iJRASET
International Journal For Research in Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 **Issue:** VII **Month of publication:** July 2025

DOI: https://doi.org/10.22214/ijraset.2025.72976

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International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VII July 2025- Available at www.ijraset.com

Design and Performance Analysis of a Hybrid Solar Charging Station for Light Motor Vehicles in Semi Urban India

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AIM: Design and Performance Analysis of a Hybrid Solar Charging Station for Light Motor Vehicles in Semi Urban India.

Abstract: As electric vehicle (EV) adoption accelerates across India, particularly in semi-urban regions, there is an urgent need for decentralized, sustainable charging infrastructure. This study presents the design and performance evaluation of a hybrid solar photovoltaic (PV) charging station intended to support up to 300 light motor vehicles (LMVs) monthly in Jabalpur, Madhya Pradesh. Utilizing the System Advisor Model (SAM), the system's technical, economic, and environmental performance was assessed. Results indicate an annual net AC output of 49,324 kWh, a capacity factor of 22.1%, and a performance ratio of 0.78. The project demonstrates a payback period of 6.8 years and annual CO_2 avoidance of 40.4 metric tons. These findings validate the feasibility of deploying scalable hybrid solar charging infrastructure in emerging urban centers.

I. INTRODUCTION

A. Context And Motivation

The rapid adoption of electric vehicles (EVs) is driving demand for sustainable and decentralized charging infrastructure. In regions with abundant solar resources, integrating solar PV with EV charging can significantly reduce grid dependency, operational costs, and carbon emissions. However, many existing charging stations rely on grid electricity, which may be carbon-intensive and expensive. For this study Jabalpur, situated in Madhya Pradesh, India, city is chosen. The analysis predicated upon the frequency of electric vehicle (EV) charging sessions, the monthly fluctuations in energy generation, the capital investment, and the reduction in carbon dioxide (CO2) emissions for Jabalpur (Madhya Pradesh), India, has been thoroughly examined.

There are 25,483 EVs under Light Motor Vehicle category, registered under city's Regional Transport Office (RTO) as of June, 2025 consisting three types of vehicle – 2 wheeler, 3 wheeler and 4 wheeler.

This study is motivated by the need to:

Support large-scale EV adoption by providing reliable, clean, and cost-effective charging solutions for LMVs.

- Demonstrate the technical and economic feasibility of hybrid solar charging stations in commercial environments.
- Address energy security and environmental concerns by leveraging renewable energy for transportation.
- Showcase the use of advanced simulation tools (SAM) to optimize system design and assess real-world performance.

B. Objectives

- To design a hybrid solar charging station capable of meeting the annual energy needs of up to 300 LMVs.
- To analyze the system's performance and losses using SAM.
- To evaluate the financial viability and environmental benefits of the proposed solution.

II. METHODOLOGY

A. Load Estimation And EV Usage Modeling

For this 3 different manufactures are chosen as their share in EV market is significant in the city and to make this study as realistic as possible,

- Ola S1 Pro(2Wheels)
- Mahendra Treo(3Wheels)
- Tata Nexon(4Wheels)

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This report outlines the planning, design, and cost estimation for a hybrid solar-powered electric vehicle (EV) charging station. The station aims to service 300 electric vehicles (EVs) monthly, accommodating a mix of two-wheelers, three-wheelers, and four-wheelers. The infrastructure is scalable, solar and grid-connected, and optimized for daytime operation.

B. Vehicle Selection and Usage Assumptions

EV Model	Battery Capacity (kWh)	Charging Power (kW)	Charging Time
Ola S1 Pro	4 kWh	3.3 kW (AC Slow)	~1.5 hours
Mahindra Treo	7.37 kWh	3.3 kW (AC Slow)	~2.5 hours
Tata Nexon EV	30 kWh	7.2 kW (AC Fast)	~4.5 hours

Key Assumptions:

The system is currently supporting an estimated 3,099 electric vehicles annually, based on actual energy usage tracked via SAM (System Advisor Model), which translates to an average of ~258 vehicles per month. The station operates on a 24-hour load schedule, optimized for energy efficiency and minimal idle time.

