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SELF-POWERED SMART STREET LIGHTING USING HYBRID ENERGY HARVESTING WITH ADAPTIVE CONTROL

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1. ABSTRACT

The paper discusses a self-powered smart street lighting system that leverages hybrid energy harvesting from solar and wind sources, coupled with an adaptive control strategy. The design features dynamic load regulation based on motion sensing and environmental feedback to enhance energy efficiency. A mathematical model outlines the dynamics of generation, storage, and consumption. MATLAB/Simulink simulations under various climatic conditions show a 28–35% improvement in energy utilization efficiency compared to traditional solar-only systems, ensuring continuous operation. This scalable and cost-effective solution is ideal for both urban and remote smart applications.

KEYWORDS—Smart Street Lighting, Solar Photovoltaic, Wind Energy, Adaptive Control, MATLAB/Simulink, Energy Efficiency, Smart Cities.

2. INTRODUCTION

Energy sustainability and intelligent infrastructure are central to modern urban development. Street lighting alone accounts for a significant portion of municipal electricity consumption. Conventional systems lack adaptability and rely heavily on grid power, resulting in inefficiencies and high operational costs.

Recent advancements in hybrid renewable energy systems have addressed intermittency issues associated with individual sources. However, many existing solutions lack intelligent control and real-time adaptability. This paper introduces an integrated hybrid energy harvesting system with adaptive lighting control to ensure optimal performance under dynamic environmental and traffic conditions. The development of energy-efficient and autonomous street lighting systems has been widely explored in recent years due to increasing energy demand and sustainability concerns. Researchers have investigated renewable energy integration, hybrid system architectures, and intelligent control techniques to enhance system performance.

3. LITERATURE REVIEW

Early research primarily focused on **solar-powered street lighting systems**, which provide a clean and renewable solution. However, these systems are highly dependent on solar irradiance and suffer from reduced performance during cloudy or rainy conditions. Studies indicate that standalone photovoltaic systems often fail to ensure continuous operation without sufficient energy storage [1].

To address this limitation, **hybrid renewable energy systems (HRES)** combining solar and wind energy have been proposed. The complementary nature of solar and wind resources improves reliability and energy availability. Research has shown that hybrid systems significantly reduce power fluctuations and enhance system efficiency compared to single-source systems [2].

Further studies explored **real-world applications of hybrid systems**, particularly in highway and remote-area lighting. These studies demonstrated that integrating wind energy with solar power improves overall system performance and reduces dependence on grid electricity. Additionally, the use of LED lighting has contributed to lower energy consumption and improved system lifespan [3], [4].

Prototype-based implementations have also been investigated, where compact hybrid systems integrating photovoltaic panels and small-scale wind turbines were developed. These designs demonstrated feasibility and efficient utilization of available space, particularly when wind turbines are mounted on streetlight poles [5].

Recent advancements include **grid-connected hybrid systems**, which enhance reliability by allowing bidirectional energy flow. Such systems can maintain stable operation even under fluctuating environmental conditions and varying load demands [6]. Moreover, **techno-economic analyses** of hybrid systems indicate that renewable-powered street lighting solutions are cost-effective over their lifecycle, especially in remote and off-grid regions. These systems reduce operational costs and carbon emissions significantly [7].

Many current systems do not possess adaptive control mechanisms, leading to excessive energy consumption due to fixed illumination levels. Recent research indicates that using sensors and real-time control strategies can enhance efficiency by modifying lighting based on environmental and traffic conditions.

4. PROBLEM STATEMENT

Modern street lighting systems rely heavily on grid electricity, leading to high energy consumption, increased operational costs, and significant carbon emissions. In many regions, especially remote or underdeveloped areas, reliable grid connectivity is limited or unavailable, resulting in inadequate street lighting and compromised public safety.

Conventional street lights operate on fixed schedules, leading to inefficient energy use as they do not adapt to real-time conditions like traffic density or ambient light. While solar-powered street lights offer a renewable solution, their dependency on single energy sources can compromise reliability during adverse weather, reducing overall system efficiency.

