iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 Issue: IV Month of publication: April 2026

DOI: https://doi.org/10.22214/ijraset.2026.79808

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue IV Apr 2026- Available at www.ijraset.com

Hybrid Solar - Grid Smart Street Lightning with Fault and Battery Monitoring System

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***Abstract:* Street lighting consumes a considerable amount of energy, especially in rural and off-grid areas where grid-based systems are inefficient and unreliable. This work presents a hybrid solar–battery powered smart street-light system using an ESP32 microcontroller for autonomous and energy-efficient operation. Solar energy is harvested through a photovoltaic panel and stored in a rechargeable battery, which powers an LED street light during nighttime. Automatic ON/OFF control is achieved using an ambient light sensor (LDR).The system employs dual voltage-sensing circuits to monitor battery and solar-panel voltages, enabling intelligent power management and system health monitoring. Fault-detection logic identifies lamp failure, battery issues, and solar-panel performance degradation. Real-time monitoring and fault alerts are provided through a WiFi-enabled dashboard using ESP32.The proposed system offers a reliable, off-grid-capable, and low-maintenance street-lighting solution suitable for rural areas and smart-city applications.**

***Index Terms:* Solar street lighting, Hybrid energy system, ESP32 microcontroller, Battery energy storage, Light dependent resistor (LDR), Voltage sensing, Fault detection, Internet of Things (IoT), Smart lighting system.**

I. INTRODUCTION

Street lighting plays a vital role in ensuring road safety, public security, and accessibility during nighttime. Conventional street-light systems are generally powered by grid electricity and operated using manual switches or fixed timers. Such systems often suffer from high energy consumption, recurring electricity costs, frequent maintenance requirements, and inefficient operation. In many cases, street lights remain switched ON during daylight hours or fail to operate during power outages, leading to energy wastage and safety concerns. These problems are more severe in rural and remote areas where grid power is unreliable or completely unavailable.

With increasing global emphasis on energy conservation and environmental sustainability, renewable energy–based lighting solutions have gained significant attention. Solar energy, being abundant, renewable, and environmentally friendly, provides an effective alternative to conventional grid-powered street lighting. Solar-powered street-light systems combine photovoltaic panels with rechargeable batteries to store energy during the day and provide illumination at night. Such systems reduce dependency on grid electricity, lower operational costs, and minimize carbon emissions.Recent advancements in microcontrollers and embedded systems have enabled the development of intelligent and autonomous street-lighting solutions. Automatic street-light control using ambient light sensors, such as Light Dependent Resistors (LDRs), allows lights to switch ON at dusk and OFF at dawn without human intervention. While many existing solar street-light systems achieve basic automation, they often lack intelligent energy management, system health monitoring, and fault-detection capabilities. As a result, issues such as battery degradation, lamp failure, or reduced solar-panel performance may remain undetected for long periods, increasing maintenance cost and reducing system reliability.To address these limitations, this project proposes a hybrid solar–battery powered smart street-light system controlled by an ESP32 microcontroller. The system integrates solar energy harvesting, battery storage, automatic lighting control, dual voltage monitoring, and fault detection. Furthermore, real-time system data and alerts are made available through a WiFi-enabled monitoring dashboard, enabling remote supervision and preventive maintenance. The proposed solution aims to provide a reliable, energy-efficient, and low-maintenance street-lighting system suitable for rural areas, highways, and smart-city infrastructure.

A. Role of Renewable Energy and Automation in Smart Street Lighting

The increasing demand for sustainable energy solutions has led to widespread adoption of renewable energy sources, particularly solar energy, for public infrastructure. Solar-powered street-light systems utilize photovoltaic panels to convert sunlight into electrical energy, which is stored in batteries for nighttime operation. Such systems significantly reduce dependence on grid electricity, lower carbon emissions, and decrease long-term operational costs.

Automation using sensors and microcontrollers further enhances system efficiency. Ambient light sensors such as Light Dependent Resistors (LDRs) enable automatic switching of street lights based on day and night conditions, eliminating the need for manual control. However, many existing solar street-light systems focus only on basic automation and do not provide intelligent power management, system health monitoring, or fault-detection mechanisms. This limitation reduces system reliability and increases maintenance challenges over long-term operation.