On average, the station facilitates approximately 9–10 vehicles per day, delivered across 2.5 to 3 full charging sessions, with each session typically serving 6 EVs (a mix of electric cars, two-wheelers, and e-autos). The infrastructure is scalable, solar and grid-connected, and optimized for daytime operation.

$$\text{Daily sessions} = \frac{\text{Total EVs per year}}{365 * \text{vehicles per session}} = 3099 / (365*6)$$

$$= 1.41 \text{ session / day}$$

$$\text{Max Module in series} = \frac{\text{Max Inverter Voltage}}{\text{Voc} * \text{Temp correction factor}} = 1000/(49*1.2) = 17 \text{ module}$$

(In cold temps, voltage rises and Temp correction factor is needed, it is assumed 1.2 for safety)

Min Module per string (MPPT Range):

$$\text{Min Modules} = \frac{\text{MPPT minimum Voltage}}{\text{Vmp}} = 480/41 \sim 12 \text{ module}$$

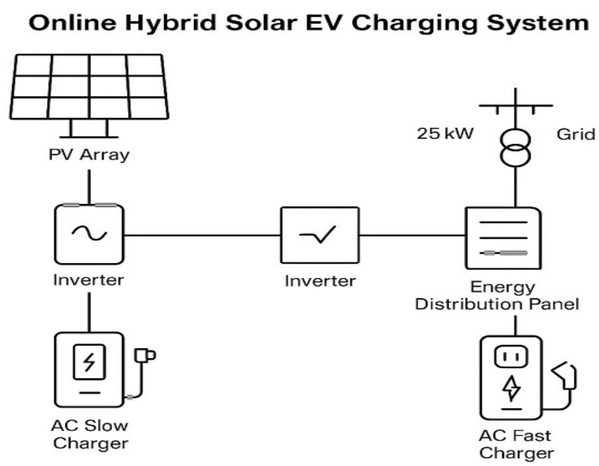
String in Parallel (Current limit):
There are 12 modules per string
Each module has: Imp = 12.8 amp.
Inverter support 45.16 amp.
String in parallel = 45.16 / 12.8 = 3.52 ~ 4 Strings

Array Configuration:
12 module in series * 4 strings in parallel= total 48 panels total
Total DC system size: 530 W * 48 = 25.44kW

C. Peak Power Demand Estimation

In the worst-case scenario where all three types of electric vehicles are charging simultaneously, the estimated peak power demand reaches 13.8 kW.

This includes 3.3 kW drawn by the Ola S1 Pro (two-wheeler), 3.3 kW by the Mahindra Treo (three-wheeler), and 7.2 kW by the Tata Nexon EV (four-wheeler). This combined load forms the basis for sizing the charging infrastructure and ensuring adequate power supply during concurrent usage.



D. Charging Station Infrastructure Design

Charger Requirement

Charger Type	Power (kW)	Quantity	Total Power (kW)
Slow AC	3.3 kW	2	6.6 kW
Fast AC	7.2 kW	1	7.2 kW
Total	-	3	13.8 kW

Grid Connection:
Capacity: 25kW (3-phase, 440V)
Purpose: Supports peak load and nighttime charging when solar generation is unavailable

E. Jabalpur's Location and Climate Analysis

India is located in the northern hemisphere, with the Tropic of Cancer (23.5 N) traversing its expanse. According to the National Building Code (NBC), India is predominantly classified into five principal climatic zones: frigid, composite, arid and torrid, temperate, and warm and humid. Jabalpur experiences a subtropical climate characterized by hot, humid summers and cool, mild winters. The hottest month is May, with temperatures potentially reaching 47°C, while January is the coldest, with temperatures sometimes dropping to 4°C. The monsoon season, with an average rainfall of 1331mm, typically begins in the third week of June and lasts until the fourth week of October.

F. System Design

- PV Modules: 48 Aptos DNA-144-BF10-530W bifacial mono-c-Si modules (25.48 kW DC)

