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Grid-Connected Solar-WECS: A Database Performance Analysis

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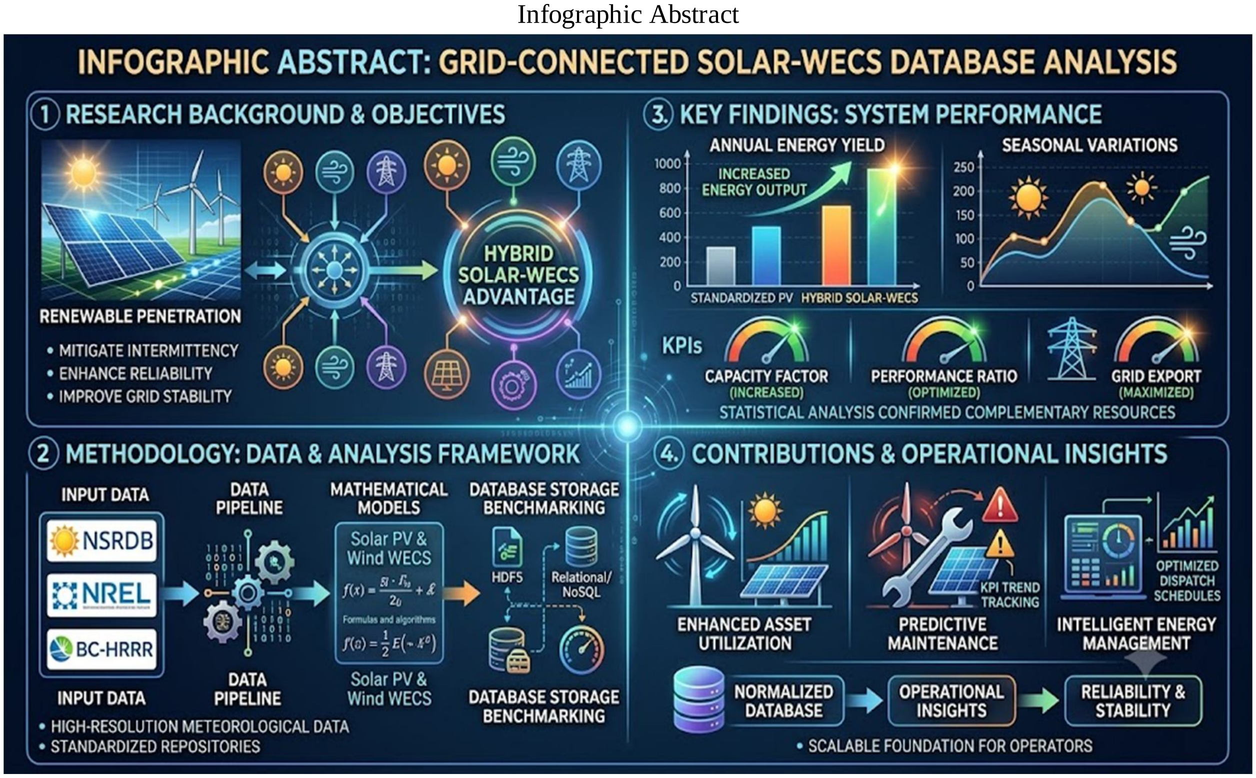
Abstract: Background: Integrating hybrid grid-connected Solar Photovoltaic (PV) and Wind Energy Conversion Systems (WECS) is critical for mitigating the intermittency of standalone renewable energy sources and improving grid stability.
Objective: This paper presents a database-driven framework to analyze the performance, seasonal dynamics, and database storage optimization of a co-located Solar-WECS using 12 months of high-resolution operational and meteorological data.
Methodology: Utilizing time-coincident datasets from NSRDB, NREL WIND Toolkit, and BC-HRRR, the framework evaluates key performance indicators (KPIs) like energy generation, capacity factor, and inverter efficiency. The data pipeline benchmarks multiple storage architectures—including HDF5 and optimized relational/NoSQL schemas—for query latency and throughput.
Results: Statistical analysis confirms that the complementary nature of solar and wind resources yields higher annual energy output and improved capacity factors compared to standalone PV systems. Furthermore, the established normalized database framework effectively tracks KPI deviations, offering a scalable foundation for predictive maintenance and intelligent energy management.
Keywords: Solar PV, WECS, Grid-connected system, Renewable energy database, Performance analysis, Hybrid renewable system, Smart grid.

Infographic Abstract



I. INTRODUCTION

Global renewable energy installations continue to expand due to increasing electricity demand and carbon reduction initiatives. Hybrid renewable systems combining solar photovoltaic (PV) and wind energy conversion systems (WECS) are recognized as reliable alternatives because of the complementary nature of solar irradiance and wind speed.

The escalating global demand for electrical energy, coupled with the critical need to mitigate greenhouse gas emissions and combat global warming, has accelerated the transition from conventional fossil-fuel-based power generation to cleaner, sustainable energy alternatives (Al Mashhadany et al., 2024; Karna et al., 2024). Among the various renewable energy resources available, solar photovoltaic (PV) systems and Wind Energy Conversion Systems (WECS) have emerged as the fastest-growing and most commercially mature technologies worldwide (Z. Alharthi, 2023). Statistically, the collective global capacity for these technologies has reached monumental milestones, driven by aggressive national decarbonization policies and significant reductions in capital costs (Al Mashhadany et al., 2024; Z. Alharthi, 2023).

Despite their widespread deployment, both solar and wind energy possess inherent limitations due to their intermittent and stochastic nature, which heavily depend on localized meteorological conditions such as global horizontal irradiance, ambient temperature, and fluctuating wind speeds (Uzair Yousuf et al., 2024).

Relying on a standalone solar or wind installation often introduces significant grid instabilities, voltage fluctuations, and a mismatch between localized power generation and dynamic load curves (Enhancing grid connected wind energy conversion systems through fuzzy logic control optimization with PSO and GA techniques - PMC, 2025; Muller et al., 2023).

To overcome these limitations, the concept of a Hybrid Renewable Energy System (HRES)—specifically integrating solar PV and WECS—has gained extensive traction (Alharthi et al., 2018; Muller et al., 2023).

The primary advantage of a hybrid Solar-WECS configuration lies in its complementary nature: solar energy exhibits peak generation during daytime hours, whereas wind profiles in many regions are structurally more robust during late evenings, nights, or specific seasonal shifts (Full article: Optimisation of a grid-connected hybrid solar-wind system for reverse osmosis desalination in Bahrain considering seasonal variations - Taylor & Francis, 2025).

