An overview of the application of artificial intelligence in renewable energy management

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ABSTRACT

The integration of artificial intelligence (AI) in sustainable and renewable energy systems has become a pivotal driver for enhancing productivity, reducing costs, and overcoming complex challenges. This review aims to consolidate recent advancements in AI applications within renewable energy technologies and systems. By analyzing research reports, this study explores diverse AI approaches across various renewable energy sources, including solar power, photovoltaics, microgrid integration, energy storage, wind energy, and geothermal energy. The review discusses current technological advancements, key methodologies, challenges, and achievements in the field, emphasizing the role of AI in optimizing different facets of renewable energy systems. It also highlights potential challenges and their solutions, along with expected advancements and future trends, providing valuable insights for researchers and engineers in the sustainable energy sector.

Keywords: Renewable energy,Artificial intelligence,Technologies

1. *INTRODUCTION*

The integration of artificial intelligence (AI) in the field of sustainable and renewable energy has emerged as a transformative force, enhancing productivity, reducing costs, and addressing complex challenges. Despite the significant advancements made in recent years, there is a lack of a single comprehensive source that covers the experimental implementations and associated challenges. This review aims to provide a consolidated resource offering a recent, advanced, and detailed overview of AI applications in renewable energy technologies and systems, including real-world implementation examples .By retrieving and analyzing over 150 research reports from various databases using specific keywords and selection criteria to ensure relevance, this review delves into the applications of diverse AI approaches across a broad spectrum of renewable energy sources. These sources include solar power, photovoltaics, microgrid integration , energy storage, power management, wind energy, and geothermal energy.The review discusses current technological advancements, research findings, and case studies related to the implications of AI in renewable energy systems. It covers potential challenges that may arise and explores possible solutions to address them effectively. Furthermore, the review outlines expected advancements and future trends in the field, providing valuable insights for researchers, investigators, and engineers to navigate through advancements and overcome existing challenges.By offering a comprehensive analysis of the role of AI in renewable energy technologies, this review serves as a valuable resource for understanding the current landscape, identifying opportunities for improvement, and shaping the future direction of research and development in the field of sustainable energy [1].The global shift towards sustainable energy sources has led to the widespread integration of renewable energy systems (RES) into existing power grids. To enhance the efficiency, reliability, and economic viability of these systems, the synergistic use of artificial intelligence (AI) methods has emerged as a promising approach. This study offers a comprehensive review of the current research landscape at the intersection of renewable energy and AI, emphasizing key methodologies, challenges, and achievements .The review encompasses various AI applications in optimizing different aspects of RES, including resource assessment, energy forecasting, system monitoring, control strategies, and grid integration. Machine learning algorithms, neural networks, and optimization techniques are examined for their roles in handling complex data sets, improving predictive capabilities, and dynamically adapting RES operations .Challenges in implementing AI in RES, such as data variability, model interpretability, and real-time adaptability, are discussed. Overcoming these challenges could lead to benefits like increased energy yield, reduced operational costs, and enhanced grid stability.The review also explores future prospects and emerging trends in the field. Anticipated advancements in AI, including explainable AI, reinforcement learning, and edge computing, are considered for their potential impact on optimizing RES. The paper envisions the integration of AI-driven solutions into smart grids, decentralized energy systems, and the development of autonomous energy management systems. Overall, this investigation provides valuable insights into the current status of AI applications in RES and sheds light on the potential future developments in the field, emphasizing the importance of leveraging AI to advance sustainable energy solutions[2].

