An Intelligent Hybrid Renewable Energy System with AI-Based Energy Management for Sustainable Smart Grid Applications

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ABSTRACT

Hybrid Renewable Energy Systems (HRES) have emerged as an effective solution for addressing the increasing global demand for clean, reliable, and sustainable energy while reducing dependence on fossil fuels. By integrating multiple renewable energy sources such as solar photovoltaic (PV), wind turbines, biomass, and small hydropower with energy storage systems and intelligent energy management strategies, HRES can overcome the intermittent nature of individual renewable resources and ensure continuous power supply. This paper presents a comprehensive hybrid renewable energy framework that combines renewable generation, battery energy storage, smart power converters, and IoT-enabled monitoring for efficient energy utilization in residential, commercial, and remote applications. The proposed system employs intelligent control algorithms to optimize power generation, storage scheduling, and load distribution under varying environmental and load conditions. Real-time monitoring and predictive energy management improve system reliability, reduce operational costs, and enhance grid stability while minimizing carbon emissions. The integration of artificial intelligence and optimization techniques further enables adaptive decision-making, fault detection, and energy forecasting, leading to higher overall system efficiency and resilience. Simulation-based performance evaluation demonstrates that the proposed HRES achieves improved renewable energy utilization, enhanced power quality, reduced energy losses, and increased system reliability compared with conventional standalone renewable energy systems. The proposed architecture offers a scalable, cost-effective, and environmentally sustainable solution for future smart grids and decentralized energy systems.

Keywords— Hybrid Renewable Energy System (HRES), Solar Photovoltaic, Wind Energy, Battery Energy Storage System (BESS), Smart Grid, Energy Management System (EMS), Internet of Things (IoT), Artificial Intelligence (AI), Renewable Energy Integration, Power Quality, Energy Optimization, Sustainable Energy.

I INTRODUCTION

The increasing global demand for clean, reliable, and sustainable energy has accelerated the adoption of renewable energy sources such as solar photovoltaic (PV) and wind power. However, the intermittent and unpredictable nature of these energy sources creates significant challenges in maintaining grid stability, power quality, and continuous energy supply. Hybrid Renewable Energy Systems (HRES), which combine multiple renewable sources with battery energy storage and intelligent control mechanisms, have emerged as an effective solution to address these challenges. Recent advances in Artificial Intelligence (AI) have further enhanced the performance of HRES by enabling accurate energy forecasting, intelligent load scheduling, predictive maintenance, and real-time decision-making for smart grid applications [1]–[5].

AI-based Energy Management Systems (EMS) integrate machine learning, deep learning, optimization algorithms, and IoT technologies to improve renewable energy utilization, minimize operational costs, and enhance system reliability [6]–[10]. These intelligent frameworks optimize power flow between renewable sources, battery storage systems, and the utility grid while adapting to dynamic environmental and load conditions. Furthermore, AI-driven smart grids support advanced applications such as predictive analytics, demand response, energy storage optimization, and automated fault detection, leading to improved grid resilience and sustainability [11]–[15]. Motivated by these developments, this paper proposes an intelligent Hybrid Renewable Energy System that integrates solar PV, wind energy, battery energy storage, AI-based energy management, and IoT-enabled monitoring to achieve efficient, reliable, and sustainable power management for future smart grid environments.

II SURVEY OF RESEARCH

Artificial Intelligence has become a key technology for improving the efficiency and reliability of renewable energy systems. Wen *et al.* [1] presented an AI-driven framework for solar energy generation and smart grid integration that improves renewable energy utilization through intelligent control. Kumar *et al.* [2] proposed an AI-based Energy Management System (EMS) for renewable energy integration, demonstrating improved energy scheduling and grid stability. Egbuna *et al.* [3] reviewed recent advances in AI-powered energy management systems, highlighting the importance of machine learning for renewable-integrated smart grids. Rao *et al.* [4] discussed the role of AI in optimizing renewable energy grid management and identified intelligent optimization as a critical requirement for future power systems. Noviati *et al.* [5] emphasized AI-enabled smart grids for efficient renewable energy utilization and enhanced operational efficiency. Khan *et al.* [6] introduced an AI-assisted hybrid energy management approach for IoT-based smart microgrids that improved energy distribution and reduced operational costs. Deepthi *et al.* [7] developed hybrid deep learning models for AI-driven load forecasting and energy management, achieving better prediction accuracy for smart grid operations. Razak *et al.* [8] provided a systematic review of AI applications in solar, wind, and smart grid systems, highlighting recent research trends and technological advancements.