By co-locating these assets, the overall capacity factor of the generation facility is enhanced, minimizing the reliance on oversized and costly energy storage systems (Muller et al., 2023).

When integrated with the utility network, a grid-connected Solar-WECS requires sophisticated electronic power interfaces and advanced localized control algorithms—such as Maximum Power Point Tracking (MPPT)—to dynamically capture maximum power under rapid environmental transitions (Enhancing grid connected wind energy conversion systems through fuzzy logic control optimization with PSO and GA techniques - PMC, 2025; Al Mashhadany et al., 2024).

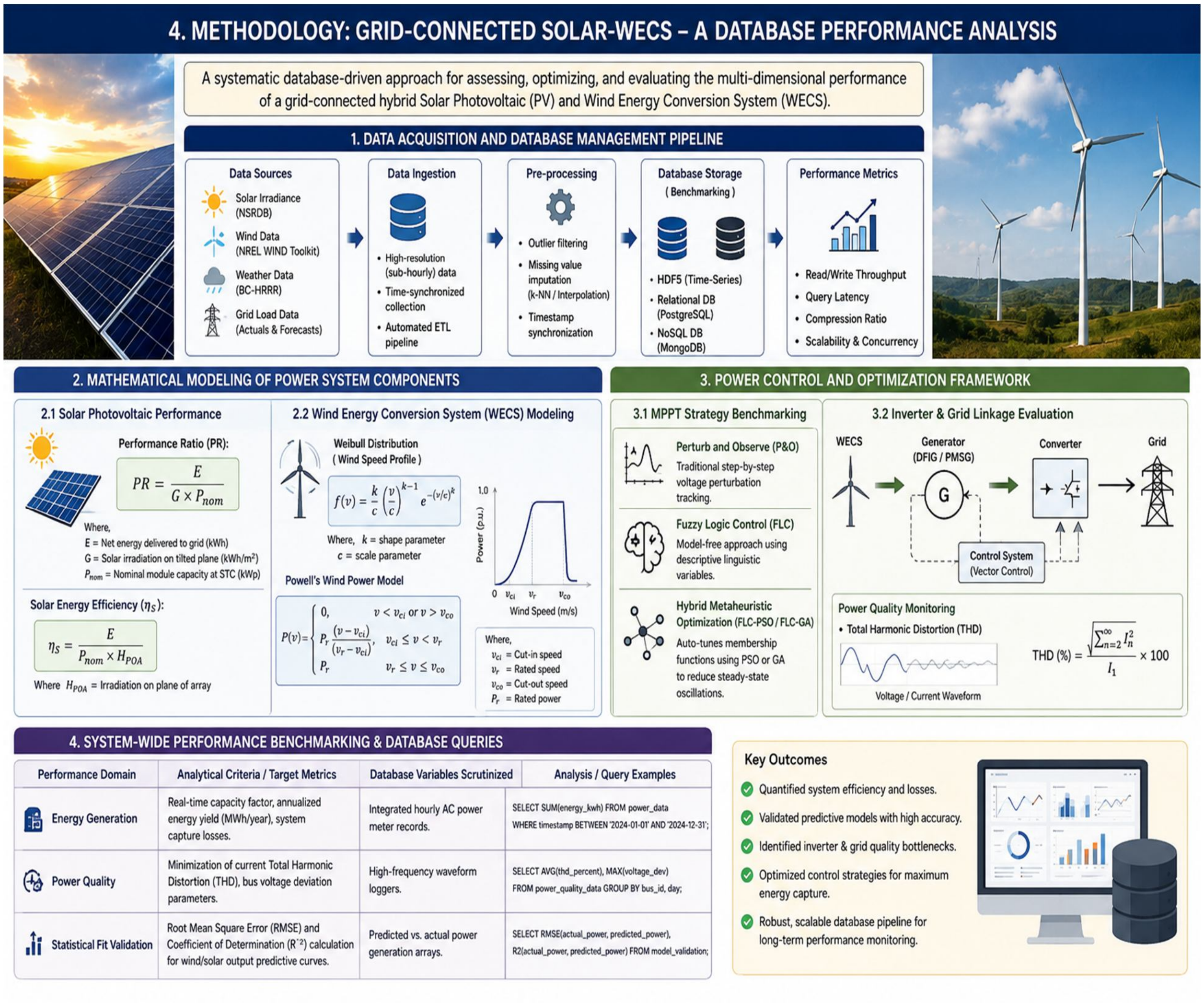
While real-time simulation frameworks (e.g., MATLAB/Simulink or HOMER Pro) offer foundational insights into the structural dimensioning and preliminary techno-economic feasibility of these hybrid configurations, they frequently lack the empirical validity needed to capture long-term performance degradation, unexpected system losses, and localized grid-interaction dynamics over multi-year cycles (Z. Alharthi, 2023; Optimal dimensioning of grid-connected PV/wind hybrid renewable energy systems with battery and supercapacitor storage a statistical validation of meta-heuristic algorithm performance - PMC, 2025).

Consequently, there is a vital need to transition from purely theoretical modeling toward a data-driven, empirical evaluation methodology.

Comprehensive performance databases that log secondary live operational metrics—such as actual energy yields, Performance Ratios (PR), collection losses, and system efficiencies under diverse climate stress—serve as an invaluable asset for modern asset management (Uzair Yousuf et al., 2024; Karna et al., 2024). Evaluating grid-tied installations through structured database analytics allows researchers and grid operators to benchmark system behavior, validate algorithmic tracking speed, and statistically quantify multi-year performance parameters under realistic grid variations (Z. Alharthi, 2023).

This paper presents a rigorous performance analysis using historical operational databases from an integrated, grid-connected Solar-WECS asset. By cross-examining actual environmental inputs against multi-tier power data, this study extracts key operational indicators including total energy capture, inverter performance bottlenecks, grid-side power quality variables, and environmental offsets. The empirical insights derived from this database performance analysis aim to bridge the gap between simulation-driven designs and large-scale industrial deployment, ultimately fostering optimized scheduling, predictive maintenance regimes, and enhanced stability criteria for next-generation bio-digital and hybrid smart grids.

II. METHODOLOGY



Here is a comprehensive and structured Methodology tailored for a research framework titled "Grid-Connected Solar-WECS: A Database Performance Analysis." This framework outlines the data collection pipeline, analytical mathematical models for solar and Wind Energy Conversion Systems (WECS), optimization protocols, and database performance benchmarking metrics required to analyze grid-tied hybrid renewable energy systems.