1.1 AI applications in RES

Societal progress is intrinsically linked to the utilization of energy resources. The global demand for energy in everyday life is witnessing a rapid surge due to factors like population growth, urbanization, and economic expansion. Traditional energy sources such as coal, natural gas, and oil have historically served as the primary means of meeting these energy needs across various sectors [3]. However, the extensive use of non-renewable energy sources has led to their depletion on a large scale, contributing to significant environmental challenges such as climate change and global warming caused by the substantial emission of greenhouse gases (GHGs) [4]. These environmental impacts encompass a range of issues, including sea-level rise, glacier melting, deforestation, air pollution, ozone depletion, water and land degradation, radioactive emissions, acid rain, GHG emissions, loss of biodiversity, and ecological damage, posing serious threats to both the economy and society at large [5].Publications from the International Energy Agency (IEA) have underscored the potential consequences of energy-related GHG emissions, warning that a global temperature rise of 6°C could lead to severe environmental degradation [6]. Addressing these challenges necessitates a shift towards energy solutions that have minimal negative impacts on the environment and the economy, paving the way for a more sustainable and promising energy future for humanity.In response to the adverse effects associated with conventional energy sources, particularly fossil fuels, and their impact on sustainable development, the focus has shifted towards exploring alternative energy solutions. Renewable energy (RE) has emerged as a prominent and sustainable alternative to mitigate the negative repercussions of traditional energy sources and is seen as the future of energy development [7]. Projections by the International Energy Agency (IEA) suggest that by 2040, the global renewable energy capacity is expected to reach 10,800 GW [8].Renewable energy technologies encompass solar, hydro, biomass, wind, geothermal, among others, and are recognized for their sustainability, cost-effectiveness, minimal carbon footprint, environmental friendliness, and most notably, their renewability compared to non-renewable sources like fossil fuels [9]. The advancement of innovative technologies for optimal energy generation from existing natural resources, enhanced system management and distribution, and a focus on environmental awareness are key areas of interest in current and future RE endeavors [10].In recent decades, significant progress has been made in harnessing solar and wind energy as major sources of renewable energy [11], leading to a shift towards technologies such as solar photovoltaic (PV), wind, geothermal, hydropower, tidal, biomass, and others [12]. This energy transition towards sustainable RE technologies offers numerous advantages for implementation in the power sector, including cost control, enhancing energy system flexibility and stability, infrastructure modernization, CO_2 emissions reduction, provision of reliable power to remote regions, and mitigating environmental changes [13].To meet the demands for emission reduction and energy conservation, energy storage systems (ESS) have seen successful development in recent years, as improving the accuracy of RE forecasts is crucial for efficient power system operations [14]. This ongoing focus on sustainable RE technologies represents a significant step towards a more environmentally conscious and efficient energy future. Various strategies have been developed to enhance the accuracy of Renewable Energy (RE) systems, with Artificial Intelligence (AI) emerging as a comprehensive high-tech approach focused on creating intelligent devices and software solutions for specific challenges [15]. Prior to the integration of AI, renewable energy decision-making systems primarily revolved around data collection and monitoring systems [16]. Over time, AI has significantly impacted everyday life and various sectors promoting sustainable growth and development, with applications spanning diverse fields such as energy, food, education, agriculture, health, safety, business, and the arts [17, 18, 19]. In the realm of RE, advancements and adaptability are emphasized as crucial factors for progress [20]. Research efforts often combine alternative power sources with cutting-edge technologies to meet the increasing demand for energy. Energy conversion systems highlighted in literature typically integrate power sources based on environmental conditions, regional requirements, and the availability of RE resources [21].RE systems can be developed from a single energy source or a combination of multiple sources, known as hybrid sources. Single-source RE types encompass solar energy, bioenergy, hydro, geothermal, wind, ocean energy, hydrogen energy, among others. On the other hand, hybrid RE systems link electrical devices and energy storage with multiple power generation options, including both non-renewable and renewable sources. Various configurations of hybrid RE systems, such as photovoltaic-based wind-diesel, hydro-wind-based photovoltaic, and fuel cell/hydrogen cell systems, can be deployed to generate electricity [22].AI tools and techniques have been employed in RE systems using a range of learning theories, including neural, statistical, and evolutionary learning, as documented in numerous literature sources. Neural network (NN) learning algorithms are commonly utilized, along with Support Vector Machines (SVM) and other algorithms like Decision Trees, Random Forests, Logistic Regressions, Linear Regression, Naïve Bayes, Nearest Neighbor, and Hidden Markov [23]. The categorization of algorithms and approaches based on AI is illustrated in Figure 1. The integration of AI technologies in various RE systems, from hydro, wind, geothermal, solar, ocean, to solar photovoltaic systems, has led to the implementation of smarter and more efficient energy solutions.

