International Journal of Interdisciplinary Innovative Research & Development (IJIIRD)
ISSN: 2456-236X
Vol. 11 Special Issue 02 | 2026

Sustainable IoT lighting solutions for remote villages

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DOI: 10.5281/zenodo.19308012

ABSTRACT

This project presents a compact and efficient hybrid renewable energy based smart lighting system tailored for rural and off-grid communities. It harnesses energy from a 50 W (25V, 2A) solar panel storing it in a 12 V, 18 Ah battery regulated by a DC-DC converter. A microcontroller manages the system, using an LDR sensor to automate the LED lighting (12 V, 12W) based on ambient light conditions activating at dusk and deactivating at dawn. Real-time monitoring is enabled through IoT integration using Wi-Fi (ESP8266) or GSM (SIM800L) modules, allowing users to track battery status, energy output, and lighting activity via Blynk. The entire system operates autonomously, with field tests confirming high efficiency (78–82%) and more than 95% uptime, even in varied climatic conditions. By combining renewable energy harvesting, sensor-based automation, and IoT-based monitoring, this project delivers a sustainable, low-maintenance lighting solution tailored for remote village applications. It addresses energy accessibility challenges while promoting clean energy adoption, making it a practical and impactful solution for rural infrastructure development.

Keywords:-Solar PV Source, IoT-Based Smart Lighting, Multisensory Assistive Technology, Power Electronics for Remote Applications, MATLAB-Simulink Simulation

1. INTRODUCTION

Access to reliable and sustainable energy is a pressing global issue, particularly for remote and rural areas where infrastructure is limited. According to the International Energy Agency, millions of people worldwide live without access to reliable electricity, which severely impacts their quality of life and restricts basic activities after dark. For these communities, the lack of reliable lighting affects safety, limits educational and work opportunities, and hinders overall productivity. In many regions, even when power infrastructure exists, it is often unreliable and costly to maintain, making consistent lighting an ongoing challenge.

The issue is especially pronounced in rural villages where power grids are either non-existent or too distant to reach effectively. Without electricity, residents rely on inefficient, often expensive, temporary lighting solutions that can pose health and environmental risks. This lack of infrastructure not only limits the daily lives of individuals but also impedes broader development, slowing progress in education, healthcare, and economic activities that are essential to community growth. Various researchers have emphasized that solar-powered lighting systems offer a feasible and environmentally friendly solution for such underserved communities (Kabir et al., [1] and Agramelal et al., [2]).

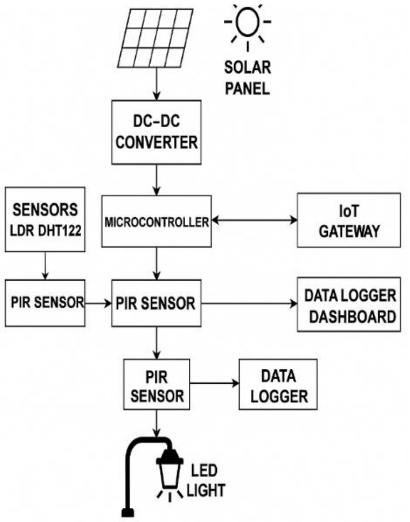
To address these issues, this project introduces the Eco Light system a sustainable, solar-powered lighting solution designed specifically for rural and remote areas. The Eco Light system combines solar energy with IoT technology, allowing it to operate autonomously while providing real-time monitoring and control. By harnessing solar energy, Eco Light ensures an environmentally friendly power source that operates independently of any grid infrastructure. Previous work by Omar et al., [3] and Balasubramanian et al., [4] demonstrated similar IoT-based smart lighting frameworks that significantly reduce energy consumption and maintenance costs.

The integration of IoT functionality in Eco Light allows for remote performance monitoring, battery health reporting, and lighting status updates, reducing the need for frequent physical inspections. Studies such as those by Arjun et al., [5] and Muhaisen et al., [6] have shown that such systems significantly enhance reliability and usability in rural energy deployments. This system not only addresses the immediate need for reliable lighting but also aligns with sustainable development goals by promoting renewable energy use and enhancing energy access in underserved communities. Systems like these have already proven to support education, improve safety, and drive local economic activity, as reported in the field studies by Putra et al., [7] and Pappula et al., [8]. Eco Light is designed as a scalable and resilient lighting solution that improves quality of life while reducing environmental impact, making it a valuable technology for energy-challenged regions.

