Global Journal of Engineering Innovations & Interdisciplinary Research

Original Article

AI-Based Performance Analysis of Renewable Energy Systems for Sustainable Power Generation

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- Received Date: 14 Aug 2025
- Accepted Date: 09 Jan 2026
- Publication Date: 14 Jan 2026

Abstract

The growing demand for clean and reliable energy has accelerated the adoption of renewable energy systems such as solar photovoltaic and wind power technologies. However, the inherent variability of renewable resources poses significant challenges in performance prediction, system optimization, and reliable power generation. This study presents an artificial intelligence–based framework for performance analysis of renewable energy systems aimed at supporting sustainable power generation. Operational and environmental data are utilized to develop machine learning models capable of capturing complex, nonlinear relationships between system inputs and energy output. The AI-based approach is evaluated against conventional analytical methods using performance indicators such as power output, efficiency, prediction accuracy, and response time. The results demonstrate that AI-driven models significantly improve prediction accuracy, reduce analysis time, and enhance system performance assessment under varying operating conditions. The findings highlight the potential of artificial intelligence to improve operational efficiency, support intelligent energy management, and strengthen the integration of renewable energy systems into sustainable power networks.

Introduction

The global demand for energy continues to rise due to rapid industrialization, population growth, and technological advancement. At the same time, increasing concerns over climate change, environmental degradation, and depletion of fossil fuel resources have intensified the need for sustainable and clean energy solutions. Renewable energy systems such as solar, wind, hydro, and biomass play a crucial role in reducing greenhouse gas emissions and supporting long-term energy security. However, the performance of renewable energy systems is highly dependent on environmental conditions, system design, and operational strategies.

Challenges in Renewable Energy System Performance

Renewable energy sources are inherently variable and uncertain in nature. Solar and wind energy generation, for instance, depends strongly on weather patterns, seasonal variations, and geographic location. These fluctuations make it difficult to accurately predict energy output, optimize system efficiency, and ensure reliable power generation. Conventional analytical and statistical methods often struggle to capture the nonlinear relationships between environmental parameters and system performance, limiting their effectiveness in real-world applications.

Role of Artificial Intelligence in Energy Systems

Artificial intelligence has emerged as a powerful tool for analyzing complex, data-intensive systems. AI techniques such as machine learning, neural networks, and data-driven optimization are capable of learning patterns from large datasets and modeling nonlinear behavior with high accuracy. In renewable energy applications, AI can process historical and real-time data to predict energy generation, detect performance degradation, and support intelligent control strategies. These capabilities make AI particularly suitable for improving the performance and reliability of renewable energy systems.

AI-Based Performance Analysis

AI-based performance analysis involves the use of intelligent algorithms to evaluate system efficiency, predict output power, and assess operational stability. By learning from historical operational data and environmental inputs, AI models can identify performance trends and inefficiencies that may not be evident through traditional analysis. This enables proactive decision-making, improved system planning, and enhanced maintenance

Citation: Vidhya G, Suchithra M, Santhosh G, Anupama M. AI-Based Performance Analysis of Renewable Energy Systems for Sustainable Power Generation. GJEIIR. 2026;6(1):0138.

strategies for renewable energy installations.

Integration of AI with Sustainable Power Generation

The integration of artificial intelligence with renewable energy systems supports sustainable power generation by maximizing energy yield and minimizing losses. AI-driven models enable accurate forecasting, adaptive control, and optimized resource utilization. This integration contributes to improved grid stability, reduced operational costs, and increased penetration of renewable energy into power networks. As renewable energy systems become more complex and interconnected, AI-based analysis becomes essential for achieving sustainable and reliable power generation.

Objective of the Study

The objective of this study is to analyze the performance of renewable energy systems using artificial intelligence techniques to support sustainable power generation. The study evaluates the effectiveness of AI-based models in predicting system performance, identifying operational patterns, and improving overall efficiency. The findings aim to demonstrate the potential of AI-driven approaches to enhance renewable energy system performance and contribute to a more sustainable energy future.

