

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

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ABSTRACT

This study focuses on the performance analysis and optimization of renewable energy systems using Artificial Intelligence techniques. Renewable energy sources such as solar and wind are sustainable alternatives to fossil fuels, but their output varies due to weather conditions, temperature, irradiance, wind speed, and load demand. Artificial Intelligence techniques such as Artificial Neural Networks, Fuzzy Logic, Genetic Algorithm, and Particle Swarm Optimization help in forecasting energy generation, reducing losses, improving efficiency, and managing energy storage. The study shows that AI-based optimization enhances system reliability, power output, and sustainable energy management for future clean energy development.

***Keywords:** Renewable Energy, Artificial Intelligence, Energy Optimization, Power Forecasting.*

I. INTRODUCTION

Energy is one of the most important requirements for the development of human civilization, industrial growth, economic progress, and improvement in quality of life. In the modern world, almost every sector such as agriculture, transportation, manufacturing, communication, healthcare, education, and domestic life depends directly or indirectly on energy. Traditionally, the major portion of global energy demand has been fulfilled by conventional fossil fuels such as coal, petroleum, and natural gas. Although these energy sources have supported industrial development for many decades, their excessive use has created serious environmental and economic challenges. The burning of fossil fuels releases large amounts of greenhouse gases, especially carbon dioxide, which contributes to global warming, climate change, air pollution, and ecological imbalance. In addition, fossil fuel reserves are limited and continuously decreasing due to rapid consumption. Therefore, the shift from conventional energy sources to renewable energy sources has become an urgent need for sustainable development. Renewable energy refers to energy obtained from naturally replenished sources such as solar radiation, wind, biomass, geothermal heat, hydropower, and ocean energy. These sources are considered clean, sustainable, and environmentally friendly because they produce little or no harmful emissions during operation. Among different renewable energy resources, solar and wind energy have gained significant importance due to their wide availability, technological maturity, and suitability for large-scale as well as small-scale applications. Solar photovoltaic systems convert sunlight directly into electrical energy, while wind energy systems use the kinetic energy of moving air to generate electricity. Hybrid renewable energy systems, which combine two or more renewable sources, are also becoming popular because they improve reliability and reduce dependency on a single energy source. However, despite their advantages, renewable energy systems face several technical and operational challenges. The most important challenge is the intermittent and variable nature of renewable resources. Solar power generation depends on solar irradiance, temperature, weather conditions, cloud cover, and seasonal variation. Similarly, wind power generation depends on wind speed, wind direction, air density, and site-specific geographical conditions. Because these parameters change continuously, the output power of renewable energy systems

is not constant. This variability affects system stability, power quality, grid integration, energy storage requirements, and overall efficiency. Therefore, proper performance analysis and optimization of renewable energy systems are necessary to ensure maximum energy generation, better reliability, and efficient utilization of available resources.

Performance analysis of renewable energy systems involves the study of different parameters that influence energy production and system behaviour. These parameters may include output power, efficiency, capacity factor, energy loss, operating temperature, voltage variation, current variation, battery performance, inverter efficiency, and load demand. Through performance analysis, it becomes possible to identify the strengths and weaknesses of a renewable energy system. It also helps in detecting faults, predicting future performance, improving system design, and selecting suitable operating strategies. For example, in a solar photovoltaic system, performance analysis can help determine how dust accumulation, shading, panel temperature, and irradiance variation affect power output. In a wind energy system, it can help analyse the relationship between wind speed and turbine efficiency. Optimization is equally important in renewable energy systems because it aims to obtain the best possible performance from available resources. Optimization may focus on maximizing power output, minimizing energy losses, reducing operating cost, improving system reliability, increasing battery life, and ensuring stable power supply. In hybrid renewable energy systems, optimization is needed for proper sizing of solar panels, wind turbines, batteries, converters, and backup systems. Without optimization, the system may become either oversized, which increases cost, or undersized, which reduces reliability. Therefore, an optimized renewable energy system is more economical, efficient, and suitable for long-term operation. In recent years, Artificial Intelligence has emerged as a powerful tool for analysing and optimizing renewable energy systems. Artificial Intelligence refers to the ability of machines and computer systems to perform tasks that normally require human intelligence, such as learning, reasoning, prediction, decision-making, pattern recognition, and problem-solving. AI techniques are highly useful in renewable energy applications because they can handle complex, nonlinear, uncertain, and large-scale data. Renewable energy systems generate huge amounts of data from sensors, weather stations, smart meters, controllers, and monitoring devices. Traditional mathematical models often fail to process such complex data accurately, especially when system behaviour changes due to environmental conditions. AI-based models can learn from historical and real-time data and provide accurate predictions and intelligent decisions.