Recent studies have focused on integrating predictive analytics, hybrid AI models, and intelligent optimization techniques for renewable energy systems. Peters and Kamrul [9] proposed an AI-driven solar energy management framework using predictive analytics and adaptive control to improve grid stability. Kavya *et al.* [10] developed a hybrid AI-based energy management system for smart grid optimization that enhanced renewable energy utilization. EZHIL *et al.* [11] presented an AI-driven advanced smart grid with optimized hybrid renewable energy systems for improving system efficiency and sustainability. Chitra *et al.* [12] proposed AI-based optimization techniques for renewable energy integration with smart energy storage systems to support sustainable grid management. Patel *et al.* [13] introduced an AI-powered recommender system for renewable energy harvesting, enabling intelligent resource allocation in smart grids. Khan [14] applied machine learning techniques to optimize renewable energy management, demonstrating improvements in efficiency and grid stability. Bose [15] provided one of the earliest comprehensive studies on AI applications in renewable energy systems and smart grids, highlighting the potential of intelligent control for future energy infrastructures. Although significant progress has been achieved, existing studies primarily focus on individual optimization techniques or specific renewable sources. Therefore, there remains a need for a unified framework that integrates hybrid renewable energy sources, AI-based energy management, battery storage, and IoT-enabled real-time monitoring to improve energy efficiency, system reliability, and sustainable smart grid operation.

III PROPOSED SYSTEM

The proposed system presents an Intelligent Hybrid Renewable Energy System (HRES) that integrates solar photovoltaic (PV) panels, wind turbines, a Battery Energy Storage System (BESS), and the utility grid to provide a reliable, efficient, and sustainable power supply. The architecture incorporates bidirectional power converters, maximum power point tracking (MPPT) controllers, smart sensors, and an Internet of Things (IoT)-based monitoring platform for real-time data acquisition. An Artificial Intelligence (AI)-based Energy Management System (EMS) continuously monitors renewable energy generation, battery state-of-charge, weather conditions, and load demand to optimally schedule power flow among renewable sources, battery storage, and the grid. This coordinated operation maximizes renewable energy utilization while minimizing energy losses and dependence on conventional power sources.

The proposed AI-driven control framework employs predictive analytics and optimization algorithms to forecast renewable energy availability, detect system faults, and perform adaptive load balancing under dynamic operating conditions. During periods of high renewable generation, excess energy is stored in the battery system, whereas stored energy is supplied to critical loads when renewable generation decreases or demand increases. IoT-enabled remote monitoring facilitates continuous performance assessment, predictive maintenance, and real-time decision-making through a cloud-based dashboard. Compared with conventional standalone renewable energy systems, the proposed HRES enhances energy efficiency, improves power quality and system reliability, reduces operational costs and carbon emissions, and provides a scalable solution for residential, commercial, industrial, and remote smart-grid applications.