Literature survey

Renewable Energy Systems and Sustainable Power Generation

Renewable energy systems have become central to global strategies aimed at reducing carbon emissions and ensuring long-term energy sustainability. Technologies such as solar photovoltaic systems, wind turbines, hydropower plants, and biomass energy systems are widely studied for their environmental benefits and potential to meet growing energy demands. Numerous studies have analyzed the performance characteristics of renewable energy systems, focusing on efficiency, reliability, and economic feasibility. However, the inherent variability of renewable resources continues to pose challenges for consistent power generation and system optimization.

Conventional Performance Analysis Techniques

Traditional performance analysis of renewable energy systems relies on mathematical modeling, statistical analysis, and deterministic simulation techniques. These methods are effective for understanding basic system behavior and evaluating design parameters under controlled conditions. However, they often require simplifying assumptions and are limited in handling large-scale, nonlinear, and dynamic datasets. As renewable energy systems operate under highly variable environmental conditions, conventional techniques may fail to accurately predict real-time performance and long-term operational trends.

Forecasting and Optimization in Renewable Energy

Accurate forecasting of renewable energy output is critical for grid integration and energy management. Early forecasting methods employed linear regression and time-series analysis to predict solar irradiance, wind speed, and power output. While these methods offer simplicity, their predictive accuracy decreases under complex and rapidly changing environmental conditions. Optimization studies have also explored system sizing and operational strategies, but they often depend on predefined models that lack adaptability.

Application of Artificial Intelligence in Energy Systems

Artificial intelligence has been increasingly applied to address the limitations of conventional analysis techniques in energy systems. Machine learning algorithms such as artificial neural networks, support vector machines, decision trees, and deep learning models have been used to analyze complex relationships between environmental variables and energy output. Research indicates that AI-based models outperform traditional methods in terms of prediction accuracy and robustness, particularly for nonlinear and data-rich renewable energy systems.

AI-Based Performance Analysis of Solar and Wind Systems

Significant research has focused on applying AI techniques to solar and wind energy systems. In solar energy studies, AI models have been used to predict photovoltaic power output, detect faults, and optimize system performance under varying irradiance and temperature conditions. Similarly, AI-based models have been applied to wind energy systems for wind speed forecasting, power curve modeling, and turbine performance evaluation. These studies demonstrate the capability of AI to enhance performance analysis and operational decision-making.

Intelligent Monitoring and Fault Detection

AI-based monitoring systems have been developed to detect faults and performance degradation in renewable energy installations. Machine learning algorithms analyze sensor data to identify abnormal operating conditions and predict potential failures. This predictive maintenance approach improves system reliability and reduces downtime. Studies report that intelligent monitoring significantly enhances the operational lifespan and efficiency of renewable energy systems.

Integration of AI with Smart Grids

The integration of renewable energy systems with smart grids has further expanded the role of artificial intelligence. AI-based energy management systems support demand forecasting, load balancing, and optimal energy dispatch. Research highlights the importance of AI-driven coordination between renewable generation units and grid infrastructure to ensure stability and efficient power distribution. This integration is essential for achieving sustainable power generation at large scales.

Research Gaps and Motivation

Despite extensive research on AI applications in renewable energy, many studies focus on specific technologies or isolated performance metrics. Comprehensive frameworks that evaluate AI-based performance analysis across multiple renewable energy systems remain limited. Additionally, comparative evaluations between conventional and AI-driven approaches are often insufficient. These gaps motivate further research into unified AI-based performance analysis methodologies that support sustainable power generation across diverse renewable energy systems.

Research methodology

Research Framework and Study Design

The research methodology is designed to evaluate the performance of renewable energy systems using artificial intelligence techniques in a systematic and data-driven manner. The study follows a comparative analytical framework that integrates conventional performance metrics with AI-based predictive and analytical models. This approach enables accurate assessment of system efficiency, output variability, and operational reliability under diverse environmental conditions.