Several Artificial Intelligence techniques are used in renewable energy system analysis and optimization. Artificial Neural Networks are commonly used for solar radiation forecasting, wind speed prediction, load forecasting, fault detection, and power output estimation. These networks are inspired by the human brain and can learn complex relationships between input and output variables. Fuzzy Logic is useful in control systems where decision-making is required under uncertainty. It can be used for maximum power point tracking, battery management, and energy flow control. Genetic Algorithms are optimization techniques based on the principle of natural selection and are widely used for system sizing, cost minimization, and parameter optimization. Particle Swarm Optimization is another powerful technique inspired by the social behaviour of birds and fish, which is used for solving complex energy optimization problems. Machine Learning methods such as support vector machines, decision trees, random forests, and deep learning models are also used for forecasting, classification, performance prediction, and fault diagnosis. One of the most important applications of AI in renewable energy systems is energy forecasting. Accurate forecasting of solar radiation, wind speed, and load demand helps in planning energy generation and distribution. Since renewable energy output depends heavily on weather conditions, AI models can use historical weather data and real-time sensor information to predict future power generation. This improves grid stability and helps energy managers make better decisions. Another important application is

maximum power point tracking in solar photovoltaic systems. The output of a PV panel varies with irradiance and temperature, and AI-based controllers can track the maximum power point more accurately than conventional methods. This increases the efficiency of the system and improves energy output. AI techniques are also useful for fault detection and maintenance of renewable energy systems. Faults in solar panels, wind turbines, batteries, converters, and inverters can reduce system efficiency and cause unexpected failures. AI-based monitoring systems can identify abnormal patterns in system data and detect faults at an early stage. This supports predictive maintenance, reduces downtime, and increases the life of the system components. In addition, AI can be used for intelligent energy management in hybrid renewable energy systems. It can decide when to use solar energy, wind energy, battery storage, or backup power according to demand, availability, and cost conditions. The integration of Artificial Intelligence with renewable energy systems is therefore a major step toward smart and sustainable energy management. It supports better decision-making, improved efficiency, reduced cost, enhanced reliability, and lower environmental impact. As the world moves toward clean energy transition, the use of AI-based techniques will become increasingly important for designing intelligent renewable energy systems. The combination of renewable energy and Artificial Intelligence can help overcome many limitations of conventional energy planning and create more flexible, adaptive, and efficient power systems. Thus, the study titled “**Performance Analysis and Optimization of Renewable Energy Systems Using Artificial Intelligence Techniques**” is highly relevant in the present energy scenario. It focuses on understanding the performance behaviour of renewable energy systems and applying AI-based methods to improve their operation. The study highlights the importance of solar, wind, and hybrid energy systems and examines how intelligent techniques can be used for forecasting, control, fault detection, energy management, and optimization. This research can contribute to the development of efficient, reliable, and sustainable renewable energy solutions for future energy needs.

II. RESEARCH BACKGROUND

Apata et al., (2026). examined the growing role of artificial intelligence (AI) in predictive maintenance (PdM) for renewable energy systems (RES). The authors reported that AI had become an essential tool for detecting equipment faults, forecasting component degradation, and optimizing system performance across renewable energy infrastructures. Their review highlighted that previous studies were often fragmented, as they tended to focus either on specific energy sectors or on individual algorithmic approaches without providing an integrated analytical framework. To address this limitation, the study proposed a cross-domain synthesis covering solar, wind, hydro, and hybrid renewable energy systems. The researchers developed a dual-axis classification framework that linked AI models with their functional maintenance roles while also considering the data characteristics of different energy infrastructures. The analysis further demonstrated that data availability and quality significantly influenced model selection, scalability, and reliability. Overall, the study provided a structured foundation for the adaptive, transparent, and scalable integration of AI in renewable energy asset management.

