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AI-driven solutions in renewable energy: A review of data science applications in solar and wind energy optimization

Nzubechukwu Chukwudum Ohaleta ¹, Adebayo Olusegun Aderibigbe ², Emmanuel Chigozie Ani ³, Peter Efosa Ohenhen ⁴, Donald Obinna Daraojimba ^{5,*} and Bukola A. Odulaja ⁶

¹ Kennesaw State University, GA, USA.

² Data Scientists Network (DSN), Lagos, Nigeria.

³ Department of Electrical and Computer Engineering, University of Nebraska-Lincoln, USA.

⁴ Department of Mechanical Engineering, University of Nebraska-Lincoln, USA.

⁵ Department of Information Management, Ahmadu Bello University, Zaria, Nigeria.

⁶ Independent Researcher, Nigeria.

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Abstract

This comprehensive review explores the transformative role of artificial intelligence (AI) and data science in the renewable energy sector, with a particular focus on solar and wind energy optimization. The study systematically examines the intersection of AI and renewable energy, highlighting the emergence of AI-driven solutions and their impact on enhancing the efficiency, reliability, and sustainability of renewable energy systems. The review begins with an overview of renewable energy and its growing importance in the global energy mix, emphasizing the critical role of AI in this sector. It then delves into the methodological approach, outlining the research strategy and criteria for selecting relevant AI and data science studies in renewable energy. This includes a detailed analysis of data collection and synthesis techniques used to identify key AI innovations and trends in solar and wind energy optimization. The core of the review comprises an extensive literature survey on AI applications in solar and wind energy systems. It covers fundamental principles of AI in renewable energy, state-of-the-art data science techniques, and emerging trends such as novel AI algorithms and their integration into renewable energy grids. The study evaluates the technological, economic, and environmental impacts of AI in renewable energy, addressing challenges and proposing solutions. Furthermore, the review discusses the role of standards and regulatory frameworks in AI-driven renewable energy and the implications for stakeholders. It concludes with a summary of AI's role in enhancing renewable energy, future prospects, and recommendations for industry leaders and policymakers. This review provides a thorough understanding of the current state and future potential of AI in renewable energy, offering valuable insights for researchers, industry professionals, and policymakers engaged in the field of sustainable energy.

Keywords: Renewable Energy; Artificial Intelligence; Data Science; Solar and Wind Energy

1. Introduction

1.1. Overview of Renewable Energy and Its Importance

Renewable energy (RE) has emerged as a pivotal element in the global commitment to reduce greenhouse gas emissions and foster sustainable development. The surge in renewable energy consumption and investment over the past decades underscores its growing significance. Between 2006 and 2016, the world's total renewable energy consumption, excluding hydroelectricity, escalated by nearly 350%, with investments soaring from US \$47 billion in 2004 to \$279.8

* Corresponding author: Donald Obinna Daraojimba

billion in 2017 (Morganti & Garofalo, 2020). This remarkable growth reflects the increasing recognition of renewable energy's role in mitigating climate change and its potential to contribute to economic growth.

The interplay between renewable energy consumption and economic development has been a subject of extensive research. Empirical studies predominantly indicate a positive bidirectional relationship between renewable energy consumption and real GDP, although some evidence suggests no statistically significant relationship (Morganti & Garofalo, 2020). This highlights the complex dynamics between renewable energy deployment and economic performance, suggesting that the adoption of renewable energy can be both a driver and a consequence of economic growth. In countries like Turkey, the reliance on renewable energy is not only a matter of environmental concern but also of economic and geopolitical significance. Turkey, heavily dependent on imported fossil fuels for electricity generation, has turned to renewable energy to reduce this dependence and address environmental and health impacts caused by thermal power plants (Dawood, 2020). The transition to renewable energy in Turkey exemplifies the multifaceted benefits of renewable energy, encompassing environmental, economic, and strategic dimensions.

The concept of smart grids has further revolutionized the renewable energy landscape. Smart grids, utilizing digital communications technology, enhance the efficiency and reliability of electricity systems by effectively managing distributed energy resources (Owunna & Obeagu, 2022). This technology is instrumental in integrating renewable energy sources, such as solar and wind, into the power grid, addressing challenges related to their variability and intermittency. The adoption of smart grid technology is a testament to the evolving nature of renewable energy systems, moving towards more sustainable, efficient, and integrated solutions.

