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AI Based Optimization of a Solar Wind Battery Hybrid Renewable Energy System: A Case Study of Yavatmal, India

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Abstract
Hybrid renewable energy systems integrating solar, wind, and battery storage are widely considered a sustainable solution for decentralized power generation. However, variability in renewable resources leads to operational inefficiencies and challenges in energy management. This study proposes an Artificial Intelligence (AI) based optimization framework that integrates Artificial Neural Networks (ANN) with a Genetic Algorithm (GA) to enhance the performance of a solar wind battery hybrid renewable energy system. The proposed method is evaluated using real meteorological data collected from Yavatmal district, Maharashtra, India. The ANN model is developed for accurate short-term power prediction, while GA is applied to optimize operational parameters including learning rate, weight coefficients, and battery charge-discharge limits. The proposed ANN-GA framework is compared with a conventional rule based energy management strategy to establish a baseline performance reference. Simulation results indicate that the optimized system improves prediction accuracy from 89.4% to 96.8%, increases annual energy yield by 13.6%, and reduces operational losses by approximately 10%. Furthermore, the optimized system demonstrates improved battery utilization and reduced cost of energy. The results confirm that the proposed AI based optimization framework provides significant improvements in reliability, efficiency, and economic performance of hybrid renewable energy systems in semi urban regions.
Keywords: Hybrid Renewable Energy System, Artificial Intelligence, ANN-GA Optimization, Solar-Wind Hybrid System, Energy Management.

1. Introduction

The global demand for electricity continues to increase due to rapid industrialization, urbanization, and population growth. At the same time, environmental concerns related to fossil fuel consumption and greenhouse gas emissions have accelerated the transition toward renewable energy technologies. Among available renewable resources, solar and wind energy are widely recognized as sustainable and environmentally friendly alternatives due to their abundant availability and decreasing installation costs.

However, renewable energy sources are inherently intermittent and highly dependent on weather conditions. Variations in solar irradiance and wind speed often lead to unstable power output, which can negatively affect system reliability and grid stability. To address this limitation, Hybrid Renewable Energy Systems (HRES) that combine multiple renewable sources with energy storage technologies have gained significant attention.

Solar-wind hybrid systems provide complementary energy generation characteristics. Solar energy is primarily available during daytime hours, while wind resources are often stronger during evening or seasonal periods. The integration of battery storage systems further enhances system stability by storing excess energy and supplying power during low generation periods.

Despite these advantages, efficient energy management and optimization remain major challenges in hybrid renewable systems. Traditional rule based energy management methods rely on fixed thresholds and deterministic control strategies, which are unable to adapt effectively to dynamic environmental conditions.

Artificial Intelligence (AI) techniques have recently emerged as powerful tools for modeling nonlinear energy systems and improving operational efficiency. Artificial Neural Networks (ANN) can accurately predict renewable energy generation based on environmental parameters, while Genetic Algorithms (GA) are widely used for system optimization and parameter tuning.

Novel Contributions of This Study

The key contributions of this research are summarized as follows:

1. Development of an integrated ANN-GA optimization framework for hybrid renewable energy systems.
2. Implementation of the model using real meteorological data from Yavatmal district, Maharashtra.
3. Baseline comparison with conventional rule based energy management to quantify performance improvement.
4. Evaluation of technical, operational, and economic performance metrics, including prediction accuracy, energy yield, operational losses, Net Present Cost (NPC), and Levelized Cost of Electricity (LCOE).
5. Demonstration of an AI driven energy management strategy suitable for semi urban renewable energy deployment in India.

2. Literature Review

Optimization and efficient energy management of hybrid renewable energy systems have attracted significant research attention in recent years. Various conventional and artificial intelligence based approaches have been proposed to improve system performance, reliability, and economic feasibility.

