
ROLE OF ARTIFICIAL INTELLIGENCE IN OPTIMIZING RENEWABLE ENERGY SYSTEMS: A PATHWAY TOWARDS SUSTAINABLE ENERGY MANAGEMENT

^{*1}Shweta Gupta, ²Dr Rahul Singh

¹Assistant Professor, Department of Management Moradabad Institute of Technology.

²Associate Professor, Head of Department of Management Moradabad Institute of
Technology.

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***Corresponding Author: Shweta Gupta**

Assistant Professor, Department of Management Moradabad Institute of
Technology.

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ABSTRACT

The increasing global demand for energy and the urgent need to reduce carbon emissions have accelerated the adoption of renewable energy systems. However, renewable energy sources such as solar and wind face challenges related to intermittency, energy forecasting, resource optimization, and efficient management. Artificial Intelligence (AI) has emerged as an advanced technology that provides innovative solutions for improving the performance and reliability of renewable energy systems. This study explores the role of Artificial Intelligence in optimizing renewable energy systems by examining its applications in energy forecasting, smart grid management, predictive maintenance, demand-response optimization, and intelligent energy management. Through a qualitative research approach based on thematic analysis of existing literature, the study identifies key themes related to AI-driven energy optimization, sustainability enhancement, and implementation challenges. The findings highlight that AI technologies improve renewable energy efficiency by enabling accurate prediction, real-time decision-making, and effective utilization of energy resources. The study also emphasizes challenges such as data availability, technological infrastructure, cybersecurity risks, and high implementation costs. The research proposes a conceptual framework demonstrating how AI integration can support sustainable energy development by improving operational efficiency, reducing energy wastage, and contributing to environmental sustainability. The study provides valuable insights for researchers,

policymakers, and energy organizations seeking to promote AI-enabled renewable energy transformation.

KEYWORDS: Artificial Intelligence, Renewable Energy Systems, Energy Optimization, Smart Grid, Sustainability, Machine Learning, Predictive Analytics.

1. INTRODUCTION

The rapid growth of population, industrialization, urbanization, and technological development has significantly increased global energy demand. Energy has become a fundamental requirement for economic growth, social development, and improved living standards. However, the increasing dependence on conventional fossil fuels such as coal, oil, and natural gas has resulted in serious environmental challenges, including greenhouse gas emissions, climate change, and depletion of natural resources. Therefore, ensuring a reliable, affordable, and sustainable energy supply has become a major global concern.

The transition towards renewable energy has emerged as an essential strategy to address environmental issues and reduce dependence on fossil fuels. Renewable energy sources such as solar, wind, hydro, and biomass provide cleaner alternatives with lower environmental impacts. Governments and organizations worldwide are promoting renewable energy adoption to achieve sustainable development goals, particularly in reducing carbon emissions and improving energy security. However, the integration of renewable energy into existing energy systems requires effective planning, efficient resource management, and advanced technological solutions.

Despite significant progress in renewable energy technologies, several challenges affect their effective management and utilization. Renewable energy sources are often intermittent and influenced by external factors such as weather conditions, seasonal variations, and unpredictable energy generation patterns. Other challenges include energy storage limitations, grid stability issues, inefficient energy distribution, and high operational costs. These complexities create the need for innovative approaches that can improve energy forecasting, optimize resource utilization, and enhance the reliability of renewable energy systems.

In this context, Artificial Intelligence (AI) has emerged as a promising technology for optimizing renewable energy systems. AI-based techniques such as machine learning, predictive analytics, and intelligent automation can support accurate energy forecasting, real-time monitoring, smart grid management, and efficient energy decision-making. By

improving operational efficiency and reducing energy wastage, AI has the potential to accelerate the transition towards sustainable and intelligent energy systems.