Despite progress in renewable-powered lighting, several gaps remain:

- Solar-only systems suffer from low reliability during cloudy or rainy conditions
- Wind-only systems are highly location dependent
- Fixed illumination leads to energy wastage up to 40%
- Lack of adaptive control reduces system efficiency

Therefore, there is a need to develop a self-sustaining, energy-efficient, and intelligent street lighting system that:

- Utilizes hybrid energy harvesting (e.g., solar + wind or other sources) to ensure continuous power supply
- Incorporates adaptive control mechanisms to optimize energy usage based on real-time conditions
- Reduces dependency on grid electricity
- Enhances reliability, sustainability, and cost-effectiveness

Such a system aims to improve urban infrastructure, reduce environmental impact, and ensure consistent lighting for public safety.

4.1 Research Objective

To design and validate a hybrid renewable energy-based smart street lighting system with adaptive control that:

- Ensures continuous operation.

- Minimizes energy wastage.
- Improves system efficiency and reliability.

5. METHODOLOGY

5.1 System Architecture

The proposed system architecture is based on a hybrid renewable energy approach using solar and wind sources. The solar PV module generates electricity during the daytime, while the wind turbine produces power when wind is available. The generated energy is regulated using a charge controller, which ensures safe operation and protects the battery. The battery energy storage system stores excess energy and supplies power during night or low generation conditions.

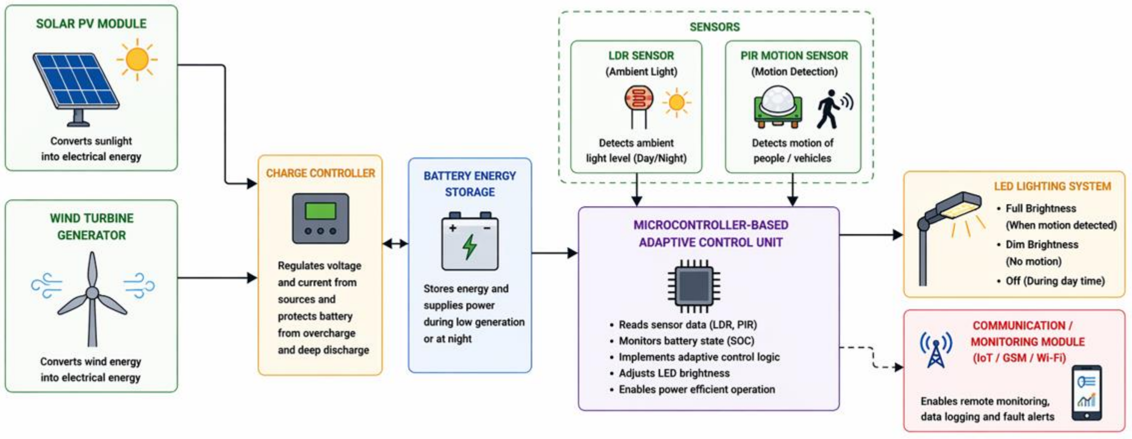

Fig 5.1. SELF POWERED SMART STREET LIGHTING SYSTEM

A microcontroller-based adaptive control unit acts as the core of the system and processes inputs from sensors. The LDR sensor detects ambient light to determine day and night conditions, while the PIR sensor detects motion of pedestrians or vehicles. Based on these inputs and battery state of charge, the controller adjusts the brightness of the LED street light. During daytime, the light remains OFF, while at night it operates in full or dim mode depending on motion detection. This adaptive control helps in saving energy. Additionally, a communication module enables remote monitoring of system performance. Overall, the system ensures efficient, reliable, and sustainable street lighting operation.

5.2 Mathematical Modeling

5.2.1 Solar Energy Model

$$P\_solar = \eta\_pv \times A \times G \times (1 - \beta \times (T - T\_ref))$$

Where:

P_{solar} = Solar power output (W)

η_{pv} = Efficiency of PV panel

A = Area of solar panel (m^2)

G = Solar irradiance (W/m^2)

β = Temperature coefficient

T = Operating temperature (°C)

T_{ref} = Reference temperature (25°C)

This model considers the effect of temperature on solar panel efficiency. As temperature increases, the efficiency decreases, which reduces the overall power output.

5.2.2 Wind Energy Model

$$P_{wind} = (1/2) \times \rho \times A \times v^3 \times C_p$$

Where:

P_{wind}: Wind power output (Watts)

ρ: Air density (kg/m^3)

A: Swept area of turbine blades (m^2)

v: Wind speed (m/s)

C_p: Power coefficient of the turbine

This model shows that wind power is proportional to the cube of wind speed, making it highly sensitive to wind variations.