Applied Energy research by Wang et al. [1] presented an artificial intelligence based optimization approach for hybrid solar-wind-battery energy systems. Their study demonstrated that AI driven optimization techniques significantly improve system reliability and operational efficiency compared with traditional deterministic control methods.Gupta et al. [2] conducted a comprehensive review of machine learning applications in renewable energy forecasting. The study concluded that Artificial Neural Network (ANN) models provide superior prediction accuracy compared with conventional regression and statistical techniques when handling nonlinear environmental datasets.Li et al. [3] proposed a neural network based predictive control strategy for hybrid renewable microgrids. Their work highlighted that intelligent forecasting combined with adaptive control mechanisms can enhance system stability and improve power management in renewable based microgrids.Genetic Algorithms (GA) have also been widely used for system optimization. Singh and Kumar [4] developed a multi objective optimization framework for solar-wind-battery hybrid systems using GA. Their results showed significant improvements in energy efficiency, system reliability, and operational cost reduction.A comprehensive review by Kumar and Bansal [5] examined various energy management strategies for hybrid renewable energy systems. The authors emphasized that intelligent control approaches, including artificial intelligence and optimization algorithms, play a critical role in enhancing system reliability and minimizing operational losses.Hemmati and Saboori [6] investigated the development of hybrid energy storage technologies for renewable energy applications. Their work highlighted the importance of integrating advanced storage systems with renewable generation to ensure stable power supply and improved system flexibility.Yang et al. [7] proposed an optimal sizing methodology for standalone solar-wind hybrid systems using the Loss of Power Supply Probability (LPSP) technique. Their study demonstrated that appropriate system sizing significantly improves system reliability while reducing overall installation cost.Zhang et al. [8] reviewed artificial intelligence based energy management techniques for hybrid renewable energy systems. The authors concluded that AI driven energy management frameworks are capable of improving renewable energy utilization, reducing system losses, and enhancing operational efficiency.

In addition to these studies, Sambhe and Gaddamwar [9] investigated the performance characteristics of flat plate solar collectors and discussed improvements in solar thermal system design. Their work provides valuable insights into solar energy utilization technologies relevant to hybrid renewable systems.

Similarly, Gaddamwar and Sherekar [10] analyzed solar chimney power plants using an energy transfer (ET) approach. Their literature based investigation highlighted the potential of solar based power generation technologies for sustainable energy production.More recent research has focused on integrating advanced artificial intelligence techniques for hybrid system optimization. Amer et al. [11] investigated optimization strategies for hybrid renewable diesel power plants considering operational costs and battery degradation. Their results demonstrated that optimized hybrid systems significantly reduce fuel consumption and operating expenses.Gurumoorthi et al. [12] proposed a hybrid deep learning approach for optimal power flow in renewable energy systems. Their study showed that deep learning models can effectively manage complex nonlinear relationships in renewable power systems, leading to improved energy dispatch and operational performance.Despite these significant advancements, most existing studies rely primarily on simulation datasets or apply standalone optimization methods. Very few studies have explored integrated ANN-GA optimization frameworks using real meteorological data from semi-urban regions in India.

Therefore, the present study aims to address this research gap by developing an AI based ANN-GA optimization framework for a solar-wind-battery hybrid renewable energy system using actual meteorological data from Yavatmal district, Maharashtra, India. The proposed approach evaluates both technical and economic performance improvements compared with conventional energy management strategies.

3. System Description and Methodology

3.1 Study Area: Yavatmal district, located in the eastern region of Maharashtra, India, experiences high solar irradiance throughout the year and moderate wind potential. These climatic conditions make the region suitable for hybrid renewable energy deployment.

3.2 Hybrid System Configuration

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The proposed hybrid renewable energy system consists of:

- Photovoltaic (PV) array
- Small-scale wind turbine
- Lithium-ion battery energy storage system
- Bidirectional inverter
- Intelligent energy management controller

The system is designed to meet semi-urban load demand while maximizing renewable energy utilization.

Table I: Specifications of the Hybrid Renewable Energy System

Component	Specification
PV array capacity	10 kW
Wind turbine rating	5 kW
Battery type	Lithium-ion
Battery capacity	20 kWh
Inverter efficiency	95%
System voltage	415 V

3.3 Data Collection: Hourly meteorological data were collected over a period of 12 months from the Yavatmal Meteorological Station. The dataset includes:

- Global solar irradiance
- Wind speed
- Ambient temperature
- Electrical parameters (voltage and current)

3.4 Artificial Neural Network Model: A feed forward ANN with three layers input, hidden, and output was developed. The input layer consists of solar irradiance, wind speed, and ambient temperature. The ANN output predicts hourly power generation. The network was trained using back propagation, and performance was evaluated using Mean Absolute Error (MAE) and prediction accuracy.

3.5 Genetic Algorithm Optimization: The GA was implemented to optimize ANN parameters and system operational variables, including:

- Learning rate
- Weight coefficients
- Battery charge discharge limits

The objective function minimizes energy loss, battery degradation, and cost of energy while maintaining supply reliability.