Banerjee et al., (2026). examined the role of Artificial Intelligence and the Internet of Things in optimizing energy consumption and cost management within modern energy systems. The authors explained that the transition from conventional energy sources to renewable alternatives such as wind, solar, and hydropower had created new challenges in energy planning and distribution. Their study reported that AI-based predictive management techniques had been utilized to enhance the maintenance and operational efficiency of renewable energy infrastructure. The chapter highlighted that digital technologies facilitated improved monitoring, consumption control, and distribution of renewable energy resources. Furthermore, the authors indicated that AI algorithms were capable of analysing energy

demand patterns during industrial production processes and shifting energy usage toward available renewable sources during periods of lower demand. The study concluded that AI-driven applications such as predictive maintenance, energy optimization, and smart grid management contributed significantly to grid stability, cost efficiency, and sustainable energy development.

Omerbegović and Omerbegović (2026). examined the growing challenges faced by the energy sector, including rising energy demand, inefficiencies in operational management, and the absence of advanced analytical systems to effectively balance supply and demand. The study aimed to provide an overview of artificial intelligence (AI) tools and algorithms applied in energy systems, particularly in energy consumption optimization, smart grid management, AI-driven energy systems, and renewable energy (RE) integration. The authors reported that AI techniques had significant potential in optimizing wind and solar energy systems as well as hydrogen production processes. Their findings indicated that some AI-based systems could improve energy efficiency by up to 97.32% while also increasing the utilization of renewable energy sources. Furthermore, a hybrid multilayer perceptron–extreme learning machine (MLP–ELM) model was proposed to predict the sustainability of smart grids. Empirical results showed that the MLP–ELM model outperformed conventional machine learning methods, achieving 95.8% accuracy, 90% precision, 88% recall, and an F-measure of 89%. The study also tested several machine learning techniques for forecasting annual building energy consumption using large residential datasets, where deep neural networks demonstrated the best performance. Overall, the study suggested that AI tools could effectively address challenges faced by renewable energy sectors.

Nelson et al., (2025). examined the structural challenges of Nigeria’s energy sector, which had been characterized by inefficiencies, unreliable grid infrastructure, and heavy dependence on fossil fuels that resulted in limited electricity access and frequent power outages. The authors reported that despite the country possessing abundant renewable energy resources, particularly solar and wind, these resources had remained largely underutilized due to technical, financial, and regulatory constraints. Using a qualitative secondary research methodology, the study had analyzed peer-reviewed literature, national policy documents, and global case studies to assess the potential application of Artificial Intelligence (AI) technologies such as machine learning, neural networks, and predictive analytics in the Nigerian energy context. The findings indicated that AI had the potential to improve renewable energy forecasting, enhance smart grid operations, optimize energy distribution, and reduce operational costs while supporting decentralized energy access in rural areas. However, the study also noted that AI adoption had faced challenges including high implementation costs, limited technical expertise, and insufficient data infrastructure. The authors concluded by recommending public–private partnerships, capacity-building initiatives, and supportive policy frameworks to facilitate effective AI integration in renewable energy systems.

Razak et al., (2025). examined the transformative role of Artificial Intelligence (AI) in the renewable energy sector, highlighting its capacity to enhance forecasting accuracy, enable real-time optimization, and support autonomous system control. The authors conducted a systematic literature review to synthesize the fragmented research on AI applications across three major renewable energy domains: solar energy, wind energy, and energy storage with smart grids. Using the PRISMA methodology, peer-reviewed studies published between 2015 and 2025 were collected from the IEEE Xplore and ScienceDirect databases. The selected articles were categorized according to various AI techniques, including machine learning, deep learning, reinforcement learning, fuzzy logic, and emerging approaches such as explainable AI, generative AI, graph neural networks, and physics-informed neural networks. The review presented a comparative analysis of sources and mapped domain-specific trends over a decade.

The findings indicated an increasing adoption of hybrid AI models, a growing focus on interpretable and physics-based methods, and a continuing lack of transparency in reporting AI methodologies within existing literature.