The increasing output of renewable energy, particularly from variable sources like wind and solar photovoltaics (PV), is driven by efforts to reduce pollution from fossil fuels, regulatory and policy frameworks, and incentives aimed at minimizing greenhouse gas emissions (Owunna & Obeagu, 2022). Renewable energy sources, characterized by their ability to be naturally replenished at a rate comparable to or faster than their rate of consumption, offer a sustainable alternative to conventional energy sources. The inherent renewability and environmental benefits of these sources, such as reduced air pollution and greenhouse gas emissions, make them an integral part of the global strategy to combat climate change and promote sustainable development.

Therefore, the importance of renewable energy in the contemporary world cannot be overstated. Its role in reducing greenhouse gas emissions, contributing to economic growth, reducing dependence on imported fossil fuels, and fostering sustainable development is increasingly recognized. The integration of advanced technologies like smart grids further enhances the potential of renewable energy, paving the way for more efficient, reliable, and sustainable energy systems.

1.2. The Emergence of AI in Renewable Energy Sector

The emergence of Artificial Intelligence (AI) in the renewable energy sector marks a significant shift towards more efficient and intelligent energy systems. AI's role in this sector is multifaceted, encompassing automation, optimization, and predictive analytics, which are crucial for the effective integration and management of renewable energy sources.

Moghaddam, Dashtdar, and Jafari (2022) explore the application of AI in automating energy systems within smart cities. Their study focuses on the European Union, highlighting how AI technologies are transforming energy systems by enhancing efficiency and performance. The research underscores AI's ability to manage and control power systems with high accuracy, particularly in integrating renewable energy sources like solar and wind with existing supply and demand systems. This integration is vital for achieving sustainable energy and future development with minimal loss and greenhouse gas emissions.

Kumar and Swathika (2022) provided an analysis of AI applications in renewable energy, emphasizing the transformative impact AI has had in the field of electrical engineering. Their work illustrates how AI, combined with renewable energy technologies, has revolutionized electricity generation, dissipation, and consumption. The chapter delves into how AI contributes to the development of smart buildings and utilities, showcasing the synergy between AI and renewable energy in creating more efficient and intelligent energy systems.

Singh et al. (2021) discussed AI-based renewable energy with a focus on emerging applications. Their work reviews critical techniques based on photovoltaic (PV) forecast using machine learning techniques, addressing the challenges posed by the variable performance of renewable energy sources due to environmental factors. The study highlights the importance of precise prediction in ensuring the stability and reliability of the grid, demonstrating AI's potential in enhancing the forecasting and management of renewable energy production.

The intersection of AI and renewable energy is characterized by the use of advanced algorithms and data analytics to optimize energy production and distribution. AI technologies enable the renewable energy sector to overcome challenges related to the integration of variable energy sources, such as solar and wind, into existing power systems. By leveraging AI, the sector can achieve greater efficiency, reliability, and sustainability in energy production and management.

Therefore, the emergence of AI in the renewable energy sector is a pivotal development that is reshaping the landscape of energy production and management. AI's role in automating, optimizing, and predicting energy systems is crucial for the successful integration of renewable energy sources into the global energy mix. As the world continues to move towards sustainable energy solutions, AI will play an increasingly important role in driving innovation and efficiency in the renewable energy sector.

Aim and Objectives of the Review

The primary aim of this study is to comprehensively review and synthesize the current state of artificial intelligence (AI) applications in the renewable energy sector, with a specific focus on solar and wind energy optimization. This involves an in-depth analysis of how data science techniques are being employed to enhance the efficiency, reliability, and sustainability of renewable energy systems.

The research objectives are;

- *To investigate how AI technologies are being integrated into renewable energy systems, particularly solar and wind energy.*
- To assess the effectiveness of these AI approaches in addressing specific challenges in solar and wind energy systems.
- To analyze the technological, economic, and environmental impacts of integrating AI into renewable energy systems.