Artificial Intelligence (AI) has emerged as a powerful technology for improving the efficiency, reliability, and sustainability of renewable energy systems. By using advanced computational techniques such as machine learning, deep learning, and predictive analytics, AI enables energy systems to analyze large volumes of data, identify patterns, and make intelligent decisions. The integration of AI helps overcome several challenges associated with renewable energy, including uncertainty in energy generation, demand fluctuations, and inefficient resource utilization.

One of the significant applications of AI in renewable energy systems is **energy forecasting**. Renewable energy sources such as solar and wind are highly dependent on environmental conditions, making accurate prediction of energy generation challenging. AI-based forecasting models analyze historical energy data, weather conditions, and consumption patterns to predict future energy production and demand. Accurate forecasting supports better energy planning, reduces uncertainty, improves grid stability, and enables efficient integration of renewable energy into power systems.

AI also plays an important role in **smart energy management** by enabling real-time monitoring, automated control, and intelligent decision-making. AI-driven energy management systems continuously analyze energy generation, storage, and consumption data to optimize energy distribution. Smart grids integrated with AI can automatically balance electricity supply and demand, manage energy flows, and improve overall system efficiency. This allows consumers and organizations to use energy more effectively while reducing unnecessary consumption.

Another major contribution of AI is the **optimization of energy resources**. AI algorithms help determine the most efficient ways to utilize renewable energy resources by optimizing energy generation, storage, and distribution processes. For example, AI can improve the performance of solar and wind energy systems by identifying optimal operating conditions and reducing energy losses. Through intelligent optimization techniques, AI supports cost reduction, improved energy efficiency, and better utilization of renewable resources.

AI further supports renewable energy systems through **predictive maintenance**. Traditional maintenance approaches often rely on fixed schedules, which may lead to unnecessary costs or unexpected equipment failures. AI-based predictive maintenance systems use sensors and real-time data analysis to identify early signs of equipment problems. This enables timely

maintenance decisions, reduces downtime, increases equipment lifespan, and improves the reliability of renewable energy infrastructure.

Overall, AI acts as an enabling technology that transforms renewable energy systems into intelligent, adaptive, and efficient networks. By improving forecasting accuracy, energy management, resource optimization, and maintenance practices, AI contributes significantly to sustainable energy development and the global transition toward cleaner energy systems.

2. Research Problem

“Despite the rapid growth of renewable energy technologies, challenges related to energy forecasting, resource optimization, and efficient management limit their effectiveness. This research aims to explore how Artificial Intelligence can optimize renewable energy systems and contribute to sustainable energy development.”The increasing global demand for energy and the need for sustainable development have accelerated the adoption of renewable energy systems. However, renewable energy sources such as solar and wind face several operational challenges due to their intermittent nature, unpredictable generation patterns, and dependence on environmental conditions. These limitations affect energy forecasting accuracy, resource utilization, grid stability, and overall system efficiency.

Although renewable energy technologies have advanced significantly, traditional energy management approaches often lack the capability to handle complex energy data and real-time decision-making requirements. Inefficient energy distribution, limited storage management, and unexpected equipment failures continue to reduce the effectiveness of renewable energy systems.

Artificial Intelligence (AI) offers potential solutions through machine learning, predictive analytics, smart energy management, and predictive maintenance. However, the successful integration of AI into renewable energy systems remains challenging due to issues such as high implementation costs, data availability, technological infrastructure limitations, cybersecurity concerns, and lack of technical expertise.

Furthermore, existing research primarily focuses on the technical performance of AI algorithms, while limited attention has been given to understanding how AI contributes to overall renewable energy optimization and sustainable energy management. Therefore, there is a need to explore the role of AI in improving energy efficiency, enhancing system reliability, and supporting the transition toward sustainable renewable energy systems.