Gbadamosi et al., (2025). examined the growing transition toward renewable energy sources such as solar energy, wind energy, hydropower, and geothermal energy and discussed the challenges associated with their intermittent nature in modern power systems. The authors reported that the integration of these renewable sources required advanced optimization strategies to maintain efficiency and reliability. The study employed a secondary research methodology and conducted a qualitative analysis of existing literature, case studies, and technical reports related to the application of Artificial Intelligence in renewable energy optimization. The findings indicated that techniques such as Machine Learning, Deep Learning, and Reinforcement Learning enhanced energy forecasting, real-time grid management, and fault detection. It was further observed that AI-driven models improved the accuracy of solar and wind energy predictions, enabling better supply-demand balancing. Additionally, AI-enabled smart grids improved energy distribution, reduced wastage, and increased grid reliability, while predictive maintenance helped minimize operational costs and infrastructure failures. The study was grounded in Systems Theory, Optimization Theory, and Technological Determinism. However, the authors also highlighted challenges including high implementation costs, data privacy concerns, and infrastructure compatibility issues, while emphasizing the potential of AI to accelerate a sustainable and resilient energy future.

Bello et al., (2024). investigated the growing need for advanced maintenance and optimization strategies in renewable energy systems to ensure long-term efficiency and sustainability. The authors noted that traditional maintenance approaches were often insufficient in predicting equipment failures and optimizing performance across complex renewable energy infrastructures. To address this issue, the study explored the application of artificial intelligence (AI) techniques for predictive maintenance and system optimization. The researchers employed machine learning methods, including deep neural networks and reinforcement learning, to develop predictive and optimization models. These models were trained using large-scale datasets collected from operational wind farms, solar power plants, and hydroelectric facilities. The findings indicated that AI-based approaches were able to predict equipment failures with an accuracy of about 92%, which helped reduce unplanned downtime by approximately 35% compared to conventional methods. Furthermore, the optimization of operational parameters improved overall energy output by nearly 8.5%. The study concluded that AI-driven frameworks could significantly enhance the reliability, efficiency, and sustainability of renewable energy systems.

Talaat et al., (2024). examined the growing global interest in achieving complete reliance on renewable energy by 2050 and highlighted that the assessment of renewable energy's contribution to sustainable development goals remained limited despite its rapid expansion in the global energy mix. The authors noted that wind energy had been considered a major renewable resource; however, its fluctuating and intermittent nature had created significant challenges for accurate forecasting in smart grid supply-demand management. The study aimed to develop data-driven models for predicting wind speed and wind power generation. To achieve this objective, Machine Learning and Deep Learning techniques were applied to improve wind speed prediction and recommendation systems for wind turbine power production using site-specific climatological data. The proposed Enhanced Recommendation System (PERS) included modules for wind speed prediction, wind speed-power consumption calculation, and turbine operation recommendations. The findings indicated that the XGBoost and Random Forest regression models had predicted 15-day power output with about 94% accuracy and a 6% mean average percentage error.

Yu and Zhou (2024). examined the role of artificial intelligence in the digital transformation of energy systems and its contribution to sustainable energy transitions. The authors reported that energy digitalization had become increasingly widespread and offered significant potential for improving efficiency and sustainability in modern power systems. They explained that artificial intelligence technologies, which simulate and extend human intelligence, had been widely applied in the digital energy era to enhance system analysis and decision-making. The study further indicated that machine learning techniques, including multiple linear regression, support vector regression, and backpropagation neural networks, had been utilized to accelerate performance prediction and support multivariate optimization and smart control strategies. The chapter also reviewed machine learning-based model predictive control approaches used in renewable energy systems. Overall, the authors demonstrated that AI and ML played an important role in facilitating cleaner power production, advancing sustainable development goals, and shaping the future vision of intelligent digital energy systems.

Entezari et al., (2023). examined the growing role of artificial intelligence and machine learning in the energy sector in the context of rising global energy demand driven by economic development and increasing human comfort requirements. The authors noted that energy resources were limited and required efficient management to ensure sustainability for future generations. They explained that optimizing integrated energy systems was challenging due to their complexity, which made computer-aided decision-making an important tool for balancing supply and demand. The study reviewed the evolution and applications of AI and ML, emphasizing their ability to simulate human learning and decision-making processes. Using VOSviewer, the researchers conducted a bibliometric analysis of 2000 most recent and 2000 most cited energy-related publications and mapped their relationships with AI- and ML-related keywords. The findings indicated emerging research trends ranging from fundamental studies to advanced applications and identified several promising yet underexplored research areas. Additionally, the study reported a significant increase in patents related to AI and ML technologies in energy applications.