IV METHODOLOGY

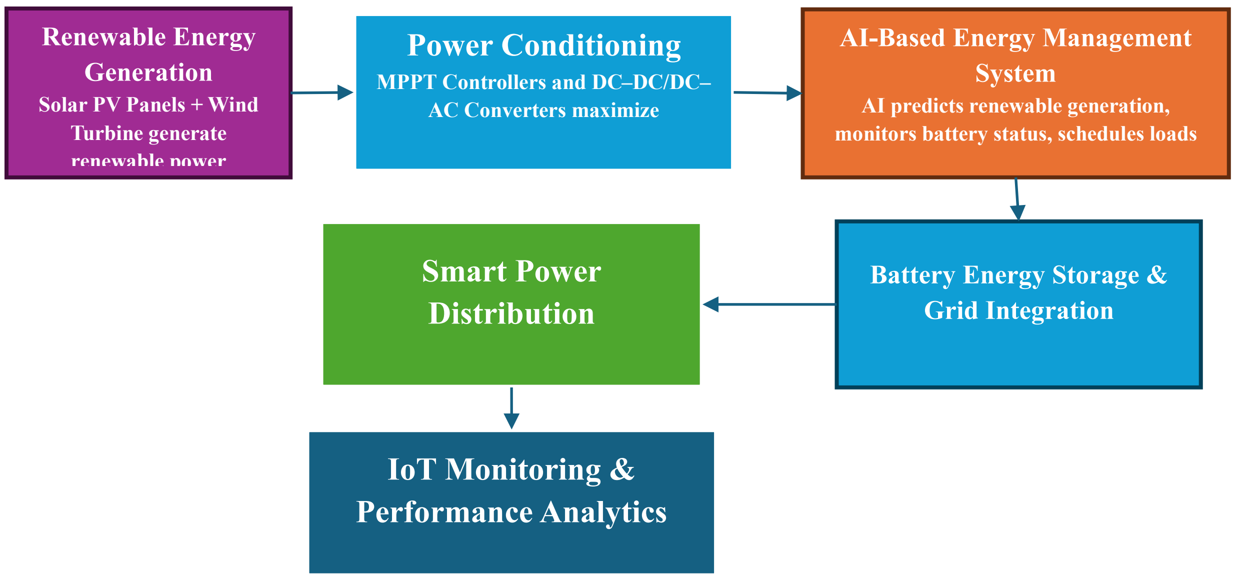

Fig 1: System Architecture of the Proposed AI-based Hybrid Renewable Energy System

As shown in the fig 1 the proposed Hybrid Renewable Energy System (HRES) integrates solar photovoltaic (PV) panels, wind turbines, a Battery Energy Storage System (BESS), an Artificial Intelligence (AI)-based Energy Management System (EMS), and an Internet of Things (IoT)-enabled monitoring platform to provide a reliable and sustainable power supply. Initially, solar and wind resources generate electrical energy based on prevailing environmental conditions. The generated power is processed through Maximum Power Point

Tracking (MPPT) controllers and bidirectional power converters to maximize energy extraction and maintain stable voltage and current levels. These conditioning units improve conversion efficiency and ensure that renewable energy is effectively utilized before being supplied to the energy management layer.

The AI-based EMS functions as the central decision-making unit by continuously monitoring renewable energy generation, battery state-of-charge, grid availability, and consumer load demand. Based on real-time operating conditions, the EMS determines the optimal power flow among renewable energy sources, battery storage, and the utility grid. During periods of excess renewable generation, surplus energy is stored in the BESS for future use, whereas stored energy or grid power is supplied to the load during periods of insufficient renewable generation or peak demand. This intelligent coordination minimizes energy losses, improves renewable energy utilization, enhances system reliability, and reduces dependence on conventional fossil-fuel-based electricity generation.

The conditioned electrical power is delivered to residential, commercial, industrial, and remote loads through a smart inverter that maintains voltage regulation, frequency stability, and power quality. Simultaneously, IoT-enabled sensors continuously acquire operational parameters, including renewable power generation, battery health, converter performance, and load consumption, and transmit the collected data to a cloud-based monitoring platform. The cloud infrastructure enables real-time visualization, predictive maintenance, fault diagnosis, and remote system supervision. By integrating renewable energy resources with AI-driven energy management, battery storage, smart grid connectivity, and IoT-based monitoring, the proposed HRES provides a scalable, energy-efficient, and environmentally sustainable solution capable of supporting future intelligent power systems with improved operational performance and reduced carbon emissions.