3. Literature Review

3.1 Artificial Intelligence in Energy Systems

Artificial Intelligence (AI) has become an important technological advancement in modern energy systems by enabling intelligent analysis, prediction, and decision-making. AI techniques help renewable energy systems manage complex operational challenges by processing large volumes of data and identifying patterns that improve efficiency and reliability. Machine Learning (ML), as a major component of AI, is widely applied in energy systems for forecasting energy generation, predicting demand patterns, optimizing energy consumption, and improving system performance. ML algorithms analyze historical and real-time data from renewable energy sources to identify trends and support accurate energy management decisions.

Deep Learning (DL), a specialized branch of machine learning, further enhances energy system optimization by handling complex and large-scale datasets. Deep learning models are increasingly used for renewable energy forecasting, particularly in solar and wind energy systems, where environmental factors influence energy generation. These models improve prediction accuracy by learning complex relationships between weather conditions, energy production, and consumption patterns.

Artificial Neural Networks (ANNs) are another important AI technique used in energy systems due to their ability to simulate human-like learning processes. ANNs are applied in areas such as load forecasting, fault detection, energy efficiency improvement, and renewable energy generation prediction. By continuously learning from new data, neural networks enhance the adaptability and performance of energy management systems.

AI-based decision-making systems support automated and intelligent control of energy resources. These systems analyze real-time information related to energy generation, storage, and consumption to make optimized decisions regarding energy distribution and utilization. AI-driven decision-making improves grid stability, reduces energy losses, and supports the integration of renewable energy sources into existing power networks. Therefore, AI technologies play a significant role in transforming traditional energy systems into intelligent, efficient, and sustainable energy management frameworks.

3.2 AI Applications in Renewable Energy

Artificial Intelligence (AI) has various applications in renewable energy systems that improve efficiency, reliability, and decision-making capabilities. By utilizing advanced techniques such as machine learning, deep learning, and predictive analytics, AI enables renewable energy systems to overcome challenges related to uncertainty, resource variability, and

operational complexity. The application of AI supports better energy forecasting, optimized resource utilization, and improved integration of renewable energy into existing power systems.

One of the important applications of AI is **solar energy prediction**. Solar energy generation depends on factors such as sunlight intensity, weather conditions, temperature, and cloud patterns. AI-based prediction models analyze historical weather data and solar generation patterns to accurately estimate future energy production. Improved solar forecasting helps in better energy planning, reduces uncertainty, and supports efficient utilization of solar power resources.

AI also plays a significant role in **wind energy forecasting** by predicting wind speed, direction, and energy generation capacity. Since wind energy production is highly influenced by environmental conditions, accurate forecasting is essential for maintaining grid stability and balancing energy supply and demand. AI models improve prediction accuracy by identifying complex relationships between weather variables and wind power output, enabling more reliable integration of wind energy into electricity networks.

Another major application of AI is **energy storage optimization**. Renewable energy sources often generate electricity inconsistently, creating challenges in energy storage and distribution. AI helps optimize battery storage systems by predicting energy demand, managing charging and discharging cycles, and improving storage efficiency. AI-based energy storage management reduces energy losses, increases battery lifespan, and ensures a continuous energy supply during periods of low renewable generation.

AI is also transforming **smart grid management** by enabling intelligent monitoring, automated control, and efficient energy distribution. AI-powered smart grids analyze real-time data from energy producers and consumers to optimize electricity flow, manage demand response, detect system failures, and improve grid reliability. Through smart grid technologies, AI supports the integration of renewable energy sources and contributes to the development of sustainable, flexible, and efficient energy systems.

3.3 AI and Energy Efficiency

Artificial Intelligence (AI) has various applications in renewable energy systems that improve efficiency, reliability, and decision-making capabilities. By utilizing advanced techniques such as machine learning, deep learning, and predictive analytics, AI enables renewable energy systems to overcome challenges related to uncertainty, resource variability, and operational complexity. The application of AI supports better energy forecasting, optimized

resource utilization, and improved integration of renewable energy into existing power systems.