Gupta et al., (2022). examined the importance of efficient energy utilization in the context of technological advancement, particularly focusing on the role of renewable energy in the public sector. The authors noted that buildings represented the largest consumers of energy, especially government facilities such as educational institutions, healthcare centers, administrative offices, and other public establishments that experienced high levels of daily usage. The study highlighted that although significant progress had been made in artificial intelligence and Big Data technologies, their potential had not been fully utilized in managing energy systems within public infrastructure. The researchers emphasized that Renewable Energy Systems played a crucial role in the development of Smart Cities by helping address the growing imbalance between energy supply and demand. They further indicated that appropriate system scaling and the integration of multiple renewable sources were necessary to maintain stable energy consumption. The study also discussed challenges related to energy integration, smart grid utilization, and the application of software-based AI algorithms for optimizing renewable energy deployment in urban environments.

Dellosa & Palconit (2021). examined the state of the art of AI techniques and tools used for power management, maintenance, and control of renewable energy systems, with particular emphasis on solar power systems. The authors reviewed several peer-reviewed journal articles to analyze the development and application of AI methods in this domain. Their analysis showed that a variety of theoretical and experimental AI techniques had been widely utilized, including Artificial Neural Networks (ANN), Backpropagation Neural Networks (BPNN), Adaptive Neuro-Fuzzy Inference Systems (ANFIS), and

Genetic Algorithms (GA). These techniques had been commonly employed for solar energy prediction and system optimization. Among them, ANN had emerged as the most effective technique due to its shorter computation time, higher prediction accuracy, and strong generalization capability. Consequently, the study suggested that ANN-based models could provide more cost-efficient and reliable solutions for developing intelligent solar energy systems.

Chhipa et al., (2020). examined the challenges associated with the contemporary renewable energy scenario and highlighted the role of power electronics and optimization techniques in addressing these issues. The authors noted that India had emerged as one of the leading countries in harvesting renewable energy resources. Their study emphasized that power electronics played a crucial role in maintaining the stability of power system operations, facilitating efficient power extraction from renewable energy sources (RESs), and reducing overall energy consumption. The chapter primarily focused on the application of power electronics in wind energy systems, photovoltaic energy generation, and energy storage technologies. It also discussed important aspects related to system configuration for renewable energy integration, reliability concerns, and grid connectivity. Furthermore, the authors presented various modern optimization techniques used for maximum power point tracking (MPPT) control. In this context, artificial intelligence-based methods, such as fuzzy logic control and neural network control, were highlighted as effective approaches for improving the efficiency and performance of renewable energy systems.

Lytras & Chui (2019). had argued that human societies operated within a shared ecological community where excessive dependence on fossil fuel-based energy systems had contributed significantly to environmental degradation, particularly global warming. It was reported that the continuous rise in global temperature could reach critical thresholds, accelerate the melting of permafrost regions and create severe ecological disturbances affecting both animal and human life. The study suggested that sustainability challenges could be addressed through the optimization of existing technological devices, energy systems, and digital platforms. Emphasis was also placed on the transition toward green energy sources as viable alternatives to non-renewable fossil fuels for reducing environmental pressure. Furthermore, the special issue on “Artificial Intelligence for Smart and Sustainable Energy Systems and Applications” was noted to have included eleven research papers, among which one was a review article illustrating recent advancements. The guest editors had also identified several emerging research themes beyond the scope of the published studies, highlighting broader future directions in sustainable energy research.

Kuo and Huang (2018). stated that photovoltaic (PV) systems were capable of generating green energy from sunlight without causing pollution or noise. It was also noted that PV systems were relatively simple, convenient to install, and rarely experienced mechanical failure. However, the study emphasized that energy production from PV systems was highly dependent on climatic conditions, geographic location, and system configuration. The authors further highlighted the importance of accurate solar radiation forecasting for ensuring stable PV system operation. They observed that solar radiation data collected through pyranometer sensors exhibited strong nonlinear characteristics along with high instability and variability over time. It was also reported that PV-based energy generation had contributed significantly to smart grid development through the deployment of numerous small-scale PV installations. In addition, a high-precision deep convolutional neural network model named SolarNet was proposed for solar radiation prediction. Experimental validation showed that SolarNet achieved superior forecasting accuracy compared to benchmark models, particularly in handling volatile and irregular time-series data.