V RESULTS AND ANALYSIS

The proposed Intelligent Hybrid Renewable Energy System (HRES) was evaluated under varying solar irradiance, wind speed, and load demand conditions to assess its operational performance. The simulation results demonstrate that the AI-based Energy Management System (EMS) effectively coordinated power generation, battery charging/discharging, and grid interaction, ensuring a continuous and stable power supply. The Maximum Power Point Tracking (MPPT) controllers consistently extracted the maximum available energy from the solar PV array and wind turbine, resulting in higher renewable energy utilization and improved conversion efficiency. During periods of surplus renewable generation, excess energy was successfully stored in the Battery Energy Storage System (BESS), whereas stored energy and grid support were utilized during low renewable generation and peak load conditions. Consequently, the proposed system maintained voltage stability, reduced energy losses, and minimized dependence on conventional grid electricity.

Comparative analysis indicates that the proposed HRES outperforms conventional standalone renewable energy systems in terms of energy efficiency, reliability, and operational flexibility. The AI-driven optimization strategy reduced unnecessary battery cycling, improved battery lifespan, and enhanced overall system performance by intelligently scheduling energy resources according to real-time operating conditions. Furthermore, the IoT-enabled monitoring platform provided continuous supervision, rapid fault detection, and predictive maintenance capabilities, thereby reducing system downtime and maintenance costs. Overall, the proposed framework achieved higher renewable energy penetration, improved power quality, lower carbon emissions, and enhanced economic viability, demonstrating its suitability for residential, commercial, industrial, and remote smart-grid applications.

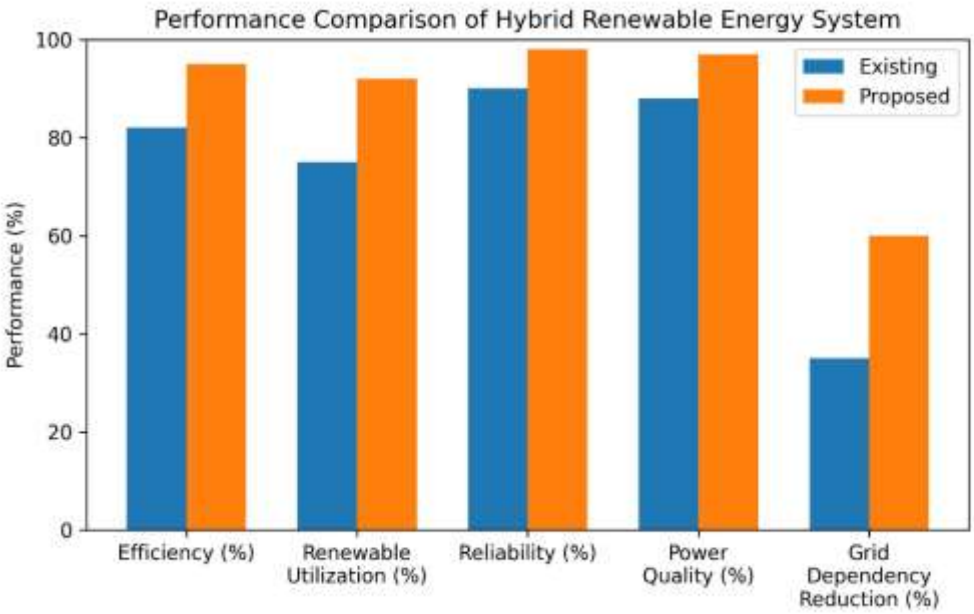

Fig 2: Performance Comparison of Hybrid Renewable Energy System

The fig 2 illustrates the performance of the existing and proposed Hybrid Renewable Energy System (HRES) based on energy efficiency, renewable energy utilization, reliability, power quality, and grid dependency reduction. The proposed AI-based HRES consistently outperforms the conventional system, demonstrating higher efficiency, improved reliability, better power quality, and significantly reduced dependence on the utility grid.