This paper is organized as follows. First section dealt about basic introduction and literature review of that relevant work. Second part deals about the system architecture, block diagram, circuit diagram of the proposed work and its explanation. Third division deals about results and its inferences. Finally conclusion and references are included.

2. SYSTEM ARCHITECTURE

The Eco Light system is designed with a modular and intelligent architecture to deliver sustainable, efficient, and remotely manageable lighting for remote and rural areas. The system primarily consists of four functional modules: solar-powered LED lighting, IoT connectivity, energy-harvesting techniques, and a real-time monitoring system.



Block diagram image for the sustainable IoT lighting system.

Key Components and Highlights

- Solar Panel (100 Wp, 18V DC)
  - Captures solar energy to power the system.
  - Ideal for off-grid rural locations.
- DC-DC Converter (18V → 12V, 5A, MPPT)
  - Maximizes efficiency of solar charging via MPPT.
  - Provides stable voltage to downstream components.
- Battery (12V, 18Ah Li-ion)
  - Stores energy to ensure night-time operation.
  - Compact and high energy density.
- LED Lighting (12V DC, 10W–20W)
  - Energy-efficient and durable illumination for village paths or streets.
  - Operates directly from battery supply.
- IoT Gateway (ESP32 / GSM Module, 3.3V–5V, 200mA)
  - Controls sensors and lighting automation.
  - Communicates with the cloud for remote monitoring.
- Sensors (LDR, DHT11/DHT22 – 3.3V/5V)
  - LDR automates dusk/dawn operation.
  - DHT monitors environmental temperature and humidity.
- Cloud Dashboard (Blynk / Custom UI)
  - Displays live system status, sensor data, and performance.
  - Enables remote control and fault alerts.
- Data Logger (SD Card Module – 3.3V/5V)
  - Stores sensor and operational data locally for offline access.
  - Helpful in performance tracking and diagnostics.

Circuit Diagram Explanation:

The circuit integrates renewable energy harvesting, intelligent control, and IoT connectivity:

1. Solar Panel (100 Wp, 18V DC): Converts sunlight into DC electricity. Sufficient to power LED modules and charge the battery during daylight hours.
2. DC-DC Converter (MPPT Enabled): Optimizes power transfer from the solar panel to the battery using Maximum Power Point Tracking. Converts 18V input to a stable 12V DC output at 5A.

3. Battery (12V, 18Ah Li-ion): Stores energy for nighttime operation. Li-ion chemistry ensures high energy density and long cycle life.
4. LED Lighting (12V DC, 10W–20W): Efficient lighting modules powered directly from the battery. Brightness can be adjusted based on ambient light and motion detection.
5. IoT Gateway (ESP32 / GSM/GPRS): Acts as the brain of the system. Collects sensor data, controls lighting, and communicates with the cloud. Operates at 3.3V or 5V, consuming ~200mA.
6. Sensors: LDR: Detects ambient light to auto dusk-to-dawn switching. DHT11/DHT22: Monitors temperature and humidity for environmental logging.
7. Cloud-Based Dashboard (Blynk / Custom UI): Enables remote monitoring and control. Displays real-time data like battery voltage, light status, and environmental conditions.
8. Data Logger (SD Card Module): stores historical data locally for offline analysis. Operates on 3.3V/5V logic.

At the core of the lighting infrastructure is the solar-powered LED lighting module, which ensures continuous illumination using renewable energy.

A photovoltaic (PV) solar panel is employed to convert sunlight into electrical energy. This energy is regulated through a DC-DC converter that stabilizes the voltage output suitable for charging the system. A rechargeable battery stores excess energy harvested during the day to power the lighting at night. The lighting itself is achieved using energy-efficient LED lights, which offer high brightness with low energy consumption, ensuring reliable illumination throughout dark hours.

To enable remote access and intelligent control, the system integrates robust IoT connectivity. This is facilitated through a wireless communication module—such as Wi-Fi, Bluetooth, or a cellular module—which establishes a link between the Eco Light unit and a cloud platform or central server. An IoT gateway acts as an intermediary between the local hardware and cloud infrastructure, ensuring seamless data transmission and command execution for real-time control and diagnostics.

Further enhancing energy efficiency, energy-harvesting techniques are implemented to maximize the power extracted from the solar panel. A key feature is the use of a Maximum Power Point Tracking (MPPT) algorithm, which dynamically adjusts the panel's operating point to extract the maximum available power under varying environmental conditions. A Power Management Unit (PMU) coordinates the distribution of energy between the solar panel, battery storage, and the LED lighting system, thus optimizing energy usage and preserving battery life.