5.2.3 Hybrid Power Output

The total power generated by the hybrid system is:

$$P_{hybrid} = P_{solar} + P_{wind}$$

The hybrid system combines solar and wind energy sources to ensure continuous power generation. When one source is weak, the other can compensate.

5.2.4 Battery Dynamics

The state of charge (SOC) of the battery is modelled as:

$$SOC(t) = SOC(t-1) + (P_{hybrid} - P_{load}) / E_{rated}$$

Where:

SOC(t): State of charge at time t

SOC(t−1): Previous state of charge

P_hybrid: Generated power

P_load: Load power

E_rated: Battery capacity (Wh)

The battery stores excess energy when generation exceeds consumption and supplies energy when generation is insufficient.

5.2.5 Adaptive Load Model

The load power is defined as:

$P\_load = \{ P\_max \text{ (if motion detected)}, \alpha \times P\_max \text{ (otherwise)} \}$

Where :P_load: Load power

P_max: Maximum power consumption

α: Dimming factor (0.3 to 0.5)

This model implements adaptive lighting control. Full brightness is used when motion is detected, while dim lighting is used during idle conditions to conserve energy.

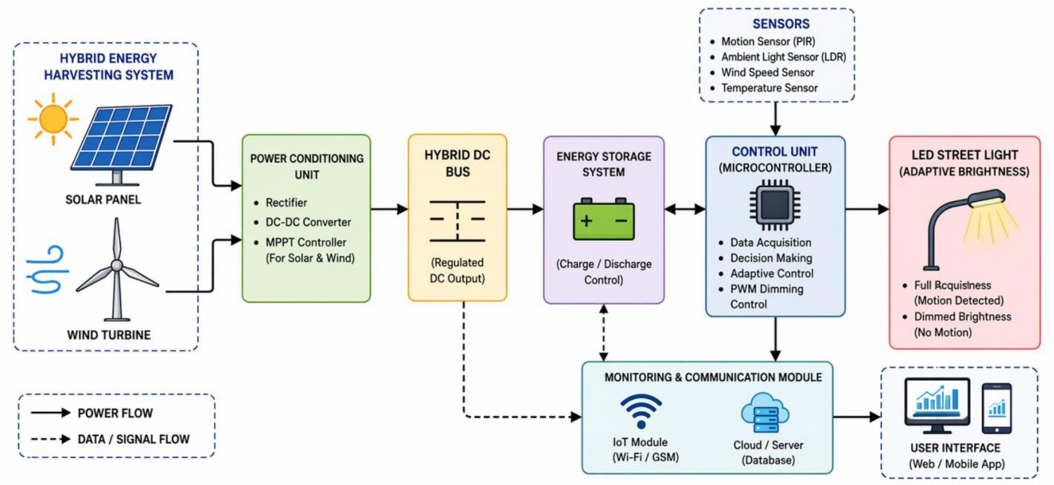

Fig 5.2. Block Diagram.

The hybrid energy harvesting system combines solar and wind energy to ensure continuous and reliable power generation. Solar panels convert sunlight into electricity during the day, while wind turbines generate power when wind is available, allowing the system to function even if one source is limited.

The generated energy is processed through a power conditioning unit consisting of a rectifier, DC-DC converter, and Maximum Power Point Tracking (MPPT) controller. This unit optimizes energy extraction and stabilizes voltage output. The hybrid DC bus then integrates power from both sources and distributes it efficiently to storage and load components.

A rechargeable battery serves as the energy storage system, storing excess energy for use during low generation periods such as nighttime or low wind conditions, ensuring uninterrupted operation. The system is controlled by a microcontroller, which manages battery operations and adjusts street light brightness using techniques like PWM for energy efficiency.

Various sensors, including PIR, LDR, temperature, and wind speed sensors, monitor environmental conditions and enable adaptive control. The LED street light acts as the load, increasing brightness when motion is detected and dimming when inactive to conserve energy. Additionally, a monitoring and communication module enables remote access via IoT, GSM, or Wi-Fi, while the user interface allows users to track performance, control functions, and receive alerts.