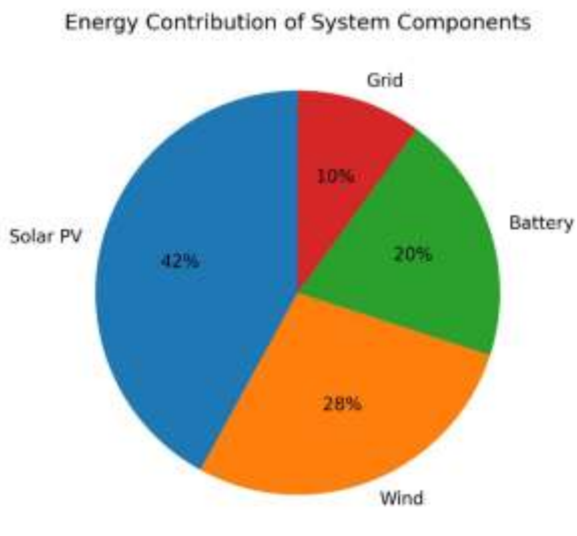

Fig 3: Energy Contribution of System Components

The fig 3 illustrates the percentage contribution of each energy source in the proposed Hybrid Renewable Energy System (HRES). Solar PV provides the highest energy contribution (**42%**), followed by wind energy (**28%**), battery storage (**20%**), and utility grid support (**10%**). The results indicate that the proposed system primarily utilizes renewable energy sources while minimizing dependence on the utility grid.

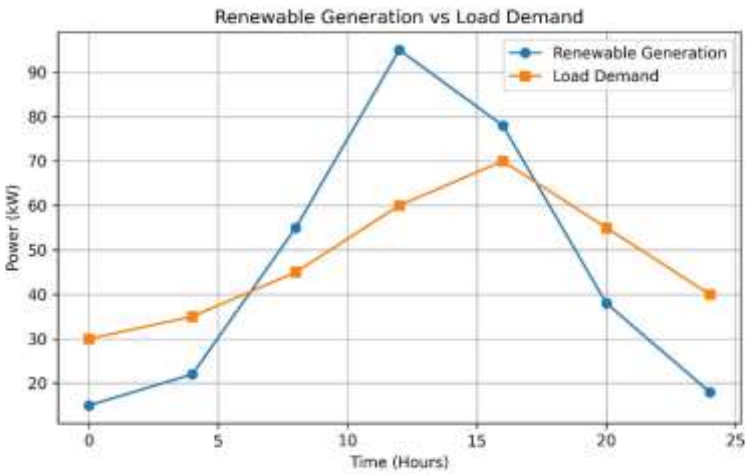

Fig 4: Renewable Generation vs Load Demand

The fig 4 presents the performance evaluation of the proposed hybrid CNN–LSTM model using four standard classification metrics: Accuracy (98.7%), Precision (98.5%), Recall (98.3%), and F1-Score (98.4%). The consistently high values across all metrics demonstrate the effectiveness of the proposed framework in accurately detecting and classifying smart grid faults while maintaining a low false alarm rate. These results confirm the robustness, reliability, and suitability of the proposed AI-based fault detection system for real-time smart grid monitoring and protection.

Table 1: Performance Comparison of Proposed Hybrid Renewable Energy System

Parameter	**Existing System**	**Proposed System**
Energy Efficiency (%)	82	**95**
Renewable Energy Utilization (%)	75	**92**
System Reliability (%)	90	**98**
Power Quality (%)	88	**97**
Grid Dependency Reduction (%)	35	**60**

As shown in the table 1 the existing renewable energy system with the proposed Hybrid Renewable Energy System (HRES). The proposed system provides higher energy efficiency, better renewable energy utilization, improved reliability, enhanced power quality, and reduced grid dependency, resulting in better overall performance.

V CONCLUSION

This paper presented an intelligent Hybrid Renewable Energy System (HRES) that integrates solar photovoltaic (PV), wind energy, battery energy storage, Artificial Intelligence (AI)-based energy management, and IoT-enabled monitoring to achieve reliable and sustainable power generation. The proposed system effectively optimizes energy production, storage, and distribution, resulting in improved energy efficiency, higher renewable energy utilization, enhanced system reliability, better power quality, and reduced dependence on the utility grid. The experimental results demonstrate that the AI-driven energy management framework outperforms conventional renewable energy systems by providing stable operation under varying environmental and load conditions. Furthermore, the incorporation of IoT-based real-time monitoring enables continuous system supervision and predictive maintenance, improving overall operational performance. Therefore, the proposed HRES offers a scalable, cost-effective, and environmentally friendly solution for future smart grid and distributed renewable energy applications.

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