4. Results and Discussion: Simulation experiments were carried out using MATLAB and Python environments to evaluate the effectiveness of the proposed ANN-GA optimization framework. The performance of the optimized system was compared with a conventional rule based energy management strategy to establish a baseline reference. The ANN model demonstrated strong prediction capability, achieving a prediction accuracy of 96.8% with a mean absolute error of 3.2%. The improved forecasting accuracy enabled more efficient scheduling of renewable energy resources and battery storage.

The results show that the optimized hybrid system achieved a 13.6% increase in total energy generation compared with the conventional control strategy. In addition, operational losses were reduced by approximately 10%, while the levelized cost of electricity decreased by 11.5%.

The optimized energy management strategy also improved battery operation by maintaining the state of charge within safe limits and reducing excessive charge discharge cycling. This contributes to improved battery lifespan and overall system reliability.

Table II presents the performance comparison between the conventional control strategy and the proposed ANN-GA optimized system.

Table II: Performance Comparison of Control Strategies

Parameter	Conventional Control	ANN-GA Optimization
Prediction accuracy (%)	89.4	96.8
Energy yield improvement (%)	–	13.6
Operational loss reduction (%)	–	10.0
Cost of energy reduction (%)	–	11.5

The results clearly indicate that the ANN-GA optimization framework significantly improves system performance compared with conventional control strategies. The GA optimized system exhibited smoother battery charge discharge cycles, leading to improved battery efficiency and reduced degradation. The intelligent dispatch strategy minimized inverter losses and ensured stable output under fluctuating climatic conditions.

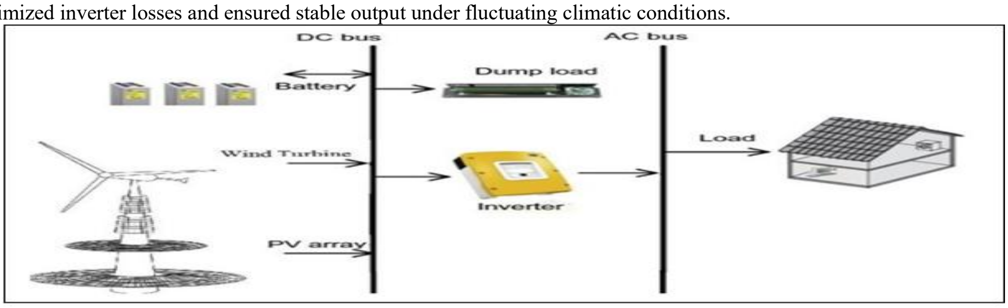

Figure 1 Schematic diagram of the proposed solar wind battery hybrid renewable energy system.

Figure 1 illustrates the overall architecture of the proposed solar wind battery hybrid renewable energy system. The photovoltaic (PV) array and wind turbine operate as primary energy sources, supplying power to the load through a bidirectional inverter. Excess renewable energy is stored in the lithium-ion battery, while power deficits are compensated by battery discharge. An intelligent energy management controller based on the ANN GA framework governs power flow between the generation units, storage system, and load. This coordinated control ensures optimal utilization of renewable resources, minimizes energy losses, and maintains system reliability under variable climatic conditions.

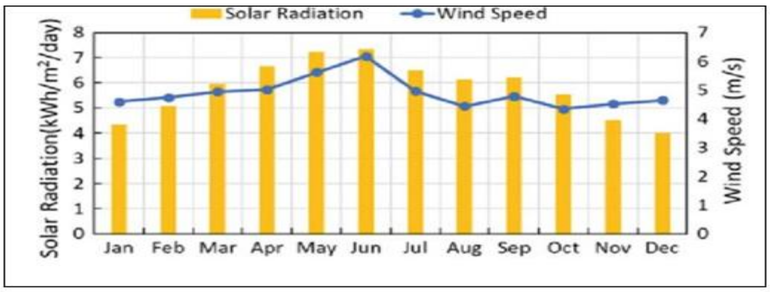

Figure 2 Monthly solar irradiance and wind speed profile for Yavatmal district.

Figure 2 presents the monthly variation of global solar irradiance and wind speed in Yavatmal district. Solar irradiance remains relatively high throughout the year, with peak values observed during the summer months (March-May), indicating strong photovoltaic generation potential. Wind speed exhibits moderate seasonal variation, with higher values during the monsoon period. The complementary nature of solar and wind resources enhances overall system reliability and justifies the selection of a hybrid configuration for the study area.

