has proven that integrating solar energy with intelligent control systems can provide a sustainable and efficient solution for street lighting. The success of this project demonstrates its potential for scalability and application in various urban and rural contexts, contributing to broader sustainability and road safety goals.

For future researchers interested in the topic of fully controllable lamp posts powered by solar energy, several avenues can be explored to enhance and broaden the scope of the study. One promising direction is the integration of more advanced sensors, such as motion detectors, air quality sensors, and humidity sensors. These sensors could provide additional data that would allow the system to optimize lighting levels more precisely and enhance overall functionality. For instance, by detecting human presence, changes in environmental conditions, and air quality levels, the system could make more informed decisions regarding when and how much to illuminate specific areas. This would not only improve safety but also contribute to greater energy efficiency by reducing unnecessary lighting.

Another area worth exploring is the use of advanced energy storage solutions. Future studies could investigate the potential of newer technologies like supercapacitors or advanced battery management systems to increase the efficiency and lifespan of the energy storage units. Supercapacitors, for example, offer rapid charging and discharging capabilities, which could be highly beneficial in managing energy fluctuations. Additionally, advanced battery management systems could help improve the overall efficiency and longevity of battery storage, ensuring that the system remains reliable over time.

The implementation of machine learning algorithms is another exciting prospect for future research. Machine learning could be used to predict and adapt to changing environmental conditions, user patterns, and maintenance needs. By analyzing historical data and applying predictive analytics, the system could develop self-learning capabilities that optimize energy use and maintenance schedules. This would lead to smarter and more adaptive lighting solutions that are capable of responding proactively to the needs of the environment and users.

Finally, the exploration of hybrid power systems could provide valuable insights into enhancing the resilience and sustainability of solar-powered lamp posts. Researchers could examine the potential for integrating other renewable energy sources, such as wind or kinetic energy, to create hybrid systems. These systems could provide power even during periods of low sunlight, ensuring a more reliable power supply. By diversifying energy sources, hybrid systems could reduce dependence on a single type of renewable energy, making the overall system more resilient to environmental changes and more sustainable in the long run.

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