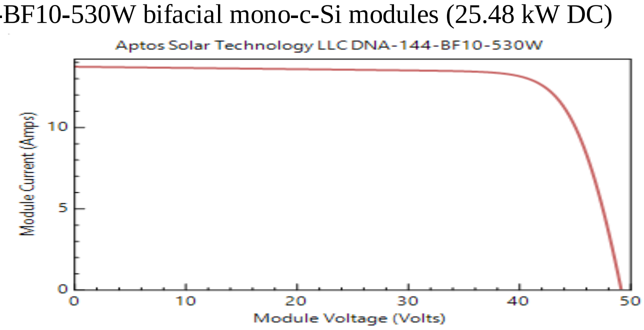


Fig: Current Vs Voltage curve

- Inverter: 25 kW Yaskawa Solectria Solar PVI 25TL-208

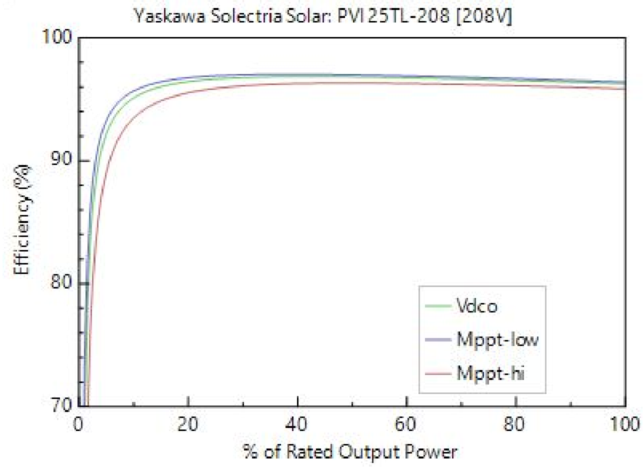


Fig: Efficiency curve of Inverter.

- MPPT Voltage Range : 480 - 850Vdc
- Array Configuration: 4 strings × 12 modules; 23.17° tilt, 180° azimuth
- Site: Commercial location with 123 m² available area

G. Simulation Approach

A.Tool:System Advisor Model (SAM) 2025.4.16

B.Inputs:

Average Solar Output (India): 4–5 kWh/kW/day

Annual Contribution: ~105,000–125,000 kWh,

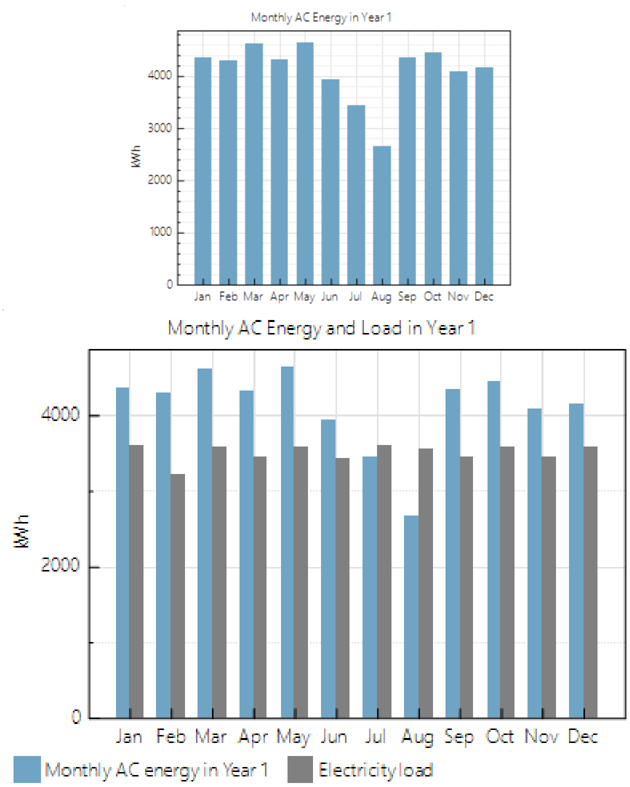


Fig: Monthly AC Energy Generated by Solar System in Jabalpur load profile for 300 LMVs

Hour	Load(kW)	Energy Used(kWh)
6.00	7.2 +3.3+3.3	13.80
7.00	7.2+3.3+1.65	12.18
8.00	7.2+1.65+0	08.85
9.00	7.2 + 0 + 0	07.20
10.00	3.6 + 0 + 0	03.60
11.00	0 + 0 + 0	0

Hour	Load(kW)	Energy Used(kWh)
12.00	7.2 +3.3+3.3	13.80
1.00	7.2+3.3+1.65	12.18
2.00	7.2+1.65+0	08.85
3.00	7.2+ 0 + 0	07.20
4.00	3.6 + 0 + 0	03.60
5.00	0 + 0 + 0	0