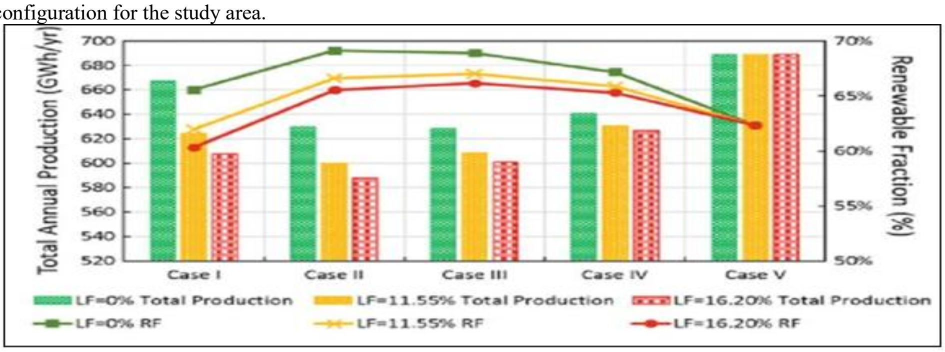

Figure 3 Annual energy production and renewable fraction (RF)

Figure 3 depicts the annual energy production contributed by solar PV and wind sources along with the renewable fraction of the system. The results demonstrate that the optimized hybrid system achieves a high renewable fraction, indicating reduced dependence on battery cycling and auxiliary sources. The ANN GA optimization effectively balances power generation from solar and wind resources, thereby maximizing annual energy output and improving overall system sustainability.

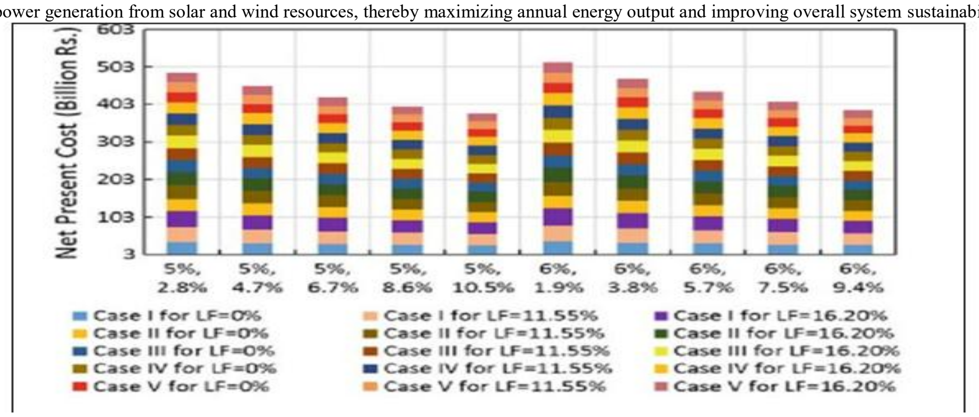

Figure 4 Net present cost variation for different cases of hybrid system with turbine loss factor, inflation rate and nominal discount rate

Figure 4 shows the variation of net present cost (NPC) for different hybrid system configurations under varying turbine loss factors, inflation rates, and nominal discount rates. The results indicate that NPC increases with higher turbine losses and inflation rates, while higher discount rates lead to a reduction in present cost values. The ANN GA optimized system consistently demonstrates lower NPC compared to non optimized cases, highlighting the economic benefits of AI based optimization.

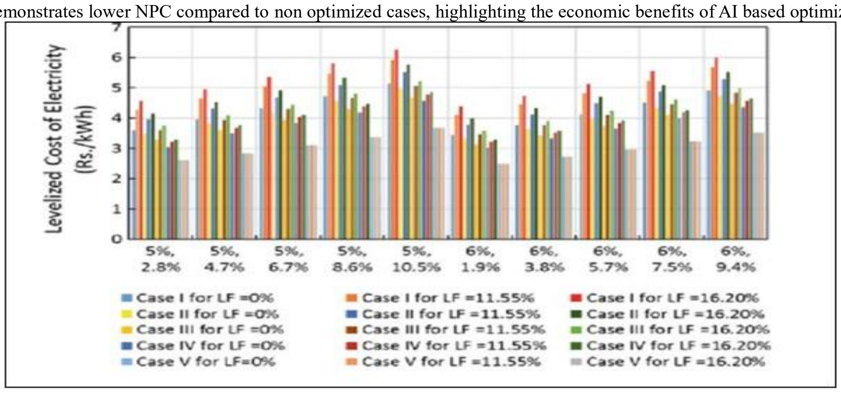

Figure 5 Levelized cost of electricity variation with respect to inflation and discount rate

Figure 5 presents the sensitivity of the levelized cost of electricity (LCOE) to inflation and discount rates. The LCOE increases with rising inflation due to higher operational and maintenance costs, whereas an increase in discount rate reduces the present value of future costs. The optimized hybrid system achieves a lower LCOE across all economic scenarios, confirming its cost effectiveness for semi-urban renewable energy applications.