B. Proposed Hybrid Smart Street-Light System Using ESP32

To address the shortcomings of existing systems, this project proposes a hybrid solar–battery powered smart street-light system using an ESP32 microcontroller. The system integrates solar energy harvesting, rechargeable battery storage, automatic ON/OFF control using an LDR, and dual voltage-sensing circuits for continuous monitoring of battery and solar-panel performance.The ESP32-based controller implements intelligent power-management logic to select the appropriate power source and protect the battery from deep discharge. Fault-detection mechanisms are included to identify lamp failure, battery charging issues, and solar-panel performance degradation due to shading or dust accumulation. Furthermore, the system provides real-time monitoring and fault alerts through a WiFi-enabled dashboard, allowing remote supervision and preventive maintenance. The proposed system is suitable for deployment in rural areas, highways, and smart-city infrastructure, offering a reliable, energy-efficient, and low-maintenance street-lighting solution.

II. LITERATURE SURVEY

Several researchers have worked on automatic street-lighting systems to improve energy efficiency and reduce manual intervention. Early studies focused on the use of microcontrollers combined with Light Dependent Resistors (LDRs) to automatically switch street lights ON at dusk and OFF at dawn. These systems demonstrated significant energy savings and simple implementation; however, they primarily addressed basic automation and did not include monitoring or diagnostic capabilities [1], [11].

With the increasing demand for renewable energy solutions, solar-powered street-lighting systems gained attention. Researchers proposed off-grid solar street lights using photovoltaic panels and battery storage to provide reliable illumination in remote and rural areas. These systems reduced dependency on grid electricity and operational costs but required proper sizing of solar panels and batteries to ensure reliability [3], [9]. Some studies further explored hybrid systems combining solar energy with battery storage or grid backup to enhance availability and system robustness [10]. Automation was further improved by integrating motion detection and adaptive lighting techniques. Several works combined LDR sensors with PIR or IR motion sensors to dynamically control light intensity based on traffic or pedestrian movement, thereby reducing power consumption and extending battery life [4], [8], [14]. Although these systems improved energy efficiency, they still lacked comprehensive power-source health monitoring.

Recent research emphasized fault detection and maintenance-oriented designs. IoT-based street-light systems were developed to detect lamp failure, wiring faults, and abnormal operating conditions using voltage and current sensing techniques. These systems transmitted fault information via GSM, SMS, or WiFi to maintenance personnel, reducing downtime and manual inspection requirements [2], [7], [12], [13].

Advancements in IoT and embedded platforms led to the adoption of ESP32 and similar WiFi-enabled microcontrollers for real-time monitoring. Several studies implemented ESP32-based systems capable of monitoring battery voltage, solar-panel output, and ambient light conditions, with data visualized on web dashboards or cloud platforms. Such approaches improved system visibility and enabled remote supervision [5], [6], [15]. To improve measurement accuracy, researchers incorporated precision voltage and current sensors such as INA219 and INA226. These sensors enabled real-time estimation of battery state, load current, and energy consumption, allowing better fault detection and power-management decisions [5]. Some studies also introduced intelligent control strategies such as hybrid source switching and maximum power point tracking (MPPT) to maximize solar energy utilization and protect battery health [1], [6].

Despite these advancements, existing literature reveals certain limitations. Many systems focus either on automation or monitoring but do not integrate dual-voltage sensing for both solar and battery health. Additionally, fault-detection mechanisms capable of distinguishing between lamp failure, battery degradation, and solar-panel issues are limited. Comprehensive systems combining hybrid power management, fault detection, and real-time monitoring using ESP32 remain relatively underexplored [2], [3]. These gaps motivate the proposed hybrid solar–battery powered smart street-light system with integrated diagnostics and IoT-based monitoring.

A. Equations

1) Equation 1: Solar Panel Output Power

The electrical power generated by the solar panel is given by Eq. 1.

The electrical power generated by the solar panel is given by:

$$P_{solar} = V_{solar} \times I_{solar}$$

where:
Psolar = solar panel output power (W)
Vsolar = solar panel voltage (V)
Isolar = solar panel current (A)
Equation 1 is used to calculate the instantaneous power produced by the photovoltaic panel during daylight hours.

2) Equation 2: Battery Stored Energy
The energy stored in the battery is expressed using Eq. 2.
The energy stored in the battery is expressed as:

$$E_{battery} = V_{battery} \times C_{battery}$$

where:
Ebattery = stored energy (Wh)
Vbattery = battery voltage (V)
Cbattery = battery capacity (Ah)
Equation 2 represents the total electrical energy available for night-time operation of the street light.