Daily load	105.66kw/per day	38,037.6kwh /year

III. RESULTS AND DISCUSSION

A. *Technical Performance*

- Annual Net AC Output: 49,324 kWh
- Capacity Factor : 22.1%
- Performance Ratio: 0.78
- Major Losses: Soiling (5%), module deviation from STC (8%), inverter MPPT clipping (4.6%)
- No shading or snow losses due to optimal site selection

The hybrid solar EV charging station demonstrates robust technical performance, with an annual net AC output of 49,324 kWh. The system operates at a capacity factor of 22.1%, which is consistent with expectations for fixed-tilt photovoltaic arrays in central India. A performance ratio of 0.78 indicates effective system efficiency after accounting for all system losses. The primary sources of energy loss include soiling on the panels (5%), module deviation from standard test conditions (8%), and inverter MPPT clipping losses (4.6%). Thanks to strategic site selection, the system experiences no shading or snow-related losses, ensuring consistent and reliable solar energy generation throughout the year.

B. *Financial Analysis*

-Direct capital cost:
48 module = 0.5kWdc/unit=22.43Rs/Wdc = 2, 26,306.1 Rs
1 Inverter =25kWdc/unit= 5.18 Rs/Wdc = 1, 53,816.28 Rs
Balance of System equipment = 2, 19,737.92Rs
Installation labor = 10, 9,869.39 Rs

-Indirect capital cost
Grid connection cost = 10, 00,000.00 Rs
Land cost = 123sqm=1330 sqft= 1330*1500(assumption) =19,95,000 Rs

-Total Installation Cost: 34, 84,992.69 Rupees (139.39 Rs/W)
- Nominal LCOE: 2.2 cents/kWh
- Payback Period: 6.8 Years
-Net Present Value: 10, 00,537.70 Rupees
Annual Bill Saving: 2, 13,563.05 Rupees

C. Environmental Impact

The environmental benefit of the hybrid solar charging station is quantified through the avoidance of carbon dioxide (CO_2) emissions. With an annual net AC electricity generation of 49,324 kWh, and using India's average grid emission factor of 0.82 kg CO_2 per kilowatt-hour, the system effectively offsets approximately 40,445 kilograms, or 40.4 metric tons, of CO_2 emissions each year. This substantial reduction underscores the system's role in promoting cleaner transportation and supporting national climate goals.

Calculation:

CO_2 emissions avoided (kg)} = Annual generation (kWh) *Grid emission factor (0.82kg CO_2 /kWh)

= 49,324 *0.82 = 40,445.68 kgCO_2

= 40.4 Metric tons CO_2

Summary

Parameter	Value
Annual solar generation	49,324 kWh
Grid emission factor	0.82 kg CO2/kWh
Annual CO2 avoided (kg)	40,445.68
Annual CO2 avoided (tons)	40.45

IV. LIMITATIONS AND RECOMMENDATION

This study assumes consistent solar irradiance and regular EV usage patterns, which may vary in real-world applications. However the study also acknowledges certain limitations, including reliance on consistent solar irradiance and regular EV usage patterns. Future work should explore the integration of battery energy storage systems (BESS), dynamic pricing models, and policy incentives for wider deployment.

V. CONCLUSION AND DISCUSSION

Hybrid solar charging station prevents the emission of approximately 40.4 metric tons of CO2 annually supporting both clean mobility and climate action in India.

- The system's performance ratio and capacity factor are above industry averages for fixed-tilt commercial PV systems.
- Financial metrics indicate strong economic viability, with a short payback period and significant annual savings.
- The design can be scaled or replicated for larger fleets or other commercial applications.
- Limitations include reliance on solar resource availability and the need for grid backup or storage for uninterrupted service.

The hybrid solar charging station effectively mitigates approximately 40.4 metric tons of CO2 emissions annually, contributing to both clean mobility and broader climate action efforts in India. Technically, the system outperforms standard benchmarks, with a performance ratio and capacity factor that exceed typical values for fixed-tilt commercial photovoltaic installations. Financial analysis reinforces the project's viability, highlighting a short payback period and substantial annual cost savings. Moreover, the system's modular design allows for scalability and replication across larger EV fleets or different commercial settings. However, its effectiveness remains partially dependent on consistent solar irradiance, and uninterrupted service may require grid support or integration of battery storage systems.