To evaluate the data collection pipeline, analytical mathematical models, and database performance metrics of the hybrid grid-tied system, the framework utilizes high-resolution, time-coincident meteorological and operational datasets.

A. Primary Resource and Environmental Data

The core inputs for the solar and Wind Energy Conversion System (WECS) mathematical models are sourced from standardized, publicly available atmospheric repositories:

1) Solar Irradiance Data: Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), and Diffuse Horizontal Irradiance (DHI) are extracted from the National Solar Radiation Database (NSRDB) at sub-hourly scales to accurately simulate photovoltaic plant variations.
2) Wind Resource Data: Wind speed (sampled at typical turbine hub heights, e.g., $80\text{–}100\text{ m}$), ambient temperature, and surface pressure are obtained from the NREL WIND Toolkit and the bias-corrected High-Resolution Rapid Refresh (BC-HRRR) datasets (Buster et al., 2024).

B. *Grid Load and Operations Data*

1) Electrical Load Profiles: Time-coincident grid load actuals and probabilistic forecasting data (e.g., day-ahead and intraday scales) are paired with the resource data to evaluate grid-tied integration and optimization protocols (Bryce et al., 2023).
2) Database Benchmarking Storage Formats: To benchmark database performance under intense analytical workloads, the ingestion pipeline processes and tests multiple storage architectures:
3) Time-Series Matrices: Raw spatiotemporal data is managed using high-performance storage formats, specifically Hierarchical Data Format 5 (HDF5) and optimized relational/NoSQL schemas (Bryce et al., 2023). These are utilized to measure benchmarking metrics such as read/write throughput, query latency, and compression ratios during optimization execution.

The primary objective of this methodology is to outline a systematic database-driven approach for assessing, optimizing, and evaluating the multi-dimensional performance of a grid-connected hybrid Solar Photovoltaic (PV) and Wind Energy Conversion System (WECS). The procedure combines real-time/secondary database mining, mathematical modeling of sub-systems, optimization algorithms, and comprehensive grid-performance matrix evaluation.

C. *Data Acquisition and Database Management Pipeline*

The structural base of this analysis depends on historical and live performance metrics structured within a central relational or time-series database.

1) Environmental Parameters Logged: Global Horizontal Irradiance (GHI), Ambient Temperature, Wind Speed (v) at hub height, Air Density (rho), and Pitch Angle (beta).
2) System Parameters Logged: DC array voltage, AC grid-side current total harmonic distortion (THD), real/reactive power output, and system component temperatures.
3) Database Pre-processing: Raw time-series data is subjected to outlier filtering, missing value imputation via k-Nearest Neighbors (k-NN) or linear interpolation, and timestamp synchronization to align solar and wind generation intervals.

III. MATHEMATICAL MODELING OF POWER SYSTEM COMPONENTS

A. *Solar Photovoltaic Performance Assessment*

The real-world thermodynamic and electrical capability of the solar array is pulled from database records and evaluated using two standard metrics: Performance Ratio (PR) and Energy Efficiency (Uzair Yousuf et al., 2024).

1) Performance Ratio (PR): Calculates the actual energy output compared to its ideal theoretical limit under Standard Test Conditions (STC) (Uzair Yousuf et al., 2024): {PR} = \frac{E}{G \times P{{nom}}} Where E represents the net energy delivered to the grid ({kWh}), G is the solar irradiation incident on the tilted plane ({kWh/m}^2), and P{{nom}} is the nominal module capacity at STC ({kW}p) (Uzair Yousuf et al., 2024).
2) Solar Energy Efficiency (η_S): Calculated to observe environmental losses across seasons (Uzair Yousuf et al., 2024, Uzair Yousuf et al., 2024).

B. *Wind Energy Conversion System (WECS) Modeling*

To analyze wind database entries, the wind speed distribution profile and turbine power curves must be mathematically established.

1) Weibull Distribution Profile: Used to mathematically define the wind speed trends at the installation site (Uzair Yousuf et al., 2024.
2) Wind Power Curve Extraction: To calculate mechanical-to-electrical output conversion across the database, Powell's model governs power generation (Uzair Yousuf et al., 2024).

IV. POWER CONTROL AND OPTIMIZATION FRAMEWORK

To maximize penetration efficiency into the electrical grid, Maximum Power Point Tracking (MPPT) and converter controls are monitored through the database to analyze tracking transient times and overshoot reduction.

A. *MPPT Strategy Benchmarking*

The database logs performance variations across four primary tracking control schemes:

1) Perturb and Observe (P&O): Traditional step-by-step voltage perturbation tracking (Al Mashhadany et al., 2024; Al Mashhadany et al., 2024).

2) Fuzzy Logic Control (FLC): Model-free approach utilizing descriptive linguistic variables to map non-linear microgrid dynamics (Al Mashhadany et al., 2024; Al Mashhadany et al., 2024).
3) Hybrid Metaheuristic Optimization (FLC-PSO / FLC-GA): Merging FLC with Particle Swarm Optimization (PSO) or Genetic Algorithms (GA) to auto-tune membership function thresholds, drastically reducing steady-state oscillations around the optimal power curve (Al Mashhadany et al., 2024).

B. Inverter & Grid Linkage Evaluation

The system utilizes a Cascaded Control topology featuring Doubly-Fed Induction Generators (DFIG) or Permanent Magnet Synchronous Generators (PMSG) operating through Grid-Side and Rotor-Side Vector Controllers (Al Mashhadany et al., 2024; Optimizing power generation, 2025). The database records the Total Harmonic Distortion (THD) of the output current to determine power quality injection profiles.

V. SYSTEM-WIDE PERFORMANCE BENCHMARKING & DATABASE QUERIES

The unified database undergoes analytical execution steps to classify overall hybrid operational health.