3) Equation 3: Battery Charging Power
The charging power supplied to the battery during daytime is given by Eq. 3.
Battery charging power during daytime is calculated as:

$$P_{charge} = V_{battery} \times I_{charge}$$

where:
Icharge= charging current (A)
Equation 3 is used to analyze the charging performance of the battery from the solar panel.

III. RESEARCH METHODOLOGY

The methodology adopted in this research provides a systematic framework for the design, implementation, and evaluation of a hybrid solar–battery powered smart street-lighting system. The methodology focuses on defining the study population and sample, identifying data sources and variables, establishing the analytical framework, and detailing the schematic-level design of the proposed system. This structured approach ensures that the study outcomes are reliable, reproducible, and suitable for real-world deployment.

A. Block Diagram

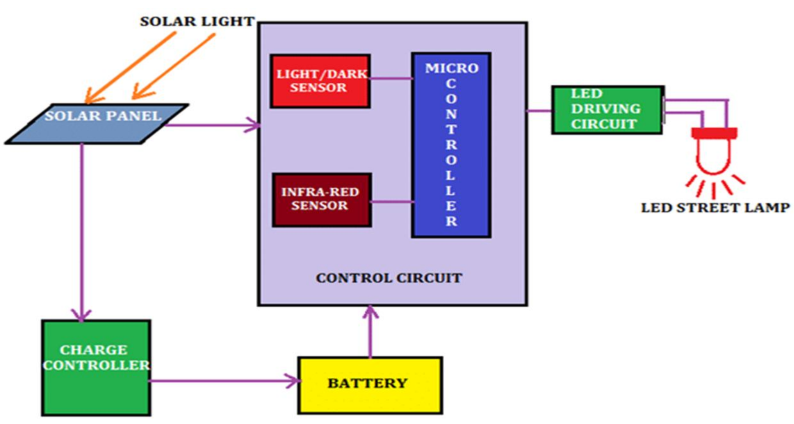

Figure 3.1: Block Diagram of the Proposed Hybrid Solar–Battery Powered Smart Street-Light System

Figure 3.1 block diagram illustrates the functional architecture of the proposed hybrid solar–battery powered smart street-light system. The system consists of a solar photovoltaic (PV) panel, battery storage unit, sensing modules, control unit, switching unit, lighting load, and a monitoring interface. During daytime, the solar panel converts sunlight into electrical energy, which is regulated by a charge controller and stored in a rechargeable battery. Voltage sensing blocks continuously monitor both solar and battery voltages and provide real-time inputs to the ESP32 microcontroller. An ambient light sensor (LDR) detects day and night conditions to enable automatic dusk-to-dawn operation. Based on sensor inputs and programmed logic, the ESP32 controls the relay or MOSFET switching unit to power the LED street light. The controller also performs fault detection for lamp failure, battery issues, and solar-panel malfunction. Using its built-in WiFi capability, the ESP32 transmits system status, voltage levels, and fault alerts to a live monitoring dashboard, enabling remote supervision and maintenance. This block-level architecture ensures efficient energy management, autonomous operation, and high system reliability.

1) Population of the Study: The population of the study comprises all types of street-lighting systems currently deployed in public infrastructure, including conventional grid-powered street lights, standalone solar street-lighting systems, and smart street-lighting solutions used in urban, semi-urban, rural, and off-grid environments. This population also includes intelligent lighting systems that integrate renewable energy sources, embedded controllers, sensors, and communication technologies for automation and monitoring. These systems serve as the reference framework against which the proposed hybrid solar–battery powered smart street-light system is conceptualized and evaluated.
2) Sample of the Study: The sample selected for this study is a single, fully functional prototype of a hybrid solar–battery powered smart street-light system developed using an ESP32 microcontroller. The prototype represents a typical street-light unit and includes a photovoltaic (PV) panel, solar charge controller, rechargeable battery, LED street lamp, ambient light sensor (LDR), dual voltage-sensing circuits, switching devices (relay or MOSFET), and a WiFi-enabled monitoring interface. The prototype is tested under controlled and real-time conditions, including daytime charging, night-time illumination, low-battery operation, and simulated fault scenarios. This sample allows detailed observation, functional validation, and performance assessment of automation, *energy management, fault detection, and real-time monitoring capabilities.*