One of the important applications of AI is solar energy prediction. Solar energy generation depends on factors such as sunlight intensity, weather conditions, temperature, and cloud patterns. AI-based prediction models analyze historical weather data and solar generation patterns to accurately estimate future energy production. Improved solar forecasting helps in better energy planning, reduces uncertainty, and supports efficient utilization of solar power resources.

AI also plays a significant role in wind energy forecasting by predicting wind speed, direction, and energy generation capacity. Since wind energy production is highly influenced by environmental conditions, accurate forecasting is essential for maintaining grid stability and balancing energy supply and demand. AI models improve prediction accuracy by identifying complex relationships between weather variables and wind power output, enabling more reliable integration of wind energy into electricity networks.

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3.4 AI and Sustainable Development

Artificial Intelligence (AI) has become an important enabler of sustainable development by supporting efficient energy management, reducing environmental impacts, and accelerating the transition towards cleaner energy systems. The integration of AI with renewable energy

technologies helps organizations and governments address climate change challenges by improving energy efficiency, optimizing resource utilization, and promoting sustainable practices. AI-driven solutions contribute to achieving global sustainability goals by enabling smarter, cleaner, and more resilient energy systems.

One of the significant contributions of AI is **carbon emission reduction**. AI-based energy optimization systems help reduce dependence on fossil fuels by improving the efficiency and integration of renewable energy sources. Through accurate energy forecasting, intelligent energy management, and optimized resource allocation, AI minimizes energy wastage and supports the reduction of greenhouse gas emissions. AI also helps industries identify energy-intensive processes and implement strategies for lowering their carbon footprint.

AI plays a crucial role in supporting the **clean energy transition** by improving the adoption and management of renewable energy sources such as solar, wind, and hydro power. AI technologies enable better prediction of renewable energy generation, efficient storage management, and stable integration of renewable resources into power grids. By overcoming challenges related to variability and reliability, AI facilitates the shift from traditional fossil fuel-based systems toward sustainable and clean energy solutions.

Furthermore, AI contributes to **environmental sustainability** by promoting responsible use of natural resources and improving overall energy system performance. AI-based monitoring systems help track environmental conditions, optimize energy consumption, and support sustainable decision-making. By enhancing energy efficiency, reducing emissions, and enabling smarter resource management, AI serves as a strategic technology for achieving long-term environmental sustainability and supporting sustainable development objectives.

4. Research Gap

The integration of Artificial Intelligence (AI) into renewable energy systems has gained significant attention due to its potential to improve energy efficiency, forecasting accuracy, and system reliability. Existing studies have extensively explored the technical applications of AI, including machine learning-based energy prediction, smart grid optimization, renewable energy forecasting, and predictive maintenance. However, several research gaps remain in understanding the broader role of AI in achieving sustainable and optimized renewable energy management.

First, most existing research focuses primarily on the development and performance evaluation of AI algorithms, while limited attention has been given to the strategic and managerial aspects of AI adoption in renewable energy systems. There is a need to explore

how organizations can effectively integrate AI technologies to improve energy optimization and sustainability outcomes.

Second, previous studies often examine individual AI applications, such as solar forecasting or wind energy prediction, but lack an integrated framework that combines multiple AI capabilities, including predictive analytics, intelligent decision-making, smart energy management, and resource optimization.

Third, although AI has demonstrated potential in improving energy efficiency and reducing carbon emissions, limited research investigates the relationship between AI-driven optimization and sustainable development outcomes. More studies are required to understand how AI contributes to clean energy transition, environmental sustainability, and long-term energy security.

Fourth, the practical implementation of AI in renewable energy systems faces challenges related to data availability, cybersecurity, technological infrastructure, high investment costs, and technical expertise. However, these barriers require further investigation to develop effective adoption strategies.

Therefore, this research aims to address these gaps by exploring the role of Artificial Intelligence in optimizing renewable energy systems and developing a conceptual understanding of how AI-driven solutions can enhance energy efficiency, operational performance, and sustainable development.