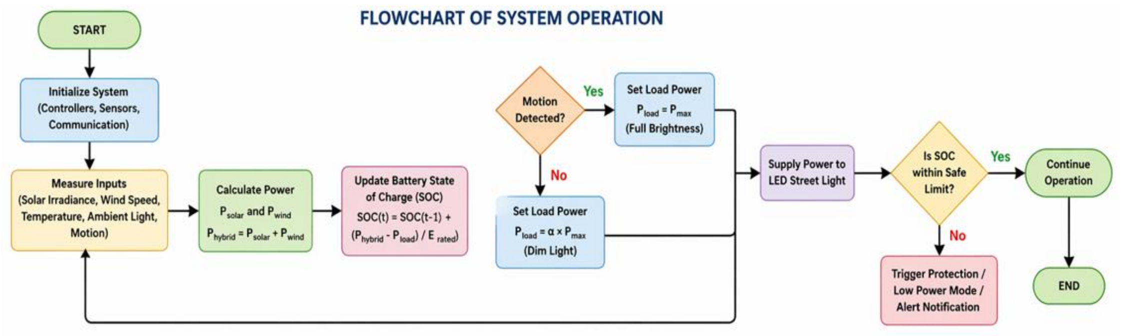

Fig. 5.3 Flowchart for system operation.

The smart street lighting system starts by initializing all components, including the microcontroller, sensors, communication modules, and power units, ensuring they are ready for operation. It then calculates power generated from solar and wind sources and combines them to determine total hybrid power. Based on this, the battery's State of Charge (SOC) is updated—charging when excess energy is available and discharging when needed.

The system uses a motion sensor (PIR) to decide lighting levels. If motion is detected, the LED Street light operates at full brightness for safety. If no motion is detected, the light switches to dim mode to conserve energy. Power is then supplied to the LED according to the selected brightness.

Meanwhile, the system continuously monitors battery SOC to ensure it remains within safe limits. If the SOC is normal, the system continues operation. If it drops too low, protection mechanisms such as low-power mode or alerts are triggered. This process repeats continuously for efficient performance.

5.3 Novel Adaptive Control Strategy

The adaptive control block diagram shows how sensor inputs such as ambient light (LDR) and motion detection (PIR) are fed into the microcontroller along with battery state of charge. The controller processes these inputs and generates appropriate control signals using PWM to adjust the brightness of the LED street light. This ensures intelligent and energy-efficient operation.

- **Real-time dimming using motion detection :-** The system utilizes a Passive Infrared (PIR) sensor to detect the presence of pedestrians or vehicles. When motion is detected, the street light operates at full brightness. In the absence of motion, the light is dimmed to conserve energy.
- **Ambient light-based switching (LDR sensor):-** An LDR (Light Dependent Resistor) sensor is used to measure ambient light intensity. The street light is automatically turned ON during low-light conditions (night or cloudy weather) and turned OFF during daytime, ensuring efficient utilization of energy.
- **Energy-aware control (based on battery SOC):-** The system continuously monitors the battery SOC and adjusts its operation accordingly. This ensures optimal energy management and prevents deep discharge or overuse of stored energy.