B. *Working Of The Model*

The proposed hybrid solar–battery powered smart street-light system operates through coordinated interaction between the power generation unit, sensing modules, control logic, switching circuit, and monitoring interface. During daytime, the solar photovoltaic (PV) panel converts sunlight into electrical energy, which is regulated by the charge controller and stored in the rechargeable battery. Simultaneously, the ESP32 microcontroller continuously monitors the solar-panel voltage and battery voltage through dedicated voltage-sensing circuits. When sufficient daylight is detected by the LDR sensor, the street light remains switched OFF to prevent unnecessary power consumption while charging continues.As ambient light intensity decreases below a predefined threshold at dusk, the LDR signals night-time conditions to the ESP32. The controller then evaluates battery voltage to ensure adequate energy availability and activates the relay or MOSFET switching circuit to power the LED street light from the battery. During night-time operation, the system continuously monitors battery voltage to avoid deep discharge. If the battery voltage falls below a safe limit, the controller can disable the load or trigger a fault alert to protect battery health.

S. No.	Component Name	Specification / Model	Function / Description
1	Solar Photovoltaic (PV) Panel	12 V, 10–20 W (typical)	Converts solar energy into electrical energy for battery charging
2	Rechargeable Battery	12 V Lead-acid / Li-ion	Stores solar energy and supplies power during night-time

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3	Charge Controller	PWM / Solar charge controller	Regulates battery charging and prevents overcharge and deep discharge
4	ESP32 Microcontroller	Dual-core, WiFi-enabled	Central control unit for sensing, control, fault detection, and monitoring
5	LED Street Light	12 V DC, High-efficiency LED	Provides illumination with low power consumption
6	Light Dependent Resistor (LDR)	Analog light sensor	Detects ambient light for automatic ON/OFF control
7	Relay / MOSFET Module	12 V relay / Power MOSFET	Switches the street light based on controller commands
8	Buck Converter	12 V to 5 V DC	Provides regulated power supply to ESP32
9	Transistor Driver	BC547 / NPN transistor	Drives relay safely from ESP32 GPIO
10	WiFi Module	Built-in (ESP32)	Enables real-time monitoring and data transmission

Table 3.1: Components Used in the Proposed System

C. Proposed System

The proposed system is a hybrid solar–battery powered smart street-lighting model designed to provide autonomous, energy-efficient, and reliable illumination for urban, rural, and off-grid areas. The system integrates renewable solar energy harvesting, battery energy storage, intelligent control, fault detection, and real-time monitoring using an ESP32 microcontroller.The system consists of a solar photovoltaic (PV) panel, charge controller, rechargeable battery, LED street light, ambient light sensor (LDR), dual voltage-sensing circuits, relay or MOSFET-based switching unit, and a WiFi-enabled ESP32 controller. During daytime, the PV panel converts solar energy into electrical power, which is regulated by the charge controller and stored in the battery. At night, the stored energy is utilized to power the LED street light, ensuring uninterrupted illumination without dependence on grid electricity.

Automatic operation is achieved using an LDR sensor that detects ambient light conditions and enables dusk-to-dawn switching. Dual voltage-sensing circuits continuously monitor the battery voltage and solar-panel (charging-line) voltage. These measurements allow the controller to assess energy availability, protect the battery from deep discharge, and detect abnormal operating conditions. The ESP32 processes sensor data and executes intelligent control logic to manage power flow and load switching.To enhance system reliability, fault-detection mechanisms are incorporated to identify lamp failure, battery charging issues, and reduced solar-panel performance due to shading or dust accumulation. In addition, the ESP32's built-in WiFi capability enables real-time transmission of system parameters and fault alerts to a monitoring dashboard. This allows remote supervision, quick fault identification, and preventive maintenance.The proposed system offers a sustainable, low-maintenance, and cost-effective street-lighting solution suitable for rural electrification, highways, campuses, and smart-city infrastructure. By combining hybrid energy management, automation, diagnostics, and IoT-based monitoring, the system overcomes limitations of