5. Research Objectives

1. To examine the role of AI in optimizing renewable energy systems. , including machine learning, deep learning, predictive analytics, and intelligent decision-making.
2. To identify major AI technologies used in renewable energy management.
3. To analyze the benefits and challenges of AI adoption.
4. To develop a conceptual framework for AI-based energy optimization.
5. To analyze the role of AI in improving renewable energy forecasting and management, particularly in solar energy prediction, wind energy forecasting, and smart grid operations.
6. To explore how AI contributes to energy optimization by reducing energy losses, improving energy utilization, and enhancing operational efficiency.
7. To identify the challenges and barriers associated with AI adoption in renewable energy systems, including technological, financial, infrastructural, and data-related issues.

8. To examine the contribution of AI-driven renewable energy optimization towards sustainable development, including carbon emission reduction, clean energy transition, and environmental sustainability.
9. To develop a conceptual framework explaining the relationship between AI capabilities, renewable energy optimization, and sustainable energy outcomes.

6. RESEARCH METHODOLOGY

This study adopts a qualitative research approach to explore the role of Artificial Intelligence (AI) in optimizing renewable energy systems. A qualitative methodology is considered appropriate as the study focuses on understanding existing knowledge, technological applications, challenges, and future opportunities associated with AI-driven renewable energy management. The research aims to examine how AI technologies contribute to improving energy efficiency, resource optimization, and sustainable energy development.

The study follows a **Systematic Literature Review (SLR)** approach along with **thematic analysis** to analyze existing research on Artificial Intelligence and renewable energy systems. The systematic review method enables the identification, evaluation, and synthesis of relevant academic literature, while thematic analysis helps in recognizing major concepts, patterns, and emerging themes from previous studies.

The data for this study will be collected from reputed academic databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, and IEEE Xplore. Research articles, review papers, and conference publications related to AI applications in renewable energy, energy optimization, smart grids, predictive analytics, and sustainability will be considered. The literature selection will focus on peer-reviewed studies that provide insights into AI-based energy management and renewable energy optimization.

The collected literature will be analyzed through thematic analysis, which involves identifying key concepts, developing codes, and grouping findings into major themes. The analysis will focus on themes such as AI-based renewable energy forecasting, smart energy management, optimization of energy resources, predictive maintenance, energy efficiency improvement, and the contribution of AI towards sustainable development.

Based on the findings from the literature analysis, a conceptual framework will be developed to explain the relationship between AI capabilities, renewable energy optimization, and sustainable development outcomes. The framework will highlight how AI technologies support efficient energy management through improved forecasting, intelligent decision-making, and optimized resource utilization.

The methodology of this study provides a comprehensive understanding of the transformative role of AI in renewable energy systems. The findings are expected to contribute to academic research and provide valuable insights for policymakers, energy organizations, and researchers working towards sustainable and intelligent energy solutions.

7. FINDINGS AND DISCUSSION

The findings of this study indicate that Artificial Intelligence (AI) has emerged as a significant enabler for improving the efficiency, reliability, and sustainability of renewable energy systems. The analysis of existing literature reveals that AI applications are transforming traditional energy management approaches by enabling accurate prediction, intelligent optimization, automated control, and data-driven decision-making. The findings are categorized into major themes including AI-based energy forecasting, smart energy management, optimization of renewable resources, energy efficiency improvement, sustainability enhancement, and implementation challenges.

AI-Based Energy Forecasting

The study findings reveal that AI plays a crucial role in improving the accuracy of renewable energy forecasting. Renewable energy sources such as solar and wind are highly dependent on environmental conditions, making energy generation unpredictable. AI-based models, including machine learning and deep learning techniques, analyze historical data, weather patterns, and energy consumption trends to predict future energy generation more accurately. Improved forecasting enables better energy planning, reduces uncertainty, and supports efficient integration of renewable energy into power systems.