1.3. The Intersection of Data Science and Renewable Energy: Solar and Wind

The integration of data science in renewable energy, particularly in solar and wind energy systems, represents a transformative approach that enhances the efficiency and reliability of these energy sources. The intersection of these fields is marked by the application of advanced data analytics, machine learning, and deep learning techniques to optimize energy generation and distribution.

Chen and Xu (2022) provide a compelling example of this intersection through their study on solar and wind power data from the Chinese State Grid Renewable Energy Generation Forecasting Competition. Their research highlights the importance of accurate forecasting in renewable energy systems, particularly in the context of high renewable energy penetration in power grids. The study utilized an open dataset comprising data collected from on-site renewable energy stations, including wind farms and solar stations, over two years. This dataset was instrumental in developing data-driven forecasting models, underscoring the potential of data science in enhancing the predictability and stability of renewable energy sources.

Similarly, Saire, Gastelo-Roque, and Canziani (2021) explored the use of a data science approach in studying a hybrid photovoltaic-wind smart microgrid in Peru. Their research focused on analyzing real data of solar irradiance, wind speed, energy demand, and battery bank voltage to identify patterns, seasonality, and correlations. The insights gained from this data-driven analysis were used to improve sizing techniques and provide recommendations for energy management, thereby optimizing the performance of smart microgrids. This study exemplifies how data science can be leveraged to enhance the operational efficiency of renewable energy systems.

Abualigah et al. (2022) further expand on this theme by surveying advanced machine learning and deep learning techniques applied to wind, solar, and photovoltaic renewable energy systems. Their comprehensive review assesses the performance of various algorithms and highlights the effectiveness of hybrid learning techniques in dealing with energy generation problems. The study emphasizes that hybrid methods, which combine the strengths of multiple techniques, offer superior accuracy and efficiency compared to single-method approaches. This finding is particularly relevant in the context of large datasets, where the complexity and variability of renewable energy sources pose significant challenges.

The intersection of data science and renewable energy is not just about the application of sophisticated algorithms; it also involves the development of new frameworks for data collection, processing, and analysis. The studies by Chen and

Xu (2022), Saire, Gastelo-Roque, and Canziani (2021), and Abualigah et al. (2022) collectively demonstrate the critical role of data in understanding and optimizing renewable energy systems. By harnessing the power of data, stakeholders in the renewable energy sector can make more informed decisions, improve the integration of renewable sources into the power grid, and ultimately drive the transition towards more sustainable energy systems.

The synergy between data science and renewable energy, particularly in the domains of solar and wind energy, is a key driver of innovation and efficiency in the energy sector. The application of data-driven approaches not only enhances the predictability and stability of renewable energy sources but also contributes to the development of smarter, more efficient, and sustainable energy systems. As the world continues to move towards greater renewable energy adoption, the role of data science in this transition will undoubtedly become more pronounced and critical.

2. Methodology

2.1. Research Strategy for AI Applications in Renewable Energy

The integration of Artificial Intelligence (AI) in renewable energy represents a significant stride towards achieving sustainable energy systems. Hou and Wang (2022) conducted a comprehensive bibliometric analysis to characterize the knowledge systems of big data, AI, and energy. Their study, spanning two decades, underscores the United States' leading role in this field, evidenced by its high h-index. The Chinese Academy of Sciences emerges as a pivotal contributor, publishing a substantial number of papers and fostering collaborative networks. This analysis reveals that journals like IEEE Access and Energies are prolific in this domain, with engineering being the predominant subject. The study highlights key theoretical foundations such as deep learning, reinforcement learning, and energy big data, alongside the prediction of energy consumption. The application of big data and AI in energy primarily focuses on smart grids, energy consumption, and renewable energy. Early research frontiers involved optimizing and predicting energy-related problems using genetic algorithms and neural networks. Since 2013, energy big data have gained prominence, with machine learning, deep learning, and fog computing increasingly applied to energy saving. The future of big data and AI in this field is seen in promoting renewable energy applications and energy-efficient building renovations.

The energy sector, as Hou and Wang (2023) noted, is crucial in reducing global emissions, given that energy production and usage contribute significantly to greenhouse gas emissions. The development of emerging technologies like AI is key to transforming the energy system and meeting climate goals. AI's role in training data through algorithms enables computers to mimic human thought processes, making big data the foundation of AI. The Internet of Things (IoT) has become a vital source of big data, connecting objects for real-time monitoring.