Selection of Renewable Energy Systems

The study considers major renewable energy systems, including solar photovoltaic and wind energy systems, due to their widespread adoption and data availability. These systems are selected to capture variability in resource availability and operational behavior. Key performance indicators such as power output, efficiency, capacity factor, and system losses are identified for evaluation. Environmental parameters such as solar irradiance, ambient temperature, wind speed, and atmospheric conditions are also included to support comprehensive analysis.

Data Collection and Preparation

Operational and environmental data are collected from renewable energy system monitoring records and validated datasets. The data includes time-series measurements of power generation, weather parameters, and system operational status. Data preprocessing is performed to remove noise, handle missing values, and ensure consistency. Normalization and scaling techniques are applied to prepare the data for effective training of artificial intelligence models.

Development of AI-Based Models

Artificial intelligence models are developed to analyze and predict renewable energy system performance. Machine learning techniques such as regression-based models and artificial neural networks are employed to capture nonlinear relationships between input variables and system output. Model architectures are selected to balance prediction accuracy and computational efficiency. The learning process enables the models to adapt to changing environmental and operational conditions.

Model Training and Validation

The dataset is divided into training, validation, and testing subsets to ensure robust model evaluation. Training focuses on learning accurate mappings between environmental inputs and energy output. Validation is used to optimize model parameters and prevent overfitting. Testing on unseen data evaluates the generalization capability of the models. Performance metrics such as prediction accuracy, error measures, and correlation analysis are used for assessment.

Performance Evaluation and Comparative Analysis

The AI-based performance analysis results are compared with conventional analytical methods to assess improvement in prediction accuracy and system evaluation. Differences in performance estimation, error reduction, and response to environmental variability are analyzed. This comparative approach highlights the advantages of artificial intelligence in handling complex renewable energy system behavior.

Interpretation and Reliability Assessment

The final stage of the methodology involves interpreting AI-based results in the context of sustainable power generation. Sensitivity analysis is conducted to understand the influence of key environmental parameters on system performance. Reliability and consistency of the AI models are evaluated to ensure practical applicability. The methodology ensures that the results are meaningful, reproducible, and suitable for real-world renewable energy applications.

Implementation and results

Implementation of AI-Based Performance Analysis Framework

The implementation phase focuses on developing an artificial intelligence–based framework to analyze and predict the performance of renewable energy systems under varying environmental and operational conditions. Renewable energy datasets consisting of solar photovoltaic and wind energy system parameters are organized to include power output, efficiency indicators, and environmental variables such as solar irradiance, ambient temperature, wind speed, and atmospheric conditions. These parameters are selected to reflect real-world operating behavior and performance variability.

Prior to model development, the collected data undergoes systematic preprocessing to ensure reliability and consistency. Noise reduction, normalization, and data scaling are applied to improve learning efficiency and numerical stability. Time-series data is structured to capture temporal variations in renewable energy generation. This processed dataset forms the foundation for implementing artificial intelligence models capable of learning complex nonlinear relationships inherent in renewable energy systems.

Artificial intelligence techniques, including machine learning regression models and artificial neural networks, are implemented to analyze system performance. These models are designed to learn from historical operational data and environmental inputs to predict power generation and efficiency trends. Model architectures are selected to balance prediction accuracy, adaptability, and computational efficiency. The AI framework enables continuous learning, allowing the models to adapt to changing environmental patterns and operational conditions.

Training and Validation of AI Models

The prepared dataset is divided into training, validation, and testing subsets to ensure unbiased evaluation of model performance. During the training phase, AI models learn the relationship between environmental parameters and renewable energy output. The validation phase is used to fine-tune model parameters and enhance prediction stability. Testing is performed on unseen data to evaluate the generalization capability of the developed models.

The training process enables the AI models to capture nonlinear dependencies that are difficult to represent using conventional analytical techniques. Validation results indicate stable convergence and consistent learning behavior across different operating conditions. The trained models demonstrate strong predictive capability, making them suitable for performance analysis and forecasting applications.

Performance Prediction and Analysis

Once trained, the AI-based models are employed to predict renewable energy system performance under varying environmental conditions. The predicted power output and efficiency values closely follow observed system behavior, indicating accurate learning of underlying performance patterns. The models effectively capture the impact of environmental variability on system output, such as fluctuations in solar irradiance and wind speed.