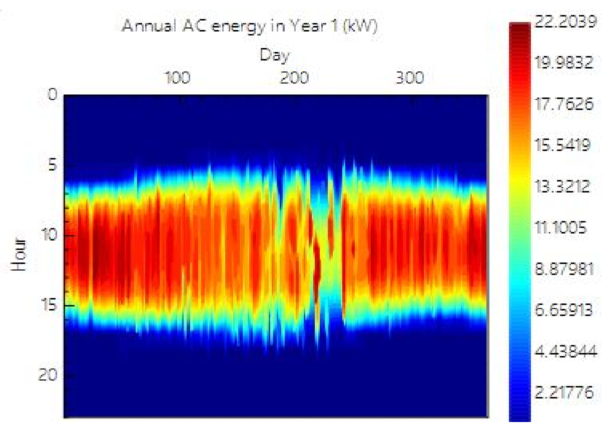


Fig: Annual AC energ(kW) in one year.

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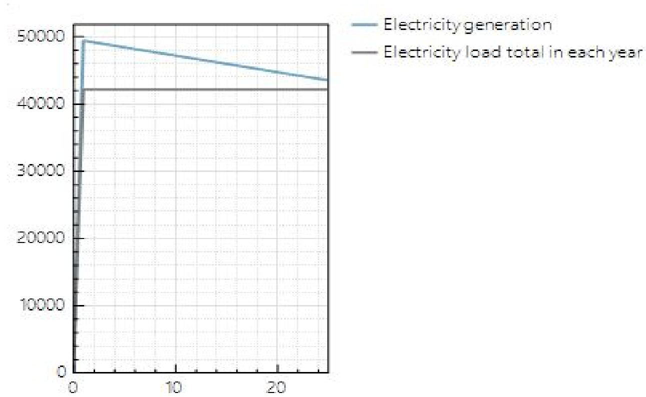
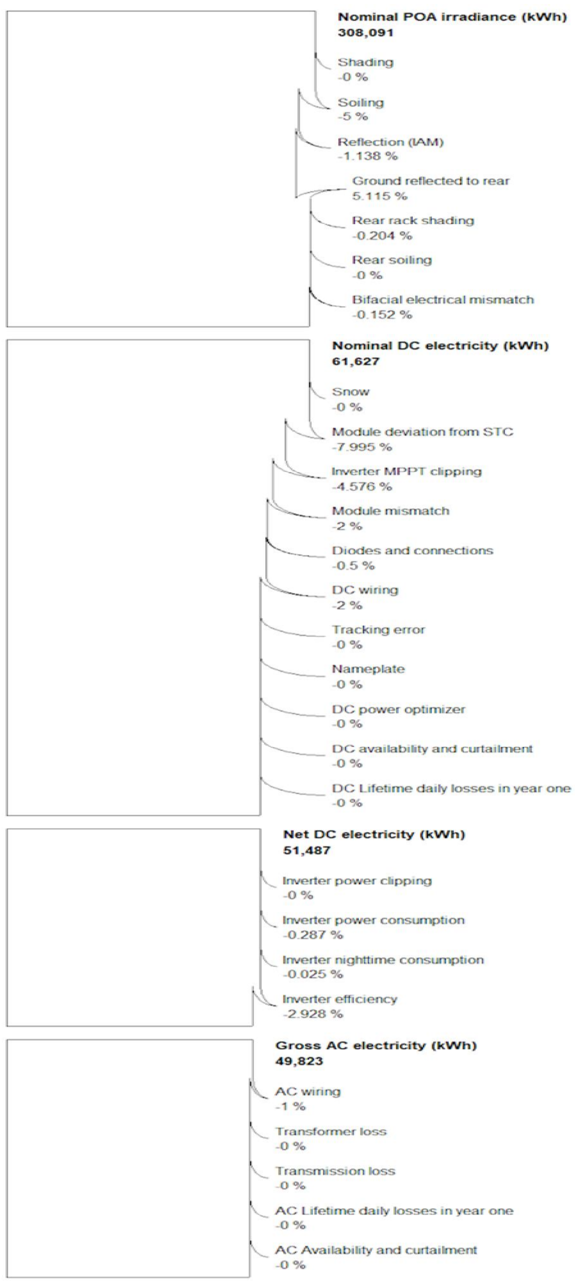


Fig: Electricity generation Vs Electricity Load total in each year.