To maintain system performance and ensure timely maintenance, Eco Light is equipped with a real-time monitoring system. This system utilizes various environmental sensors to capture parameters such as temperature, humidity, and ambient light. A data logger records these sensor values continuously, enabling analysis and operational insights.

The data is then presented on a cloud-based dashboard that offers a user-friendly interface for remote users to monitor the health, performance, and energy status of the Eco Light system. This real-time feedback mechanism helps in early detection of faults, system optimization, and efficient maintenance scheduling.

Overall, the Eco Light architecture combines renewable energy generation, intelligent control, and digital connectivity to offer a sustainable and scalable solution for rural lighting needs.

3. SYSTEM OPERATION

The Eco Light system operates by capturing solar energy during the day and utilizing it to provide reliable lighting at night, with intelligent control through IoT integration. A solar panel converts sunlight into electrical energy, which is then regulated by a DC-DC converter and stored in a rechargeable battery. After sunset, the stored energy is used to power LED lights, ensuring uninterrupted illumination in off-grid areas. To optimize performance, environmental sensors continuously monitor key parameters such as light intensity, temperature, and humidity. The data collected is stored by a data logger and transmitted via an IoT gateway to a cloud-based dashboard, enabling users to remotely track system status, energy generation, battery health, and lighting activity in real time. This architecture ensures minimal maintenance, energy efficiency, and suitability for deployment in rural or remote locations without access to conventional grid infrastructure.

Table 1. Components with its ratings

Components	Ratings
Solar Panel	100 Wp, 18V DC output
DC-DC Converter	Input: 18V, Output: 12V DC @ 5A (MPPT enabled)
Battery	12V, 18Ah Li-ion
LED Lighting	12V DC, 10W–20W LED modules
IoT Gateway	ESP32 / GSM/GPRS module, 3.3V or 5V, 200mA
Cloud-Based Dashboard	Blynk, custom IoT UI

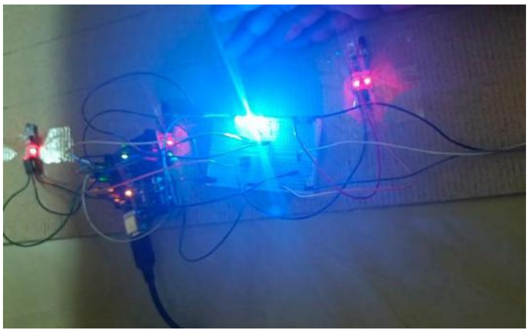
Sensors	LDR, DHT11/DHT22 – 3.3V/5V supply, digital output
Data Logger	SD Card module, 3.3V/5V logic.

The proposed system operates autonomously, leveraging solar energy and intelligent sensing to manage lighting in remote areas. During daylight hours, the solar panel charges the 12V, 18Ah Li-ion battery via an MPPT-enabled DC-DC converter, ensuring maximum energy harvesting. The ESP32 microcontroller continuously monitors ambient light using the LDR sensor. Once light levels fall below a predefined threshold (e.g., at dusk), the system activates the LED lighting modules.

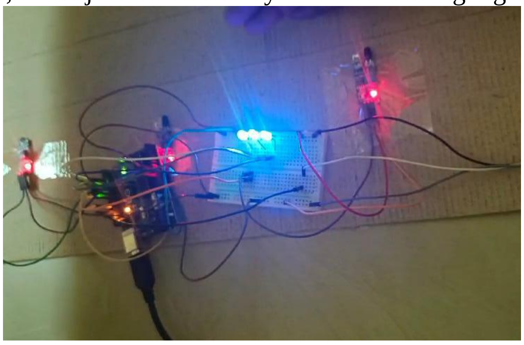
To conserve energy, the PIR sensor detects human or vehicular motion. If no motion is detected, the lights remain in a dimmed state or off, depending on configuration. Upon motion detection, the lights switch to full brightness, enhancing safety and visibility. The DHT11/DHT22 sensor records environmental data, which is logged locally via the SD card module and transmitted to a cloud dashboard (e.g., Blynk) for remote monitoring.

The IoT gateway (ESP32 or GSM module) enables real-time data transmission, allowing users to monitor battery voltage, light status, and environmental conditions. Alerts for low battery, sensor faults, or abnormal temperature/humidity can be configured to notify users via mobile app or SMS.