Smart Energy Management and Grid Optimization

The findings highlight that AI significantly contributes to smart energy management by enabling real-time monitoring, automated control, and efficient energy distribution. AI-powered smart grid systems can analyze energy supply and demand patterns, optimize electricity flow, and improve grid stability. These intelligent systems support the effective integration of renewable energy sources by balancing fluctuations in energy generation and consumption. As a result, AI enhances the reliability and flexibility of modern energy networks.

Optimization of Renewable Energy Resources

The analysis shows that AI improves the utilization of renewable energy resources by identifying optimal operating conditions and minimizing energy losses. AI algorithms help optimize solar panel performance, wind turbine operations, and energy storage systems. By analyzing real-time data, AI enables better resource allocation and improves overall energy system performance. This optimization contributes to increased efficiency and reduced operational challenges.

Improvement in Energy Efficiency and Cost Optimization

The findings suggest that AI-driven energy management systems improve energy efficiency by reducing unnecessary energy consumption and minimizing losses during generation and distribution. AI-based predictive analytics helps organizations identify energy usage patterns and implement efficient energy strategies. Furthermore, predictive maintenance supported by AI reduces equipment failures, decreases maintenance costs, and improves the operational lifespan of renewable energy infrastructure.

Contribution to Sustainable Development

The study indicates that AI plays an important role in supporting sustainable development by promoting clean energy transition and reducing environmental impacts. AI-enabled renewable energy systems contribute to carbon emission reduction by improving renewable energy utilization and decreasing dependence on fossil fuels. Through improved efficiency, optimized resource management, and intelligent decision-making, AI supports environmental sustainability and long-term energy security.

Challenges in AI Implementation

Although AI provides significant benefits, the findings identify several challenges that affect its widespread adoption in renewable energy systems. These include high implementation costs, limited availability of quality data, cybersecurity concerns, lack of technical expertise, and infrastructure limitations. Effective implementation requires supportive policies, investment in digital infrastructure, skilled workforce development, and responsible AI governance.

DISCUSSION

Overall, the findings demonstrate that AI has the potential to transform renewable energy systems from conventional operational models into intelligent, adaptive, and sustainable

energy networks. AI not only improves technical performance but also supports broader sustainability objectives by enhancing energy efficiency and reducing environmental impact. However, successful adoption requires addressing technological, financial, and organizational barriers. Future research should focus on developing integrated AI frameworks that combine technological innovation with sustainability strategies to achieve a more efficient and resilient renewable energy future.

8. CONCLUSION

The integration of Artificial Intelligence (AI) into renewable energy systems represents a significant step towards achieving efficient, reliable, and sustainable energy management. This study highlights that AI acts as a key enabler in transforming renewable energy systems by addressing major challenges such as energy uncertainty, resource optimization, and operational complexity. Through advanced technologies such as machine learning, deep learning, predictive analytics, and intelligent automation, AI improves the overall performance and adaptability of renewable energy systems.

The findings demonstrate that AI enhances renewable energy forecasting by accurately predicting energy generation and demand patterns, which supports better planning and efficient energy distribution. AI-driven optimization techniques improve energy efficiency by reducing energy losses, maximizing resource utilization, and enabling effective management of energy storage systems. Furthermore, AI-based decision-making and smart grid technologies contribute to improved reliability, flexibility, and stability of renewable energy networks.

AI also plays a crucial role in supporting sustainable development by promoting clean energy transition, reducing carbon emissions, and improving environmental sustainability. However, challenges such as high implementation costs, data limitations, cybersecurity concerns, and technological barriers need to be addressed for successful AI adoption in renewable energy systems.

In conclusion, future energy systems require intelligent, adaptive, and sustainable solutions, and AI provides the technological foundation for this transformation. The continued integration of AI with renewable energy technologies can accelerate the transition towards a cleaner, more efficient, and resilient energy future while supporting global sustainability goals.

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