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VI. CONCLUSION

This study demonstrates the technical, economic, and environmental viability of deploying a hybrid solar photovoltaic (PV) charging station for light motor vehicles (LMVs) in a semi-urban Indian context, using Jabalpur as a representative case. By integrating solar PV with grid connectivity, the designed system effectively meets the monthly charging needs of up to 300 LMVs—including two-wheelers, three-wheelers, and four-wheelers—while significantly reducing operational costs and carbon emissions.
. The approach offers a replicable model for sustainable transportation infrastructure in regions with high solar potential.

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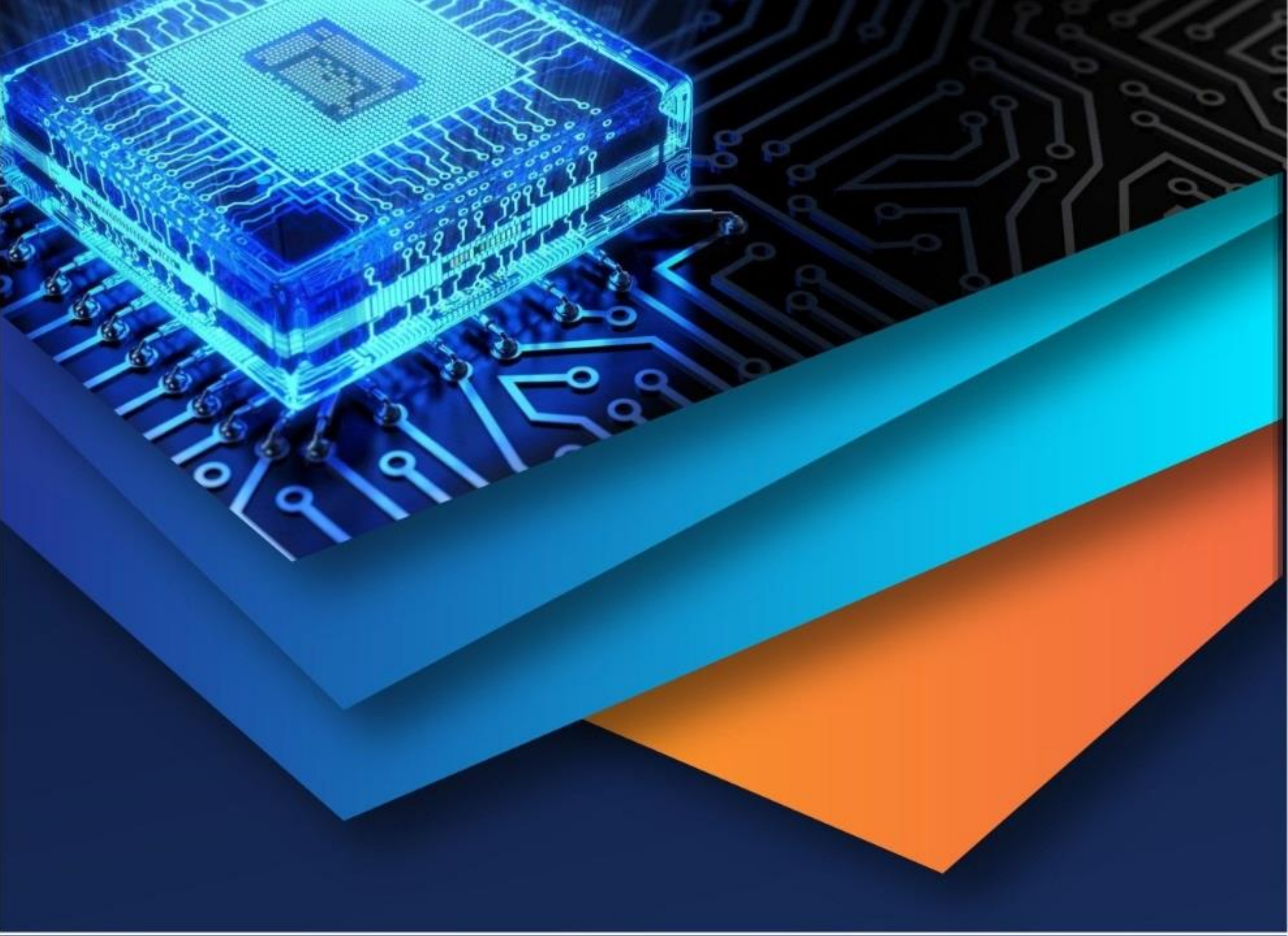

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