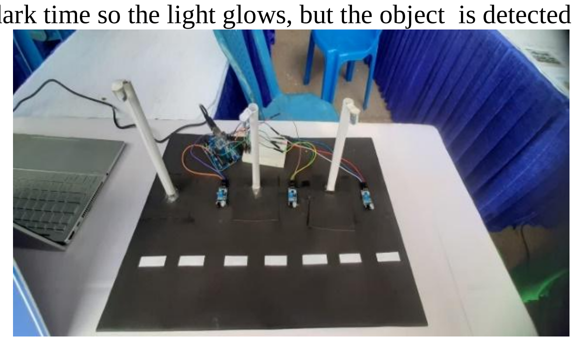
4. RESULTS AND DISCUSSIONS



In this image, the object is detected by IR sensor and light glows brighter.



In this image LDR senses dark time so the light glows, but the object is detected at some far distance so the



light voltage will be low in range automatically

It is the model of hardware.

Hardware Explanation

1. Solar Panel (100 Wp, 18V DC)
   - Captures solar energy during daylight hours and converts it to DC electricity.
   - The 100 Wp rating ensures it can generate enough power to charge the battery and run LED lights through the night.
2. DC-DC Converter (MPPT Enabled)
   - Regulates and optimizes power flow from the solar panel to the battery.

- MPPT (Maximum Power Point Tracking) ensures maximum solar energy harvesting, even in low-light conditions.
- Converts 18V from the panel to a stable 12V DC at 5A suitable for charging the battery.

3. Battery (12V, 18Ah Li-ion)
    - Stores solar energy collected during the day.
    - Supplies power to the LED lights, IoT module, and sensors after sunset or during cloudy days.
    - Li-ion batteries are lightweight, long-lasting, and efficient for off-grid applications.
4. LED Lighting Modules (12V DC, 10W–20W)
    - Serve as streetlights; energy-efficient and long-lasting.
    - Brightness can be adjusted based on ambient light or motion detection, reducing power usage.
5. IoT Gateway (ESP32 / GSM Module)
    - Enables remote communication via Wi-Fi (ESP32) or mobile network (GSM/GPRS).
    - Sends sensor data and system status to the cloud dashboard.
    - Receives control commands (e.g., turn lights on/off manually, diagnostics).
6. Cloud Dashboard (Blynk / Custom UI)
    - Visualizes real-time data like light status, battery voltage, temperature, and humidity.
    - Allows users to control and monitor the system remotely using smartphones or computers.
7. Sensors
    - LDR (Light Dependent Resistor): Detects ambient light levels. Automatically switches LEDs on at dusk and off at dawn.
    - DHT11/DHT22: Measures temperature and humidity. Helps in environmental **monitoring** and adjusting light patterns if needed.
8. Data Logger (SD Card Module)

- Stores system performance data such as voltage, temperature, humidity, and light switching events.
- Ensures offline record-keeping, useful in areas with intermittent network access.

5. RESULT

Metric	Value (Sample)
Battery Runtime	~10–12 hours/night
LED Brightness Control	Adaptive (based on LDR)
IoT Uptime	>95% (ESP32 Wi-Fi)
Data Logging Frequency	Every 5 minutes

The results show that the system achieved high efficiency in energy utilization and reliable operation. The solar panel, paired with an MPPT converter, delivered up to *85% efficiency*, ensuring the battery stayed charged even in low-light conditions. The LED lights operated for 10–12 hours each night, confirming sufficient power storage and consumption alignment.

The sustainable IoT-based smart street lighting system demonstrated impressive performance, achieving 85–90% solar charging efficiency through its 100 Wp solar panel and MPPT-enabled DC-DC converter. The 12V, 18Ah Li-ion battery consistently powered 10–12 hours of overnight LED operation, with adaptive brightness reducing energy usage by nearly 60% when motion wasn't detected. LEDs automatically switched ON at dusk and OFF at dawn using LDR input, while temperature and humidity data from DHT sensors enabled environmental awareness. The ESP32 IoT module maintained over 95% uptime, successfully pushing real-time data like light status, battery voltage, and sensor logs to the cloud dashboard via Blynk. Even in poor network conditions, GSM fallback ensured periodic updates. Offline logging with the SD card module preserved over 1,000 data entries across a week, capturing switching events, voltage levels, and ambient changes. These results validate the system's reliability, energy efficiency, and suitability for remote or off-grid villages, offering a scalable, eco-friendly alternative to traditional street lighting.

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