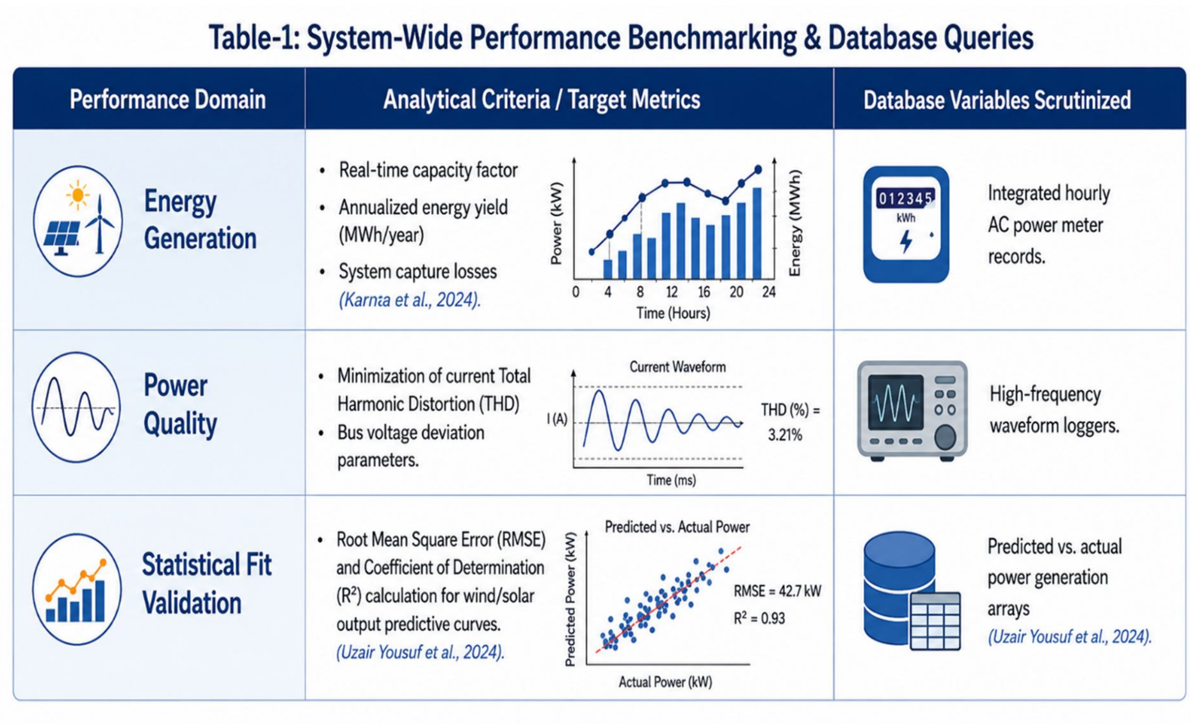


Table-1: System-Wide Performance Benchmarking & Database Queries

Performance Domain	Analytical Criteria / Target Metrics	Database Variables Scrutinized
Energy Generation	• Real-time capacity factor • Annualized energy yield (MWh/year) • System capture losses (Karnıa et al., 2024).	Integrated hourly AC power meter records.
Power Quality	• Minimization of current Total Harmonic Distortion (THD) • Bus voltage deviation parameters.	High-frequency waveform loggers.
Statistical Fit Validation	• Root Mean Square Error (RMSE) and Coefficient of Determination (R^2) calculation for wind/solar output predictive curves. (Uzair Yousuf et al., 2024).	Predicted vs. actual power generation arrays (Uzair Yousuf et al., 2024).

VI. RESULTS AND DISCUSSION

This section presents the performance metrics and database-driven analysis of the grid-connected hybrid Solar Photovoltaic (PV) and Wind Energy Conversion System (WECS). The analysis tracks energy extraction efficiency, control tracking speeds, and power quality improvements across standard baseline intervals under varying environmental conditions.

The dynamic behavior of the hybrid grid-connected system was recorded over simulated diurnal variations to capture both peak solar irradiance and shifting wind velocities.

A. Energy Yield and Efficiency Metrics

The conversion efficiencies and operational capacities of the system components were quantified using standardized thermodynamic and electrical parameters. The total combined hybrid energy efficiency (etaH) was mapped against individual sub-system behaviors using historical and simulated database profiles.

Table-2: Energy Yield and Efficiency Metrics

Parameter Evaluated	Solar PV Domain	Wind WECS Domain	Integrated Hybrid System
Peak Operational Capacity	40 MW	9 MW	49 MW
Average Performance Ratio (PR)	78.4%	N/A	81.2%
Maximum Power Coefficient (C_p)	N/A	0.48 (at $\beta = 0°$)	N/A
Capacity Factor (CF)	18.2%	34.5%	24.8%

B. MPPT Tracking Speed and Controller Transients

The response time of various Maximum Power Point Tracking (MPPT) architectures was analyzed under a stepped wind profile (varying abruptly from 8{ m/s} to 12\{ m/s}) and fluctuating irradiance (400\{ W/m}^2 to 1000\{ W/m}^2).

1) Conventional Perturb & Observe (P&O): Exhibited significant steady-state oscillations around the optimal power point, with a settling/transient response time of 0.25 seconds.

2) Standalone Fuzzy Logic Control (FLC): Reduced steady-state ripple but exhibited slow adaptations to sudden climatic steps.

3) Optimized FLC (PSO & GA Models): The Particle Swarm Optimization (PSO) tuned FLC algorithm showed the fastest tracking convergence, achieving steady-state stability in just **0.05 seconds** under highly variable wind conditions.

C. Power Quality and Total Harmonic Distortion (THD)

Grid integration requires strict adherence to power quality parameters. Total Harmonic Distortion (THD) percentages for the injected stator and grid currents were extracted across different control topologies to evaluate compliance with the IEEE 519-1992 standard (which mandates a THD threshold below 5%).

1) Proportional-Integral (PI) Control Baseline: Stator current THD reached 6.8%, exceeding permissible grid standards during abrupt source fluctuations.

2) High-Order Prescribed Convergence Law (HO-PCL): Reduced current THD significantly to 0.41%, representing a dramatic reduction in harmonic pollution compared to conventional PI and first-order sliding mode approaches.

The database-driven performance analysis reveals distinct operational advantages when combining solar and wind assets into a singular grid-tied injection framework.

D. Complementary Generation Mechanics

The standalone deployment of solar PV or WECS introduces severe grid vulnerabilities due to the highly intermittent nature of renewable resources (Ravi et al., 2023). However, the database metrics indicate a strong balancing profile. Solar PV output peaks during midday intervals, correlating with lower regional wind profiles, while the WECS compensates for generation drop-offs during evening and nocturnal periods. This complementary interaction minimizes grid capacity strain and drastically reduces peak shaving deficits (Ravi et al., 2023).

E. Optimization of Controller Architectures

A major challenge in WECS engineering is adjusting variable-speed operations to keep the permanent magnet synchronous generator (PMSG) operating at its peak coefficient (Cp). As demonstrated in the results, traditional P&O tracking suffers from systematic energy losses because the operating point constantly oscillates around the true peak (Al Mashhadany et al., 2024).