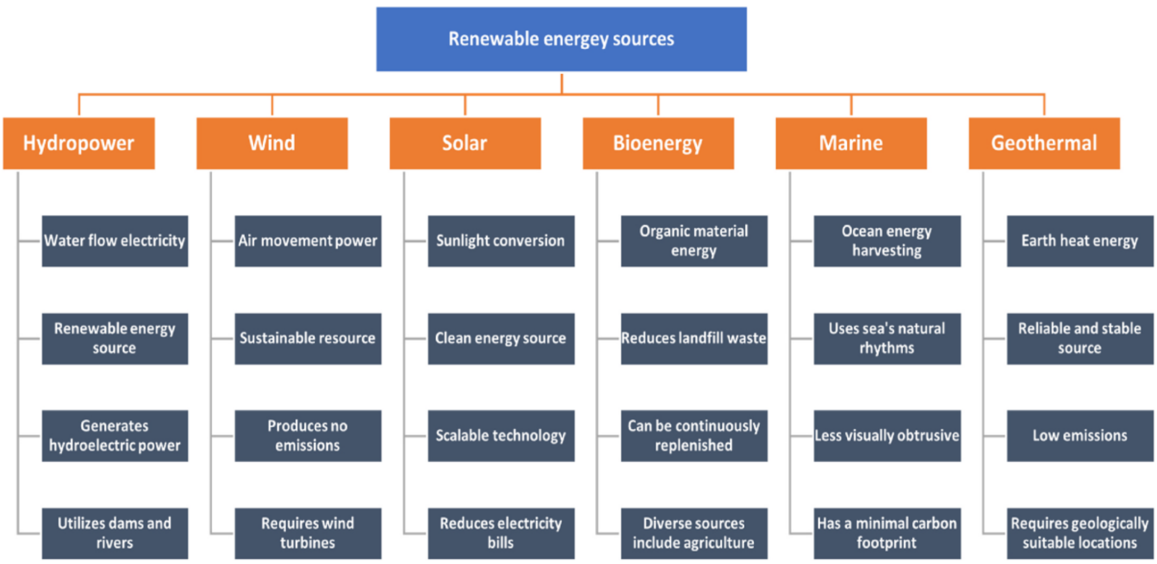

Fig. 1. *Type of RE and sources [23].*

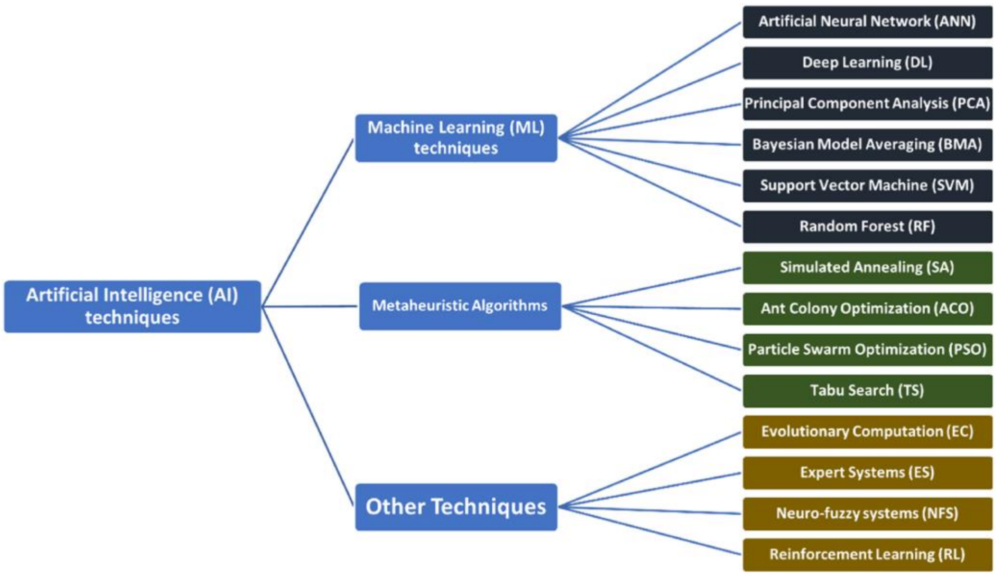

Fig. 2. *Classification of AI-Based Techniques and algorithms [24].*

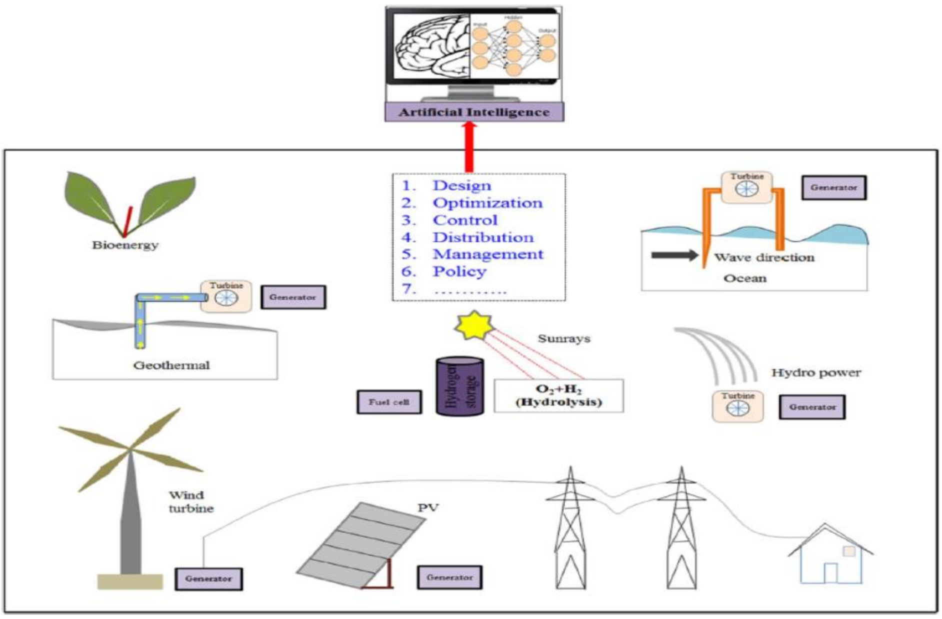

Fig. 3. *Schematic representation of AI applications in RE based technologies [25].*

Artificial Intelligence (AI) is increasingly finding applications in various sustainable Renewable Energy (RE) sectors, including hydrogen, hydro, solar, geothermal, wind, bio, ocean, and hybrid technologies, as depicted in Figure 3. Through the utilization of machine learning algorithms and statistical analytics such as P-values and confidence limits (Cls), AI demonstrates the capability to forecast energy production based on weather patterns, ensuring the balance of the energy grid. Additionally, AI plays a crucial role in predictive maintenance of energy infrastructure, reducing downtimes and ensuring a reliable energy supply. The primary applications of AI in RE encompass design, optimization, management, estimation, distribution, and policymaking, with a particular focus on five key RE technologies: solar energy, PV technologies, solar microgrids , wind turbine optimization, and geothermal energy, to assess the impact of AI applications.