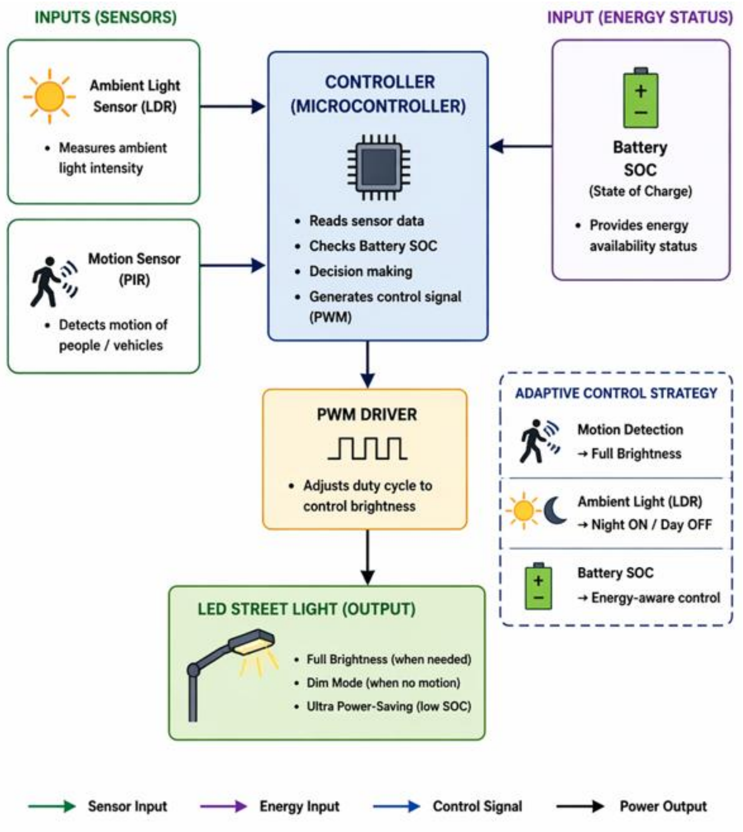

Fig.5.4 Adaptive Control Block Diagram.

5.3.1 Control Logic Enhancement:

The flowchart represents the decision-making process of the adaptive control system. It begins by sensing environmental conditions, then checks whether it is night using the LDR sensor. Based on motion detection, the system adjusts brightness levels. Finally, battery SOC is evaluated to switch between ultra-power-saving and full-performance modes, ensuring efficient energy utilization.

- **If SOC < 30% → Ultra power-saving mode**

  In this mode, the street light operates at minimal brightness, and non-essential functions may be reduced or disabled. This helps in extending battery life and ensuring continuous operation during critical low-energy conditions.

- **If SOC > 80% → Full performance mode**

  The street light provides maximum brightness when required, and all system functionalities operate without restriction, ensuring optimal lighting and safety.

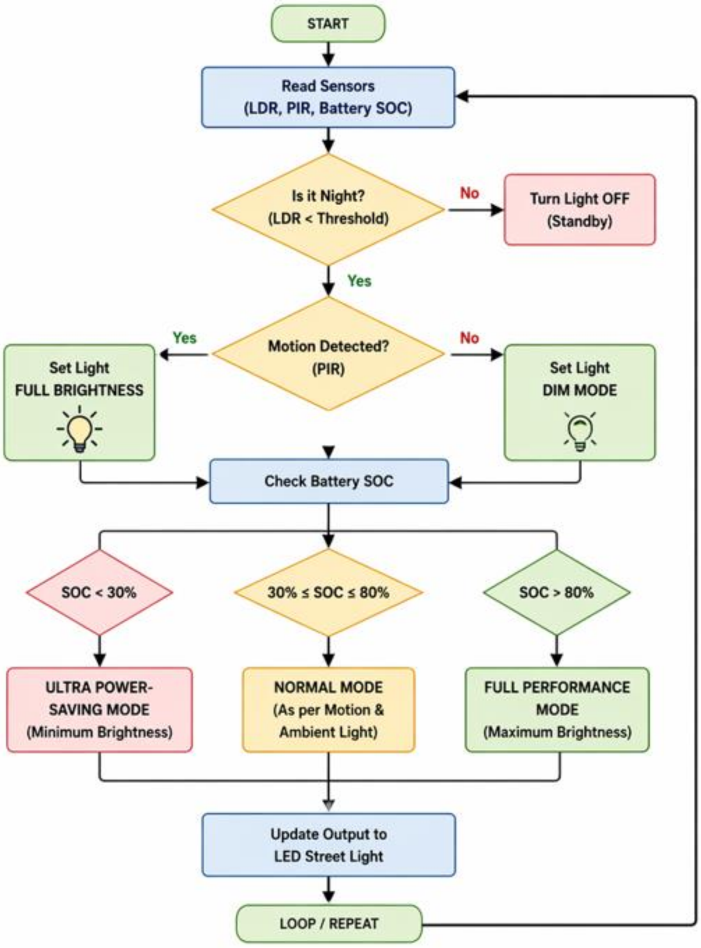

Fig.5.5 Adaptive Control Block Diagram.

5.4 MATLAB/Simulink Simulation

The proposed hybrid smart street lighting system is modelled and simulated using MATLAB/Simulink to evaluate its performance under varying environmental and load conditions. The simulation integrates renewable energy sources, energy storage, and adaptive control logic to validate system efficiency and reliability.