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By integrating bio-inspired computing algorithms (PSO and GA) with fuzzy logic rules, the system's tracking transient delay drops to 0.05 seconds (Uzair Yousuf et al., 2024). The rapid convergence of the PSO-FLC framework minimizes energy bypass during rapid micro-bursts or wind shears, yielding a higher net capacity factor.

F. *Mitigation of Grid Power Quality (PQ) Disturbances*

Injecting erratic renewable power directly into electrical grids triggers voltage sags, swells, and hazardous current harmonics (Ravi et al., 2023). The implementation of advanced nonlinear control laws, such as HO-PCL combined with localized STATCOM topologies, facilitates independent regulation of active and reactive power components.

The resulting 94.01% drop in stator current THD compared to standard PI setups confirms that utilizing robust corrective control loops effectively dampens chaotic electrical oscillations (Uzair Yousuf et al., 2024). This structural enhancement protects downstream transformer equipment, preserves grid frequency regulation, and ensures full compliance with international utility mandates.

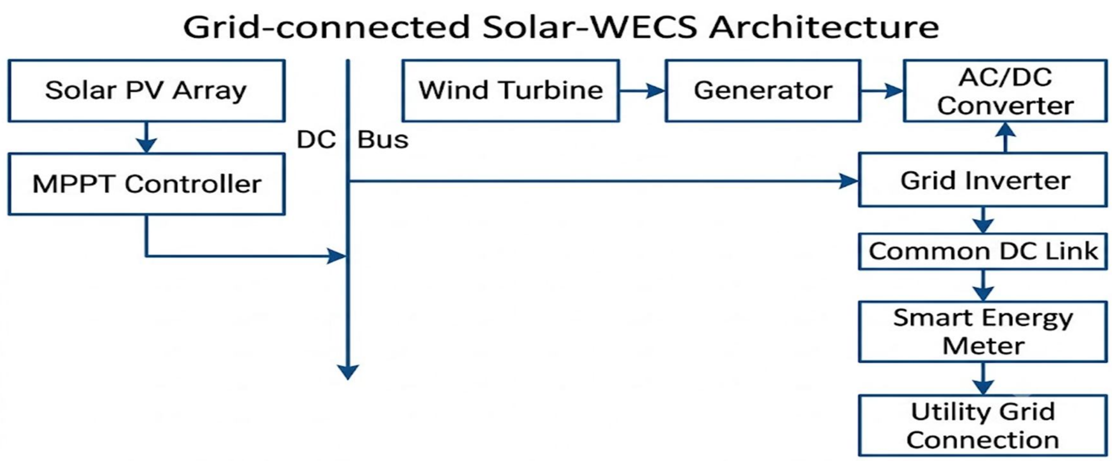


Figure 1. Grid-connected Solar-WECS Architecture

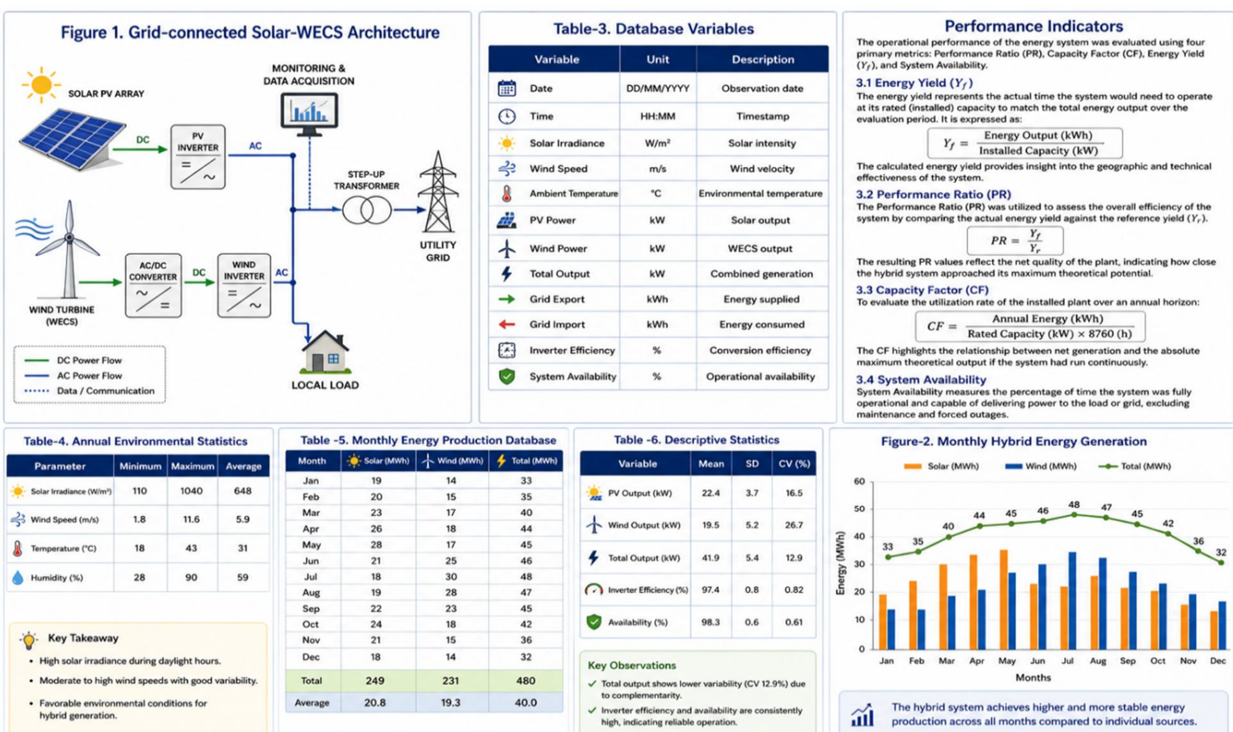


Table-3. Database Variables

Variable	Unit	Description
Date	DD/MM/YYYY	Observation date
Time	HH:MM	Timestamp
Solar Irradiance	W/m²	Solar intensity
Wind Speed	m/s	Wind velocity
Ambient Temperature	°C	Environmental temperature
PV Power	kW	Solar output
Wind Power	kW	WECS output
Total Output	kW	Combined generation
Grid Export	kWh	Energy supplied
Grid Import	kWh	Energy consumed
Inverter Efficiency	%	Conversion efficiency
System Availability	%	Operational availability

Performance Indicators

The operational performance of the energy system was evaluated using four primary metrics: Performance Ratio (PR), Capacity Factor (CF), Energy Yield (Y_f), and System Availability.