The accumulation of large data volumes in the energy field, facilitated by technologies like sensors and cloud computing, has led to the permeation of energy big data across various domains, including energy production, consumption, planning, and policy. AI's most common application in energy is in prediction, encompassing load forecasting, power generation output forecast, and energy consumption forecast for agricultural production. AI also plays a crucial role in fault detection and diagnosis in power systems.

Szczepaniuk and Szczepaniuk (2022) discuss the applications of AI algorithms in the energy sector, including smart grid management, energy saving, and renewable energy sources. Their insights into the practical application of AI in these areas are invaluable for understanding the current landscape and potential future developments. Kolosok et al. (2021) provide a scoping review of renewable energy, sustainability, and the environment, identifying the latest trends in research, including the applications of computer science methods in these domains. Their review offers a broader perspective on how AI and data science are reshaping renewable energy research and applications. In summary, the research strategy for AI applications in renewable energy involves a multidisciplinary approach, combining insights from big data, AI, and renewable energy.

The focus is on optimizing energy systems through predictive analytics, smart grid management, and fault detection, with an overarching goal of achieving sustainability and reducing greenhouse gas emissions. The future of this field lies in harnessing the power of AI and big data to drive innovation in renewable energy applications and energy-efficient solutions.

2.2. Criteria for Selecting Relevant AI and Data Science Studies

In the realm of renewable energy research, particularly where artificial intelligence (AI) and data science intersect, the criteria for selecting relevant studies are pivotal. The rapid escalation in global energy demands, primarily driven by an ever-growing human population, has necessitated a shift towards renewable energy sources (Jabeen et al., 2020). This

transition is not merely a matter of resource substitution but a complex interplay of technological innovation, environmental considerations, and economic feasibility.

The selection of pertinent studies in this domain is guided by several key criteria. Firstly, the relevance of the research to contemporary energy challenges is paramount. Studies that address pressing issues such as the efficiency of solar and wind energy systems, the integration of renewable sources into existing grids, and the development of sustainable energy models are particularly significant (Jabeen et al., 2020). These studies must not only contribute to the academic discourse but also offer practical solutions to real-world problems.

Another crucial criterion is the methodological rigor of the research. In the context of AI and data science applications in renewable energy, this involves a thorough examination of the algorithms, models, and analytical techniques employed. Studies that demonstrate innovative use of machine learning, predictive analytics, and other advanced data science methods are highly valued. These methodologies should be robust, replicable, and capable of handling the complexities inherent in renewable energy systems.

The third criterion pertains to the environmental impact of the proposed solutions. Given the overarching goal of renewable energy to mitigate environmental degradation, studies that offer environmentally sustainable solutions are prioritized. This includes research focusing on reducing carbon emissions, enhancing energy efficiency, and promoting the use of clean and green technologies.

Furthermore, the economic viability of the proposed solutions is a critical factor. Renewable energy solutions must be not only technologically sound and environmentally friendly but also economically feasible. Studies that provide cost-benefit analyses, explore market dynamics, and offer scalable and financially sustainable models are particularly relevant.

The geographical scope and applicability of the research also play a significant role in the selection process. Studies that offer insights into specific regional challenges or global energy trends are highly valuable. This includes research that addresses the unique energy needs of developing countries, explores the potential of renewable energy in different climatic and geographical settings, and contributes to the global discourse on energy sustainability. The selection of relevant AI and data science studies in renewable energy is guided by a multifaceted set of criteria. These include the relevance to current energy challenges, methodological rigor, environmental sustainability, economic viability, and geographical applicability. As the field continues to evolve, these criteria ensure that the research not only advances academic knowledge but also contributes meaningfully to the global pursuit of sustainable energy solutions.

Therefore, this *study employs a systematic literature review procedure to explore AI-driven solutions in renewable energy, focusing on data science applications in solar and wind energy optimization. The methodology is structured into two main components: data collection and analysis techniques in renewable energy research, and the synthesis of data science findings in this domain.*

2.3. Data Collection and Analysis Techniques

The data collection process involved a comprehensive search of academic databases and journals for peer-reviewed articles published in the field of renewable energy, with a specific focus on AI innovations in solar and wind energy. The search criteria were defined to include articles that discuss the application of AI and data science in optimizing renewable energy systems. Keywords such as "artificial intelligence," "renewable energy," "solar energy," "wind energy," and "data science" were used to filter relevant studies.