D. Schematic Diagram and System Design Description

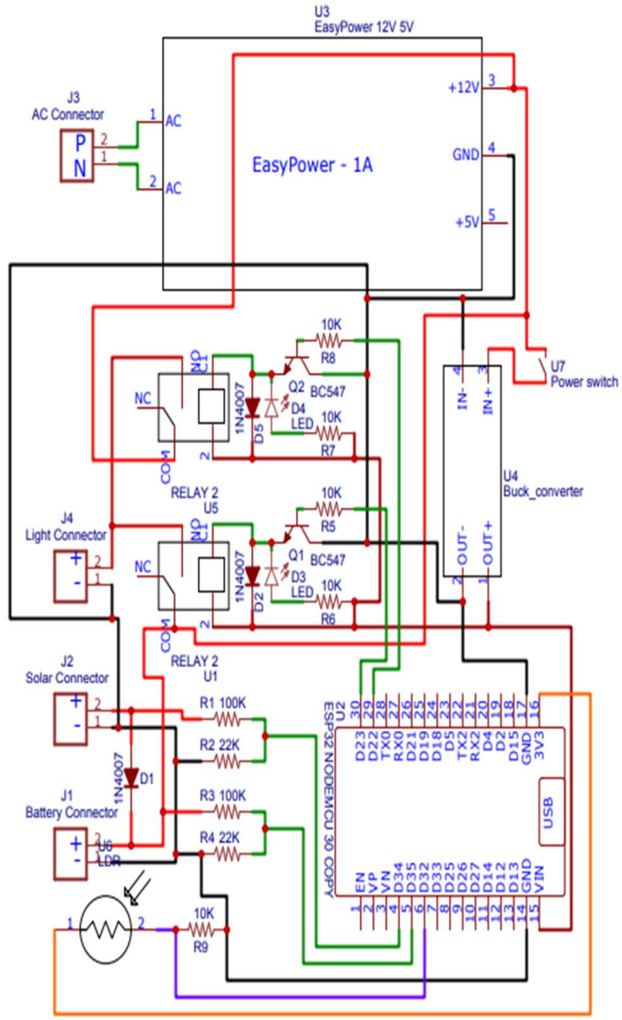

Figure 3.5: Circuit Diagram of ESP32-Based Hybrid Solar Street-Light System

The schematic diagram illustrates the complete hardware implementation of the proposed hybrid solar–battery powered smart street-light system, integrating power generation, storage, control, and monitoring units. An AC input is regulated using an EasyPower 12 V/5 V module and a buck converter to supply stable operating voltages for the ESP32 controller, relays, and peripheral circuits. The solar panel and rechargeable battery are interfaced through dedicated connectors, with protection diodes used to prevent reverse current flow. Two independent voltage-sensing circuits employing resistor divider networks scale down solar and battery voltages to safe levels for the ESP32's ADC inputs, enabling continuous monitoring of energy sources. Load switching is achieved using relay circuits driven by BC547 transistors with flyback diodes and indicator LEDs for safe and reliable operation. The street-light load is connected through a relay-controlled interface, ensuring automatic operation based on system conditions. The ESP32 functions as the central control unit, processing sensor data, executing energy management and fault detection logic, and controlling relay operation. Using its built-in WiFi capability, the controller provides real-time system monitoring and fault alerts via a dashboard, making the design suitable for reliable, energy-efficient, and low-maintenance street-lighting applications.

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IV. RESULTS AND DISCUSSION

Figure 4.1: Top View of Solar Photovoltaic Panel Mounted on the Prototype

Figure 4.1 highlights the top view of the solar photovoltaic panel used in the proposed system. The panel consists of multiple solar cells arranged in a series-parallel configuration to generate the required DC voltage for charging the battery. The sturdy mounting frame ensures mechanical stability and proper orientation of the panel. This figure demonstrates the renewable energy source that enables autonomous and off-grid operation of the street-light system.

Figure 4.2: Overall View of the Prototype Hybrid Solar Street-Light Model

Figure 4.2 shows the complete assembled prototype of the hybrid solar–battery powered smart street-light system. The model is mounted on a rigid stand fabricated using PVC pipes to simulate a real street-light pole structure. The solar panel is mounted at the top with an adjustable inclination to maximize sunlight exposure, while the LED street-light fixture is positioned below it to provide downward illumination. The compact and modular design demonstrates the feasibility of deploying the system in real-world outdoor environments such as streets, campuses, and rural areas.

Figure 4.3: Control Circuit and Power Management Module

This Figure 4.3 microcontroller, relay modules, voltage regulation components, and terminal connectors. The ESP32 serves as the central controller responsible for sensing, decision-making, and communication. Relays are used for safe switching of the street-light load, while the buck converter provides regulated power to the controller. This setup demonstrates the integration of sensing, control, and power management on a single hardware platform.

V. ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to Wainganga College of Engineering and Management, Nagpur, for providing the necessary facilities and infrastructure to carry out this research work. The authors are deeply thankful to Prof. Aparna Gale for her valuable guidance, continuous support, and encouragement throughout the development of this project. Special thanks are also extended to all faculty members of the Department of Artificial Intelligence and Data Science for their technical assistance and constructive suggestions. Finally, the authors acknowledge the support of friends and family members who contributed directly or indirectly to the successful completion of this work.

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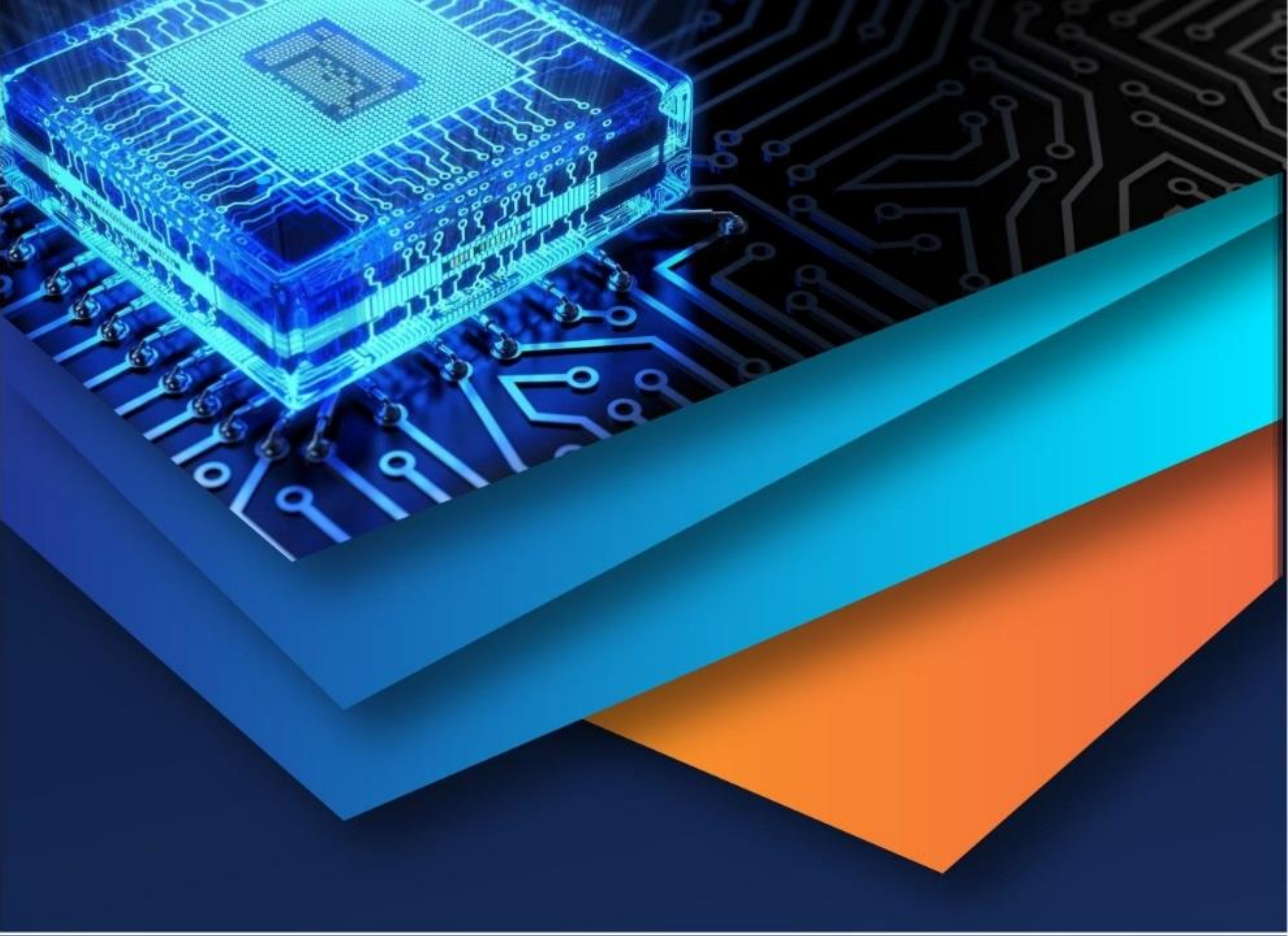

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