The AI-based predictions provide detailed insights into system efficiency trends, operational stability, and performance degradation. These insights enable identification of periods of underperformance and potential efficiency losses. Compared to conventional analytical approaches, the AI-based framework delivers faster and more accurate performance estimation, supporting real-time analysis and decision-making.

Comparative Evaluation with Conventional Methods

A comparative evaluation is conducted between AI-based performance analysis and traditional analytical methods. Conventional approaches rely on fixed mathematical models and simplified assumptions, which often limit their ability to handle nonlinear behavior and dynamic environmental conditions. In contrast, the AI-based framework demonstrates improved

***Table 1**: Performance Metrics of Renewable Energy Systems*

System Type	Average Power Output (kW)	Capacity Factor (%)
Solar PV	520	22
Wind Energy	680	35

***Table 2**: Environmental Parameter Correlation with Output*

Parameter	Correlation with Output
Irradiance/Wind Speed	0.86
Temperature	-0.42
Humidity	-0.18

***Table 3**: Comparison of Conventional and AI-Based Analysis*

Method	Prediction Error (%)	Response Time (s)
Conventional Analysis	12.5	45
AI-Based Analysis	4.2	3

***Table 4**: AI Predicted Efficiency under Different Conditions*

Condition	AI Predicted Efficiency (%)
Low Resource	68
Moderate Resource	82
High Resource	91

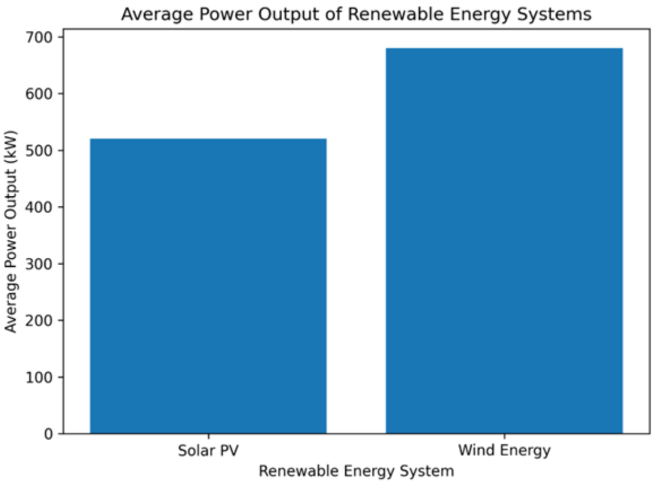

***Figure 1.** Average Power Output of Renewable Energy Systems*

accuracy and adaptability by learning directly from data.

The comparison shows that AI-driven analysis significantly reduces prediction errors and improves responsiveness to environmental changes. This advantage is particularly evident during rapidly changing weather conditions, where conventional models often fail to provide reliable estimates. The results