Applications of AI in Solar Energy

AI methodologies are extensively utilized for prediction, modeling, and forecasting of solar radiation or estimating solar resources in the domain of solar energy. In the literature, AI-based models are becoming increasingly sophisticated and responsive due to the integration of AI technologies, enhancing their capabilities. Various AI techniques reported to be employed in RE-based technologies include:

- Artificial Neural Network (ANN)
- Support Vector Machines (SVM)
- Bootstrap Aggregated Neural Networks (BANN)
- Back-propagation neural network (BPNN)
- Genetic Algorithm (GA)
- Radial basis function-neural-networks (RBFNN)
- Seasonal autoregressive integrated moving average (SARIMA)
- Adaptive Neuro-Fuzzy Inference System (ANFIS)
- Naïve Bayes (NB)
- Historical Similar Mining (HISIMI)
- Transient System Simulation Tool (TRNSYS)
- Group method of data handling neural network (GMDHNN)
- Radial basis function (RBF)
- Autoregressive integrated moving average (ARIMA)

In the literature, detailed descriptions of meta-heuristics algorithms for identifying PV cell parameters have been extensively documented, focusing on aspects such as convergence speed, accuracy, and practical applications. The nuances of each algorithm, their virtual outcomes, and comparative analyses have been thoroughly discussed in Ref. [26]. Various metaheuristic algorithms have been employed for PV cell modeling and parameter identification, categorized into bio-based, physics-based, and mathematical-based algorithms. Bio-based metaheuristic algorithms encompass techniques such as flower pollination, bacterial foraging algorithms, and grey wolf optimization. Physics-based metaheuristic algorithms include methodologies like particle swarm optimization, wind-based optimization, water cycle algorithm, lozi-map chaotic optimization algorithm, mutative scale optimization, and simulated annealing algorithm. On the other hand, mathematical-based metaheuristic algorithms are among the most commonly utilized, including the shuffled complex evolution Jaya algorithm and the pattern search algorithm [27]. Figure 4 illustrates the array of metaheuristic algorithms categorized across different categories, showcasing the diversity of approaches employed in PV cell parameter identification within the realm of metaheuristics.

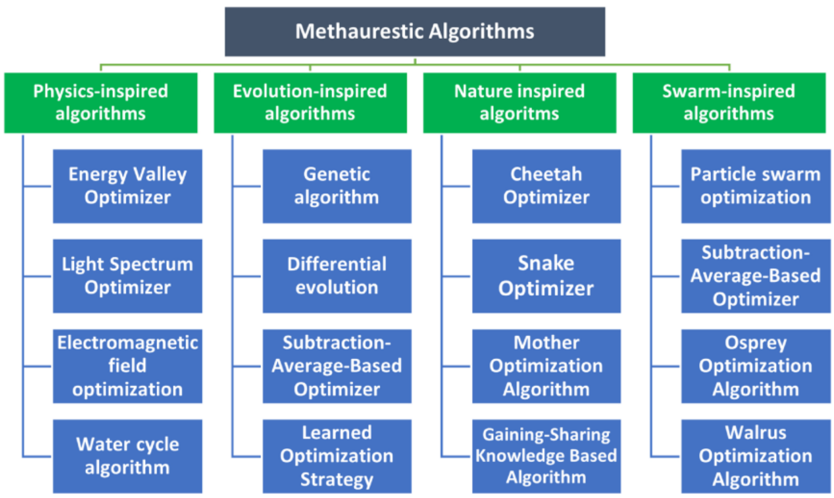

Fig. 4. *Categories of the metaheuristic algorithms.*

Challenges and Solutions in Renewable Energy Systems

Renewable energy sources offer numerous advantages but also present challenges that need to be addressed for optimal utilization. Advanced design, planning, and control optimization techniques are crucial due to issues such as generation discontinuity caused by seasonal fluctuations. Scientists are leveraging computational resources to tackle optimization problems in the renewable energy sector, facilitated by continuous advancements in computer hardware and software technologies[28].

1. Data Acquisition and Auditing

- High-quality data availability is essential for training and evaluating machine learning models, particularly deep learning, in predictive maintenance of RE systems.
- Auditing data quality is crucial to evaluate suitability and noise levels in measurements, ensuring algorithms learn from appropriate data.

2. Key Variable Selection and Parameter Tuning

- Key variable selection is vital in predictive maintenance for RE systems to determine crucial characteristics affecting model outcomes.
- The process involves selecting important variables either manually or automatically, guided by a specialist model's insights and domain knowledge.