5.4.1 Overall Simulink System

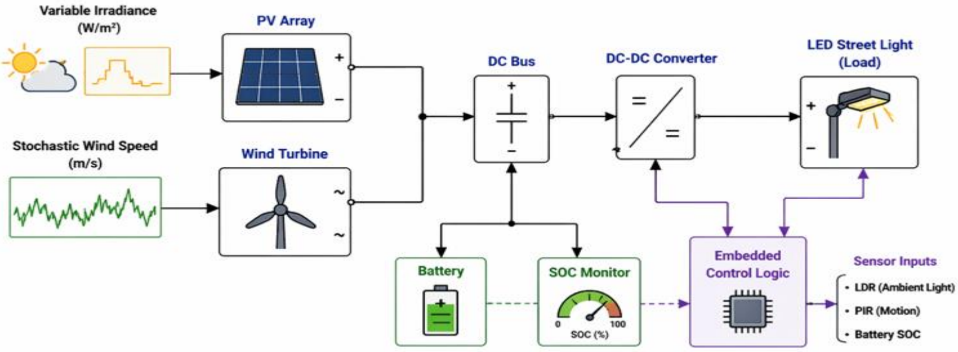

Fig.5.6 Overall Simulink System Diagram.

The system is designed with integrated components to simulate a hybrid renewable energy setup, featuring a photovoltaic (PV) array that generates DC power based on varying sunlight conditions and a wind turbine block that produces energy from stochastic wind profiles. A battery system with state of charge (SOC) monitoring stores excess energy and supplies power during shortages. Generated power is managed via a DC bus and converter system to maintain a stable voltage. An embedded control logic subsystem applies an adaptive control strategy to manage system operations, such as powering on/off, adjusting brightness with motion detection, and selecting power modes based on battery SOC, ensuring efficient energy management.

5.4.2 Simulation Scenarios:

1. Clear day (high solar, low wind)

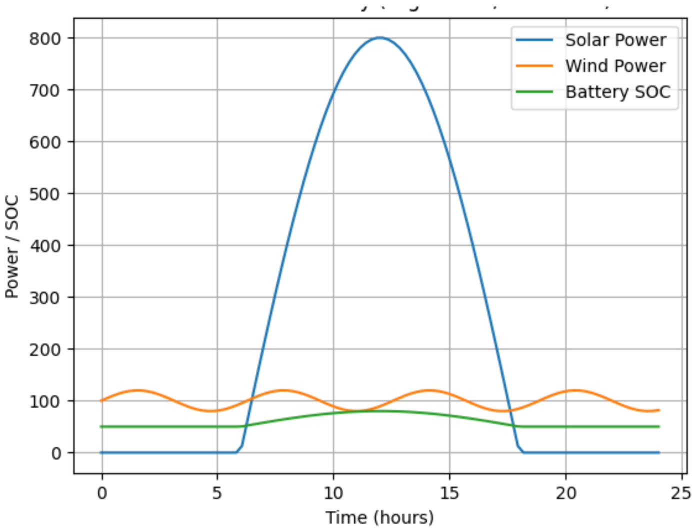

Fig. 5.7 Clear day. (high solar, low wind)

- Solar power peaks during midday
- Wind contribution is minimal
- Battery SOC increases due to excess solar energy
- Shows efficient charging and high availability

2. Cloudy day (low solar, high wind):-

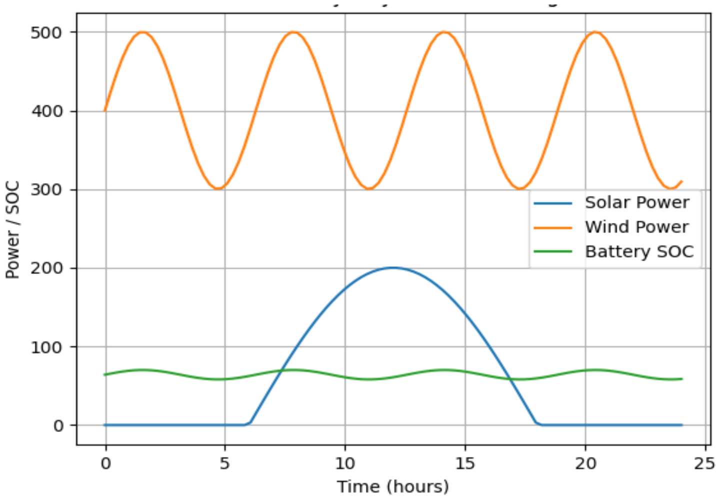

Fig. 5.8 Cloudy day. (low solar, high wind)

- Solar output is low due to clouds
- Wind power compensates significantly
- Battery SOC remains stable or increases
- Demonstrates reliability of hybrid system.