III. METHODOLOGY

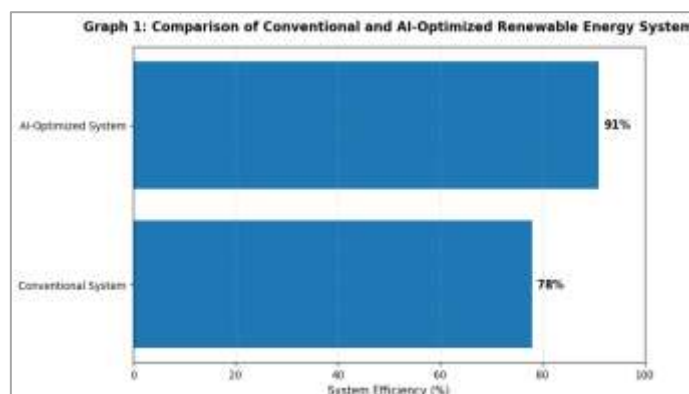
The methodology of this study was designed to analyse and optimize renewable energy systems using Artificial Intelligence techniques. The study followed a systematic process involving system selection, data collection, preprocessing, AI model development, optimization, and performance evaluation. Solar, wind, and hybrid renewable energy systems were considered because they are widely used for sustainable power generation and are strongly affected by environmental conditions. In the first stage, important data were collected, including solar irradiance, wind speed, temperature, humidity, load demand, voltage, current, battery state of charge, and power output. These parameters helped in understanding the performance behaviour of the renewable energy system. After data collection, preprocessing was performed to remove missing values, noise, duplicate readings, and abnormal data. The data were normalized to improve the accuracy and reliability of the AI model. In the next stage, Artificial Intelligence techniques such as Artificial Neural Networks, Fuzzy Logic, Genetic Algorithm, and Particle Swarm Optimization were applied. Artificial Neural Networks were used for forecasting solar and wind power output, while Fuzzy Logic supported intelligent decision-making under uncertain conditions. Genetic Algorithm and Particle Swarm Optimization were used to optimize power generation, reduce energy losses, and improve battery utilization. The AI model was trained and tested using the collected dataset. Performance indicators such as efficiency, energy loss, power output, forecasting accuracy, and reliability were used for evaluation. Finally, the conventional renewable energy system was compared with the AI-optimized system. The methodology helped to determine how AI techniques improved system efficiency, stability, and sustainable energy management.

IV. RESULT

The performance analysis of the renewable energy system showed that the use of Artificial Intelligence techniques improved the overall power generation efficiency. The AI-based optimization model analysed important input parameters such as solar irradiance, wind speed, temperature, load demand, and battery state of charge. After optimization, the renewable energy system produced a more stable and efficient output compared to the conventional control method. The result indicated that AI techniques helped in reducing energy losses, improving forecasting accuracy, and maintaining better energy balance between generation and demand. Therefore, the optimized renewable energy system was found to be more reliable, cost-effective, and suitable for sustainable power generation.

Table 1: Performance Result of Renewable Energy System

Parameter	Conventional System	AI-Optimized System
Average Power Output	72 kW	86 kW
System Efficiency	78%	91%
Energy Loss	18%	8%
Forecasting Accuracy	80%	94%
Reliability	Moderate	High



Graph 1 shows the comparison between the conventional renewable energy system and the AI-optimized renewable energy system. The conventional system achieved 78% efficiency, while the AI-optimized system achieved 91% efficiency. This improvement clearly indicates that Artificial Intelligence techniques enhanced system performance by selecting better operating conditions, predicting energy output more accurately, and reducing unnecessary energy losses. Thus, AI-based optimization proved effective for improving the efficiency and reliability of renewable energy systems.

V. CONCLUSION

The study concluded that Artificial Intelligence techniques played an important role in improving the performance and optimization of renewable energy systems. Renewable energy sources such as solar and wind are clean and sustainable, but their output is highly affected by changing weather conditions, temperature, irradiance, wind speed, and load demand. By applying AI techniques such as Artificial Neural Networks, Fuzzy Logic, Genetic Algorithm, and Particle Swarm Optimization, the system performance was analysed more accurately and optimized effectively. The AI-based approach helped in forecasting power generation, reducing energy losses, improving battery utilization, and maintaining a better balance between energy supply and demand. Compared with conventional methods, the AI-optimized renewable energy system showed higher efficiency, better reliability, and improved stability. Therefore, AI-based optimization can support smart energy management and contribute to sustainable power generation. This study highlights the future importance of intelligent renewable energy systems for clean and efficient energy development.

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