3. Modeling of Various Faults Simultaneously

- Simultaneously modeling multiple failures requires processing large datasets, impacting real-time performance and computational requirements.
- Uncertainties in RE generation systems pose challenges in AI-based approaches, requiring careful methodology to address uncertainties efficiently.

4. Stability and Generalization in Predictive Modeling

- Ensuring model reliability in the face of new errors and system complexities is crucial for effective predictive modeling in RE systems.
- Developing robust AI models that can adapt to new errors and integrate with current control devices is essential for the large-scale development of RE systems.

5. Security and Protection Against Data Breaches

- AI applications in renewable energy systems face security threats such as data breaches and identity theft due to the reliance on complex data and personal information.
- Developing robust security configurations and tools is essential to safeguard against data breaches while implementing AI solutions in RE technologies.

6. Performance and Explain ability Issues

- Explain ability in machine learning models is crucial for the predictive maintenance of RE systems, where deep learning approaches are increasingly used.
- Balancing between performance and explain ability in predictive maintenance is challenging, requiring a focus on developing deep learning-based approaches tailored for energy system maintenance.

7. Energy Storage and Grid Integration Issues

- Energy storage is vital for integrating renewable energy sources into the grid to mitigate intermittency challenges.
- AI, imaging processing, and characterization tools are leveraged to enhance energy storage technologies, leading to higher charge density and longer lifetimes.

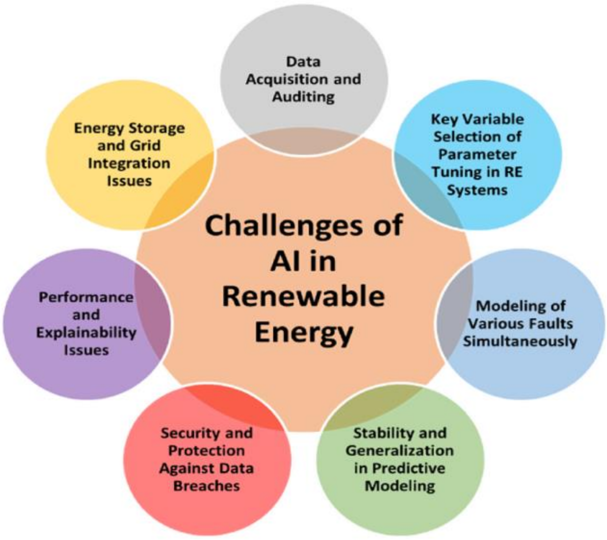

Fig 5. *The challenges and open issues of AI approaches in RE systems [29].*

Future Trends in Renewable Energy

The future of renewable energy is promising, driven by cutting-edge technology and continuous innovation. Anticipated future trends in sustainable energy include revolutionary ideas reshaping energy sources, storage, and distribution. Investigating and predicting these trends is crucial as the global scientific community moves towards a cleaner, more efficient, and integrated energy landscape with the digital revolution of AI.

Conclusion

The synergistic application of artificial intelligence (AI) methods in renewable energy systems has shown significant promise in enhancing efficiency, reliability, and economic viability. By optimizing various aspects such as resource assessment, energy forecasting, system monitoring, and grid integration, AI has the potential to revolutionize the renewable energy sector. Overcoming challenges like data variability and model interpretability can lead to increased energy yield, reduced operational costs, and improved grid stability. Looking ahead, anticipated advancements in AI, including explainable AI and reinforcement learning, hold promise for further optimizing renewable energy systems. The integration of AI-driven solutions into smart grids and decentralized energy systems represents a significant step towards a more sustainable and efficient energy future. This investigation sheds light on the current landscape of AI applications in renewable energy systems and offers insights into potential future developments in the field. Overcoming these challenges through advanced AI models, improved data acquisition, and rigorous auditing processes is essential for enhancing the efficiency and reliability of renewable energy systems. Continued research and innovation are key to addressing these challenges and advancing sustainable energy solutions.

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