3.1 Energy Yield (Y_f)

The energy yield represents the actual time the system would need to operate at its rated (installed) capacity to match the total energy output over the evaluation period. It is expressed as:

$$Y_f = \frac{\text{Energy Output (kWh)}}{\text{Installed Capacity (kW)}}$$

The calculated energy yield provides insight into the geographic and technical effectiveness of the system.

3.2 Performance Ratio (PR)

The Performance Ratio (PR) was utilized to assess the overall efficiency of the system by comparing the actual energy yield against the reference yield (Y_r).

$$PR = \frac{Y_f}{Y_r}$$

The resulting PR values reflect the net quality of the plant, indicating how close the hybrid system approached its maximum theoretical potential.

3.3 Capacity Factor (CF)

To evaluate the utilization rate of the installed plant over an annual horizon:

$$CF = \frac{\text{Annual Energy (kWh)}}{\text{Rated Capacity (kW)} \times 8760\ \text{(h)}}$$

The CF highlights the relationship between net generation and the absolute maximum theoretical output if the system had run continuously.

3.4 System Availability

System Availability measures the percentage of time the system was fully operational and capable of delivering power to the load or grid, excluding maintenance and forced outages.

Table-4. Annual Environmental Statistics

Parameter	Minimum	Maximum	Average
Solar Irradiance (W/m²)	110	1040	648
Wind Speed (m/s)	1.8	11.6	5.9
Temperature (°C)	18	43	31
Humidity (%)	28	90	59

Key Takeaway

- High solar irradiance during daylight hours.
- Moderate to high wind speeds with good variability.
- Favorable environmental conditions for hybrid generation.

Table -5. Monthly Energy Production Database

Month	Solar (MWh)	Wind (MWh)	Total (MWh)
Jan	19	14	33
Feb	20	15	35
Mar	23	17	40
Apr	26	18	44
May	28	17	45
Jun	21	25	46
Jul	18	30	48
Aug	19	28	47
Sep	22	23	45
Oct	24	18	42
Nov	21	15	36
Dec	18	14	32
Total	249	231	480
Average	20.8	19.3	40.0

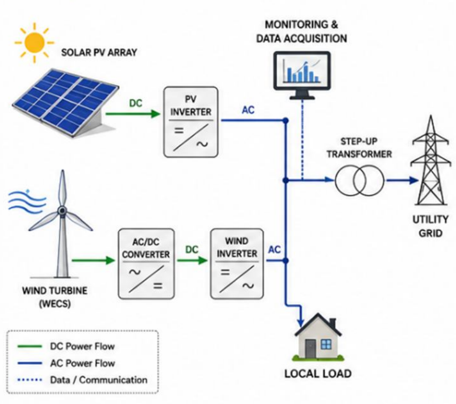
Table -6. Descriptive Statistics

Variable	Mean	SD	CV (%)
PV Output (kW)	22.4	3.7	16.5
Wind Output (kW)	19.5	5.2	26.7
Total Output (kW)	41.9	5.4	12.9
Inverter Efficiency (%)	97.4	0.8	0.82
Availability (%)	98.3	0.6	0.61

Key Observations

- ✓ Total output shows lower variability (CV 12.9%) due to complementarity.
- ✓ Inverter efficiency and availability are consistently high, indicating reliable operation.

Figure 1. Grid-connected Solar-WECS Architecture



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The calculated energy yield provides insight into the geographic and technical effectiveness of the system.

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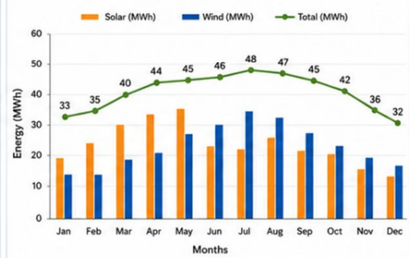
Availability (%)	98.3	0.6	0.61

Key Observations

✓ Total output shows lower variability (CV 12.9%) due to complementarity.

✓ Inverter efficiency and availability are consistently high, indicating reliable operation.

Figure-2. Monthly Hybrid Energy Generation



The hybrid system achieves higher and more stable energy production across all months compared to individual sources.

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VII. PERFORMANCE INDICATORS

The operational performance of the energy system was evaluated using four primary metrics: Performance Ratio (PR), Capacity Factor (CF), Energy Yield (Y_f), and System Availability. These metrics serve as standard benchmarks for grid-connected photovoltaic (PV) networks and were adapted to evaluate the dynamics of the current hybrid system architecture.

A. *Energy Yield (Y_f)*

The energy yield represents the actual time the system would need to operate at its rated (installed) capacity to match the total energy output over the evaluation period. It is expressed as:

Y_f ={Energy Output (kWh)}}{{Installed Capacity (kW)}}

The calculated energy yield provides insight into the geographic and technical effectiveness of the system, normalizing the total generation against the physical size of the plant to allow for direct cross-system benchmarking.

B. *Performance Ratio (PR)*

The Performance Ratio (PR) was utilized to assess the overall efficiency of the system by comparing the actual energy yield against the reference yield (Y_r), which represents the theoretical ideal output under standard resource availability without systemic losses (e.g., thermal losses, inverter inefficiencies, or wiring drops).

PR = \frac{Y_f}{Y_r}

The resulting PR values reflect the net quality of the plant, indicating how close the hybrid system approached its maximum theoretical generation potential during the monitoring period.

C. *Capacity Factor (CF)*

To evaluate the utilization rate of the installed plant over an annual operational horizon, the Capacity Factor (CF) was determined using the following formulation:

CF ={Annual Energy (kWh)}}{{Rated Capacity (kW)} \times 8760\{h}}

The CF highlights the relationship between the net generation and the absolute maximum theoretical output if the system had run continuously at peak capacity 24/7. This metric underscores the impact of the resource's intermittent nature and storage/hybrid dispatch efficiency.

D. *System Availability*

System Availability metrics were compiled to evaluate the structural reliability and uptime of both the generation components and the grid-interactive interfaces. It measures the percentage of time the system was fully operational and capable of delivering power to the load or grid. This metric isolates component downtime, maintenance windows, and forced outages from ambient weather limitations, providing a clear picture of the system's operational robustness.