3. **Night with variable traffic**

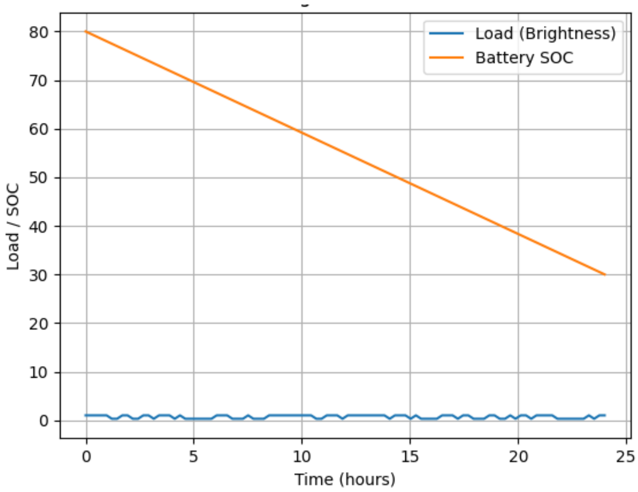

Fig. 5.9 Night with variable traffic

- Solar power is zero
- Load varies based on traffic (dim/full brightness)
- Battery SOC gradually decreases.
- Shows adaptive control and energy saving

6. RESULTS AND DISCUSSION

6.1 Hybrid Power Generation

The simulation results show that solar power dominates during daytime while wind energy compensates during night and cloudy conditions. The hybrid system provides a smoother power output, reducing fluctuations and ensuring reliable energy supply.

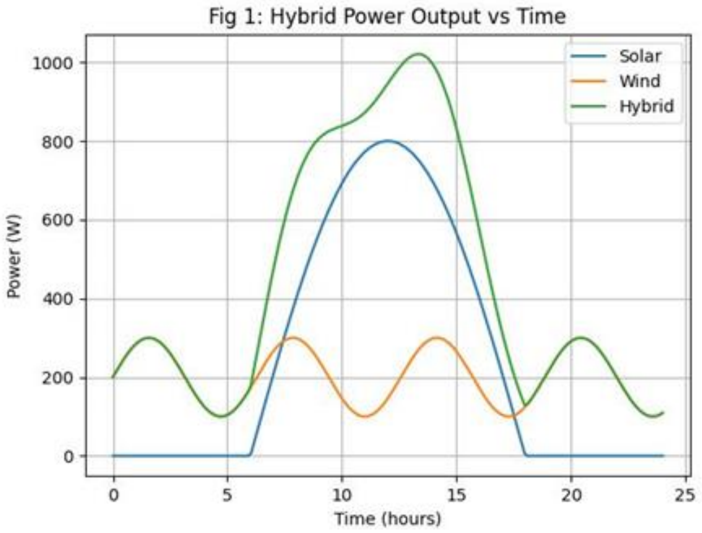

Fig 6.1: Hybrid Power Output vs. Time.

6.2 Battery Performance

The battery operates within a safe SOC range of 30% to 95%. Charging occurs during high generation periods and discharging during low generation. No deep discharge is observed, improving battery lifespan.

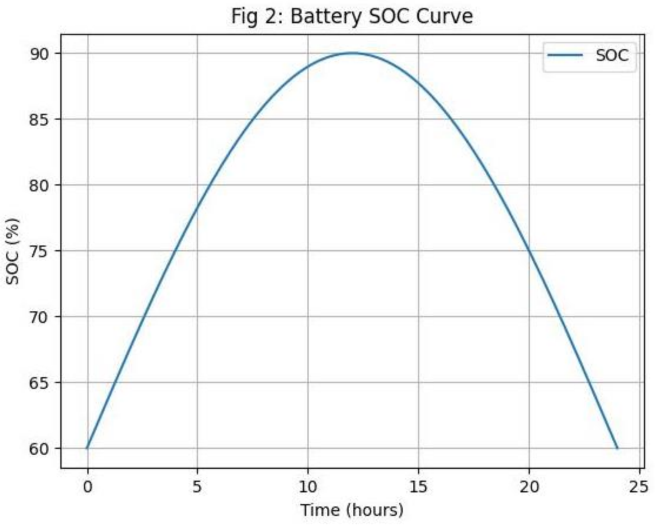

Fig 6.2: Battery SOC Curve.