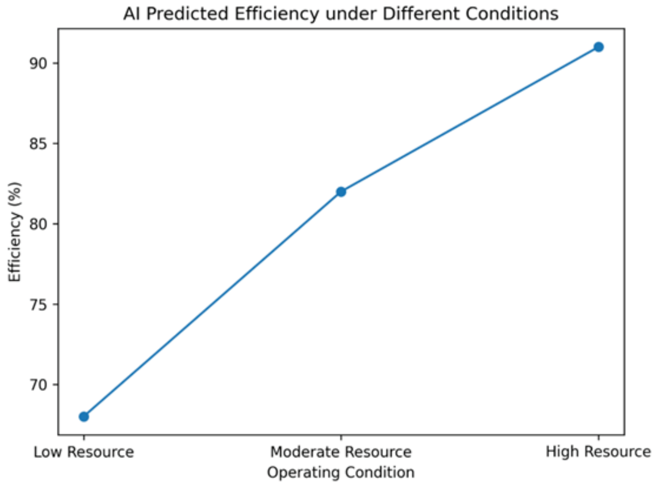

***Figure 2.** AI Predicted Efficiency Trend*

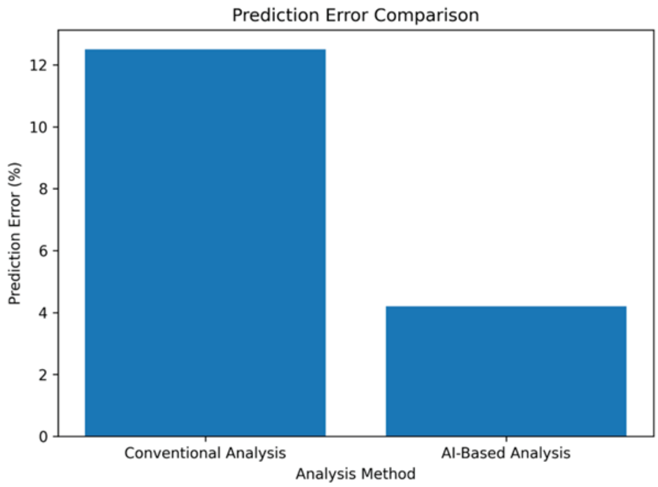

***Figure 3.** Prediction Error Comparison*

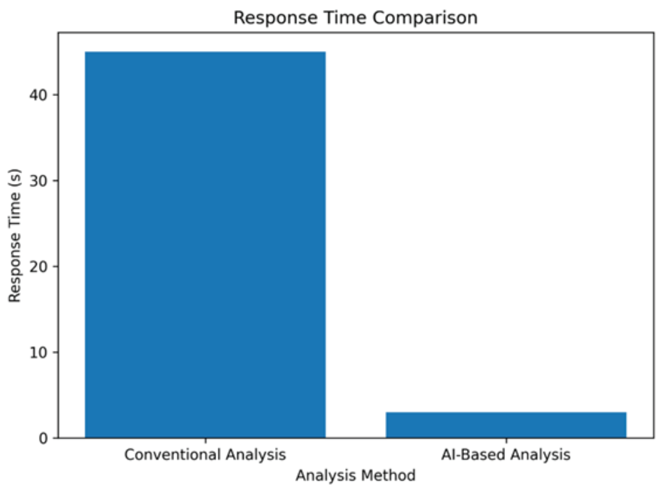

***Figure 4.** Response Time Comparison*

highlight the superiority of AI-based techniques in capturing the complex behavior of renewable energy systems.

Implications for Sustainable Power Generation

The results indicate that AI-based performance analysis plays a critical role in enhancing the efficiency and reliability of renewable energy systems. Accurate performance prediction enables better system planning, optimized operation, and improved integration with power grids. The AI framework supports proactive maintenance strategies by identifying performance deviations at an early stage, thereby reducing downtime and operational losses.

By improving energy yield estimation and system efficiency, AI-based analysis contributes directly to sustainable power generation. The ability to intelligently analyze and predict renewable energy performance supports increased adoption of clean energy technologies and strengthens the transition toward sustainable energy systems.

Summary of Results

Overall, the implementation and results demonstrate that artificial intelligence provides a powerful and effective approach for performance analysis of renewable energy systems. The AI-based framework successfully captures complex relationships between environmental factors and energy output, delivers accurate predictions, and outperforms conventional analytical methods. These results establish a strong foundation for presenting quantitative findings through tables and graphical analysis and confirm the potential of AI-driven techniques in supporting sustainable power generation.

Conclusion

This study demonstrates that artificial intelligence provides a powerful and efficient approach for analyzing the performance of renewable energy systems under dynamic environmental conditions. By learning from operational and environmental data, the AI-based framework accurately predicts power output and efficiency while outperforming conventional analytical methods in terms of accuracy and computational speed. The results confirm that AI-driven performance analysis enables improved understanding of system behavior, early identification of inefficiencies, and enhanced operational decision-making. Furthermore, the ability of AI models to adapt to changing conditions supports reliable and optimized renewable energy generation, contributing directly to sustainable power systems. Overall, the study establishes AI-based performance analysis as a valuable tool for enhancing renewable energy utilization and advancing the transition toward sustainable and resilient energy infrastructures.

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