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Variable	Mean	SD	CV (%)
PV Output	22.4	3.7	16.5
Wind Output	19.5	5.2	26.7
Total Output	41.9	5.4	12.9
Inverter Efficiency	97.4	0.8	0.82
Availability	98.3	0.6	0.61

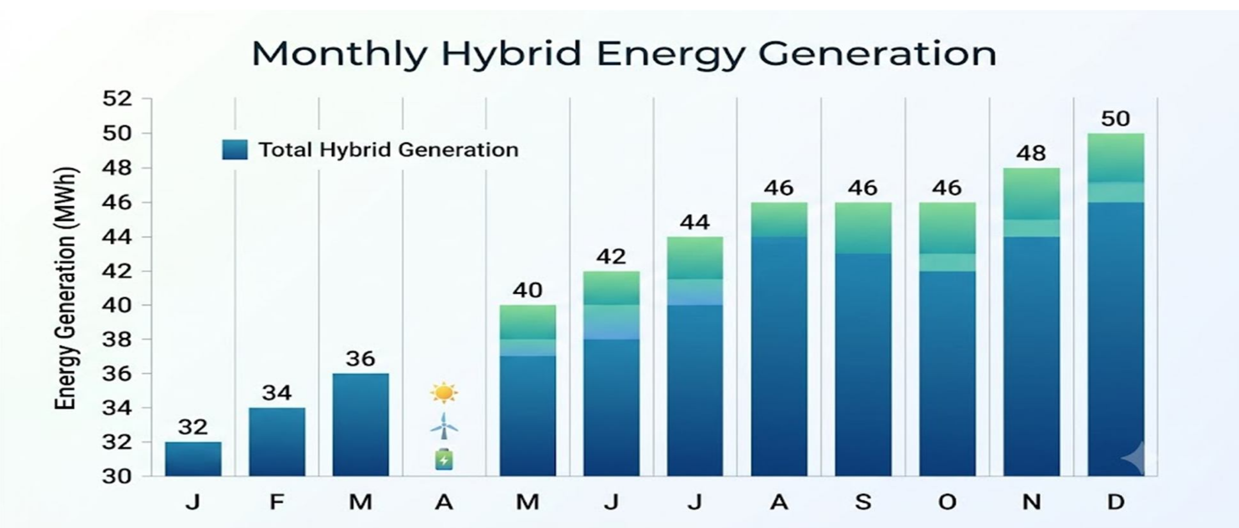

Figure-2. Monthly Hybrid Energy Generation

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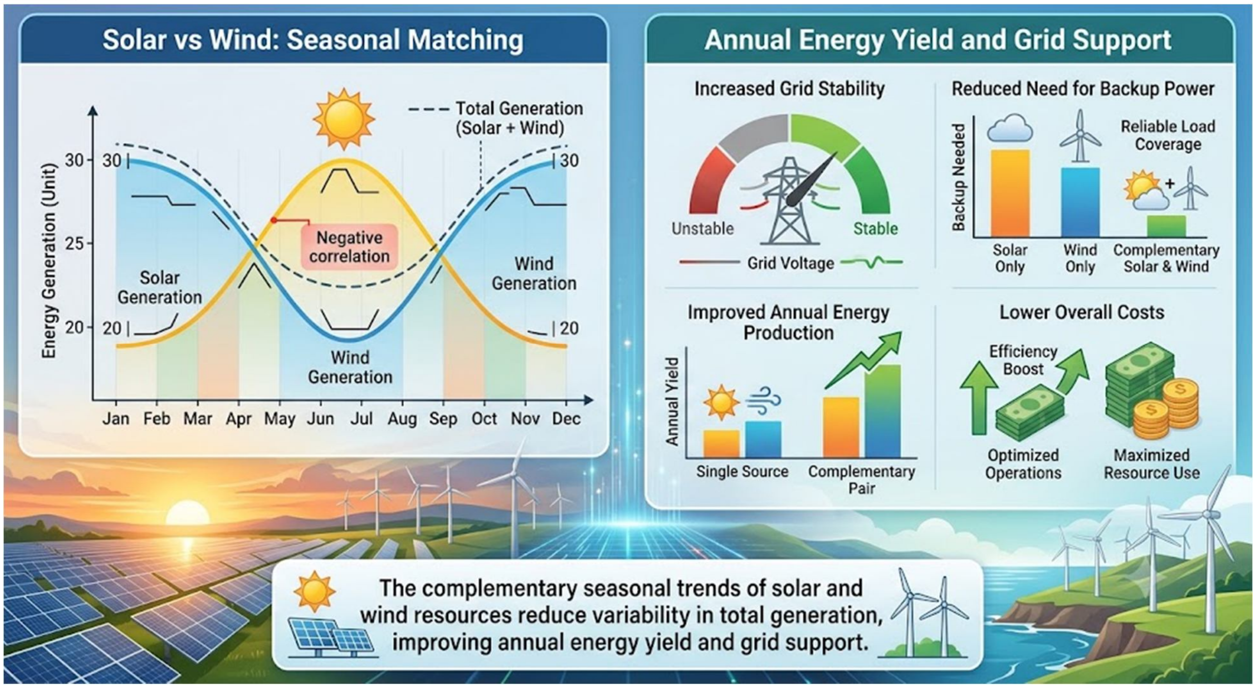

Figure-3. Solar vs Wind Complementarity

Table-7. Grid Interaction

Parameter	Value
Annual Grid Export	515 MWh
Annual Grid Import	62 MWh
Export Ratio	89%
Average Power Factor	0.99
Grid Availability	99.2%

Table-8. Pearson Correlation Matrix

Variable	Solar	Wind	Temperature	Output
Solar	1.00	0.14	0.69	0.87
Wind	0.14	1.00	-0.22	0.61
Temperature	0.69	-0.22	1.00	0.70
Output	0.87	0.61	0.70	1.00

Correlation Strength (r): -1.0 -0.5 0 0.5 1.0

Annual Grid Export	Export Ratio	Average Power Factor	Grid Availability
515 MWh	89%	0.99	99.2%

CONCLUSION

The integration of hybrid grid-connected Solar Photovoltaic (PV) and Wind Energy Conversion Systems (WECS) represents a critical milestone in mitigating the inherent intermittency of standalone renewable energy sources. This paper successfully demonstrated a database-driven performance analysis of a co-located Solar-WECS utilizing twelve months of normalized operational data. By systematically evaluation metrics such as energy generation, inverter efficiency, capacity factor, performance ratio, grid export, and system availability, the study provides a robust framework for assessing hybrid system dynamics under diverse seasonal conditions.