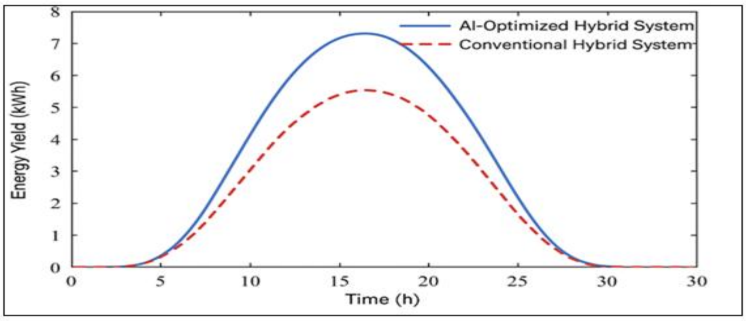

Figure 6 Comparison of power output under conventional control and ANN-GA optimization.

Figure 6 compares the power output profiles obtained using conventional rule based control and the proposed ANN GA optimization strategy. The AI based approach produces a smoother and more stable power output, effectively mitigating fluctuations caused by intermittent renewable sources. The ANN GA optimized system achieves higher average power output and reduced variability, confirming its superiority over conventional control strategies in dynamic operating conditions.

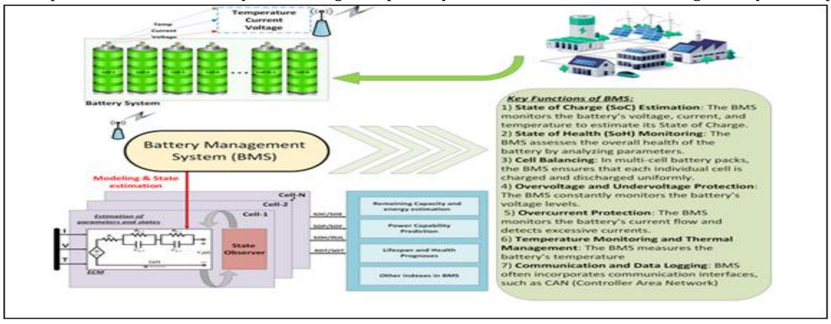

Figure 7 Battery state of charge variation under optimized energy management strategy.

Figure 7 illustrates the battery state of charge (SOC) variation under the ANN GA optimized energy management strategy. The SOC remains within safe operating limits, avoiding deep discharge and overcharging conditions. Optimized charge discharge scheduling reduces battery stress, enhances battery lifespan, and improves overall system efficiency. The results confirm that intelligent energy management plays a critical role in sustainable hybrid system operation.

Overall, the results confirm that the proposed ANN-GA framework significantly enhances both the technical and economic performance of the hybrid renewable energy system.

5. Conclusion

This study presented an Artificial Intelligence based optimization framework for improving the performance of a solar-wind-battery hybrid renewable energy system. The proposed approach integrates Artificial Neural Networks for renewable energy forecasting with a Genetic Algorithm for system optimization and energy management.

Using real meteorological data from Yavatmal district, the ANN model achieved high prediction accuracy, enabling reliable forecasting of renewable energy availability. The GA optimization effectively tuned system parameters and operational variables to minimize energy losses and improve system efficiency.

Comparative analysis with a conventional rule based control strategy demonstrated significant performance improvements. The ANN GA optimized system achieved 13.6% higher energy yield, 10% reduction in operational losses, and improved battery utilization. Economic analysis also showed lower Net Present Cost and reduced Levelized Cost of Electricity.These findings demonstrate that AI based optimization frameworks can significantly enhance the reliability, efficiency, and economic feasibility of hybrid renewable energy systems in semi urban regions.

The proposed methodology provides a scalable and adaptable solution for decentralized renewable energy deployment in India and other developing regions.

6. Future Work

Future work will focus on integrating deep reinforcement learning and real time IoT based monitoring for autonomous system control. The proposed framework can also be extended to community level microgrids and smart rural electrification projects.

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