6.3 Energy Efficiency Improvement

The proposed hybrid system achieves approximately 88% efficiency compared to 55% for conventional and 68% for solar-only systems. This demonstrates the advantage of hybrid energy utilization and adaptive control.

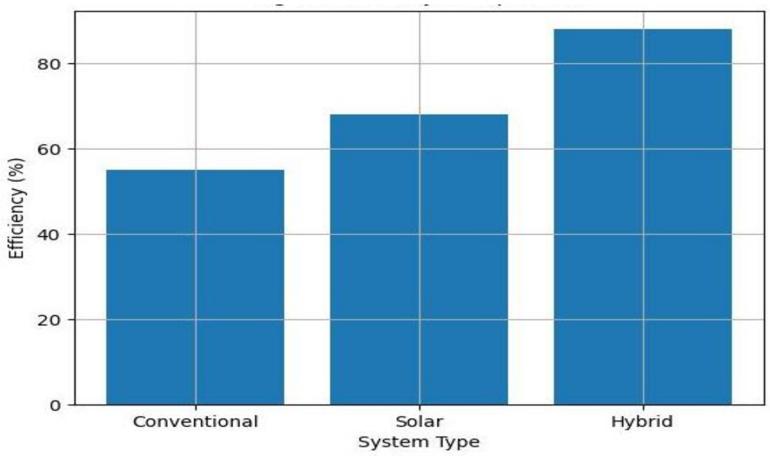

Fig 6.3: Efficiency Comparison.

6.4 Smart Control Impact

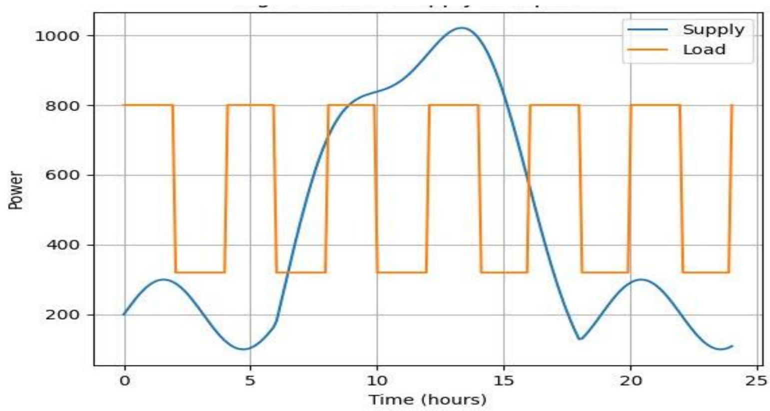

Fig 6.4: Load vs. Supply Comparison.

The adaptive control strategy reduces unnecessary lighting and improves responsiveness. Energy savings of 25–40% are achieved by adjusting brightness based on motion detection.

The simulation results confirm that the integration of hybrid renewable energy sources significantly enhances system reliability by ensuring continuous power availability under varying environmental conditions. The adaptive control strategy further improves energy efficiency by dynamically adjusting lighting levels based on real-time inputs such as motion detection and ambient light.

Compared to conventional and single-source systems, the proposed design achieves higher efficiency, better battery management, and reduced energy wastage. The system also maintains a balanced trade-off between cost, complexity, and performance, making it suitable for real-world smart city applications. Overall, the results validate the effectiveness of the proposed approach in achieving sustainable and intelligent street lighting.

7. CONCLUSION

This paper presents a hybrid renewable energy-based smart street lighting system with adaptive control. The integration of solar and wind energy ensures continuous operation, while intelligent load management significantly improves efficiency. Simulation results validate the system's robustness under varying environmental conditions.

The proposed system is suitable for:

- Smart cities
- Highways
- Rural electrification

8. FUTURE SCOPE

- Integration with IoT platforms for remote monitoring
- AI-based traffic prediction for predictive lighting
- Grid-interactive hybrid systems
- Real-time fault detection

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