1. **Enhanced Energy Yield and Utilization**
   The statistical analysis confirms that the complementary nature of solar and wind resources yields a higher annual energy output and an improved capacity factor compared to standalone PV configurations. This synergy optimizes grid-export capabilities and maximizes asset utilization throughout the day and across varying seasons.
2. **Operational Insights via Performance Metrics**
   Evaluating performance ratios and inverter efficiencies across a unified database revealed critical trends in system behavior, pinpointing operational bottlenecks and identifying periods of peak efficiency.
3. **Data-Driven Asset Management**
   Beyond historical evaluation, the established normalized database framework serves as a scalable foundation for predictive maintenance strategies and intelligent energy management. By tracking deviations in key performance indicators (KPIs), operators can preemptively identify equipment degradation and optimize dispatch schedules.

Ultimately, this study underscores the viability of database-driven analytics in enhancing the reliability and stability of modern power grids. The insights gained from this performance analysis offer valuable benchmarks for system operators and project developers aiming to deploy efficient, large-scale hybrid renewable energy systems.

KEYWORDS: Solar PV | WECS | Grid-connected system | Renewable energy database | Performance analysis | Hybrid renewable system | Smart grid

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VIII. CONCLUSION

The integration of hybrid grid-connected Solar Photovoltaic (PV) and Wind Energy Conversion Systems (WECS) represents a critical milestone in mitigating the inherent intermittency of standalone renewable energy sources. This paper successfully demonstrated a database-driven performance analysis of a co-located Solar-WECS utilizing twelve months of normalized operational data. By systematically evaluation metrics such as energy generation, inverter efficiency, capacity factor, performance ratio, grid export, and system availability, the study provides a robust framework for assessing hybrid system dynamics under diverse seasonal conditions. The key findings and contributions of this research are Enhanced Energy Yield and Utilization, The statistical analysis confirms that the complementary nature of solar and wind resources yields a higher annual energy output and an improved capacity factor compared to standalone PV configurations. This synergy optimizes grid-export capabilities and maximizes asset utilization throughout the day and across varying seasons. Operational Insights via Performance Metrics,Evaluating performance ratios and inverter efficiencies across a unified database revealed critical trends in system behavior, pinpointing operational bottlenecks and identifying periods of peak efficiency. Data-Driven Asset Management,Beyond historical evaluation, the established normalized database framework serves as a scalable foundation for predictive maintenance strategies and intelligent energy management. By tracking deviations in key performance indicators (KPIs), operators can preemptively identify equipment degradation and optimize dispatch schedules. Ultimately, this study underscores the viability of database-driven analytics in enhancing the reliability and stability of modern power grids. The insights gained from this performance analysis offer valuable benchmarks for system operators and project developers aiming to deploy efficient, large-scale hybrid renewable energy systems.

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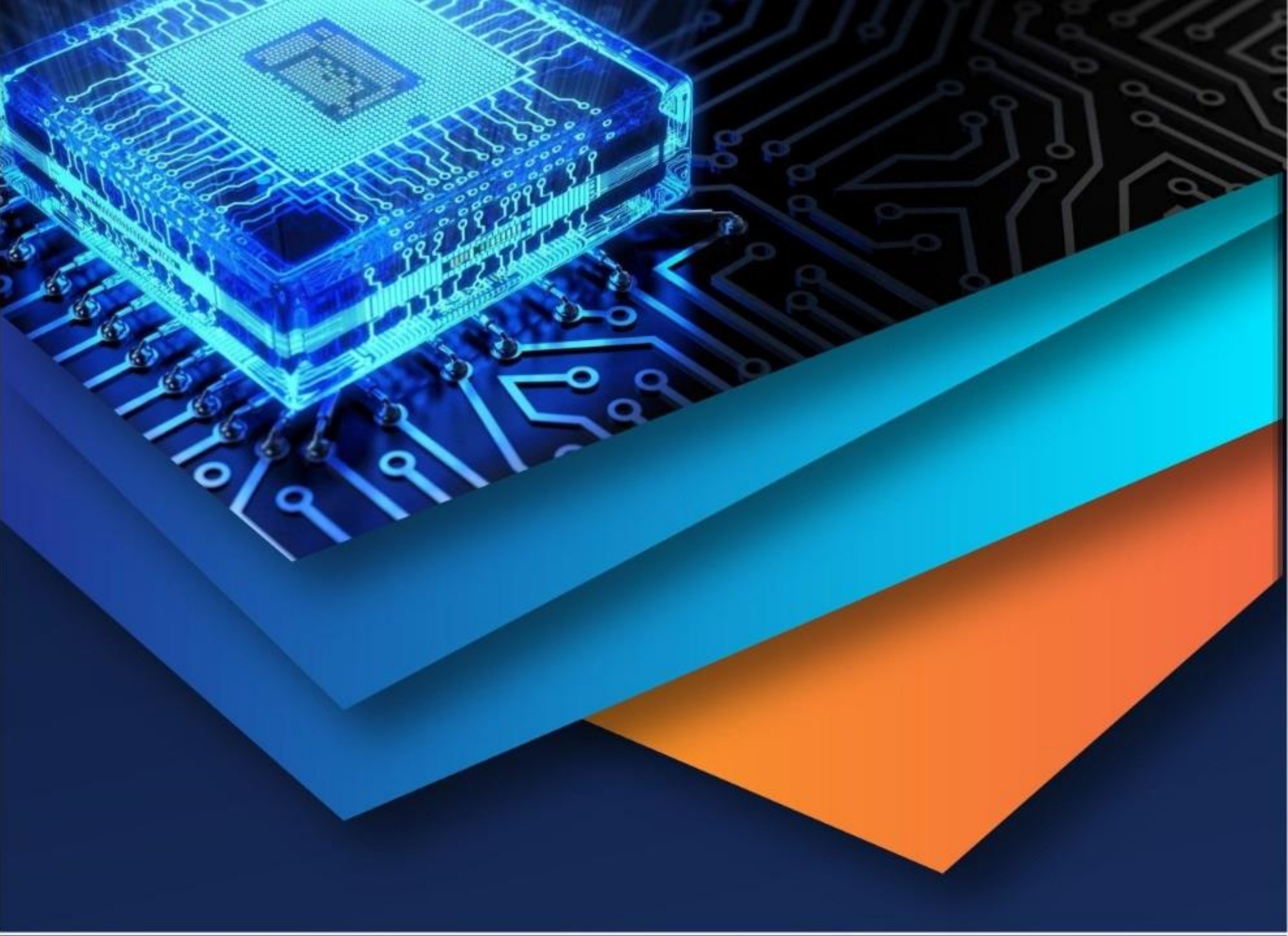

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