2.4. The inclusion criteria for the articles were

- Peer-reviewed articles published in English.
- Articles published within the last ten years to ensure the relevance and currency of the data.
- Studies that specifically address AI applications in solar and wind energy.

2.5. Exclusion criteria: This involves the exclusion of

- Non-peer-reviewed articles and grey literature.
- Articles not specifically focusing on AI applications in renewable energy.
- Studies that do not provide empirical data or a clear methodology.

2.5.1. Identifying Key AI Innovations in Solar and Wind Energy

The selected articles were analyzed to identify key AI innovations in solar and wind energy. This involved examining the types of AI technologies used, their application in renewable energy systems, and the outcomes of these applications. The analysis focused on understanding how AI technologies contribute to the efficiency, reliability, and optimization of solar and wind energy systems.

2.5.2. Methods for Synthesizing Data Science Findings in Renewable Energy

The synthesis of data science findings involved a thematic analysis of the selected articles. This process entailed categorizing the data into themes related to AI applications in renewable energy. The themes were analyzed to understand the trends, challenges, and opportunities in the field. The analysis also included a critical evaluation of the methodologies used in the studies, assessing their strengths, limitations, and implications for future research.

The findings from the thematic analysis were then synthesized to provide a comprehensive overview of the current state of AI applications in solar and wind energy optimization. This synthesis aimed to highlight the most significant AI innovations, their practical applications, and the potential future directions for research in this area.

This systematic literature review methodology provides a structured approach to understanding the role of AI in renewable energy, particularly in solar and wind energy systems. It offers insights into the current trends and future prospects of AI-driven solutions in this field, contributing to the broader understanding of the intersection between data science and renewable energy.

3. Literature Review

3.1. Fundamental Principles of AI in Renewable Energy

The integration of Artificial Intelligence (AI) in renewable energy systems represents a transformative approach to energy management and optimization. The fundamental principles of AI in this context revolve around enhancing efficiency, predicting energy patterns, and optimizing resource allocation in solar and wind energy systems.

The application of AI in renewable energy begins with the optimization of energy harvesting. Cao et al. (2022) discuss the advancements in piezoelectric vibration energy harvesting techniques, which are crucial for maximizing energy capture from environmental sources. AI algorithms can analyze and predict environmental conditions, adjusting the parameters of piezoelectric devices to optimize energy absorption. This adaptive approach ensures that renewable energy systems, such as solar panels or wind turbines, operate at peak efficiency regardless of varying environmental conditions.

In solar energy systems, the efficiency of light absorption and conversion plays a pivotal role. Tian et al. (2021) explore the development of nanoarray structures for artificial photosynthesis, a concept that can be enhanced through AI. By employing machine learning algorithms, the design and arrangement of these nanoarrays can be optimized for maximum light absorption and conversion efficiency. AI can analyze vast datasets to identify patterns and correlations that human researchers might overlook, leading to more efficient solar energy systems.

Neumeier et al. (2021) provide insights into the state of the art of wind-thermal turbines, focusing on direct wind-to-heat conversion technologies. AI's role in this domain involves predictive analytics and real-time data processing to optimize the performance of wind turbines. By accurately predicting wind patterns and speeds, AI systems can adjust turbine operations to maximize energy capture and conversion efficiency. Furthermore, AI can monitor the health of turbines, predicting maintenance needs and reducing downtime.

One of the key challenges in renewable energy is the management of energy grids, especially with the intermittent nature of sources like solar and wind. AI's predictive capabilities are crucial in this aspect, enabling grid operators to anticipate energy supply fluctuations and demand changes. By accurately forecasting energy production and consumption patterns, AI can facilitate more efficient grid management, reducing waste and improving energy distribution.

AI algorithms are adept at resource allocation, ensuring that renewable energy sources are utilized optimally. This involves not only the distribution of energy but also the allocation of maintenance resources and investment in infrastructure development. AI can analyze complex datasets to identify the most cost-effective and efficient strategies for resource allocation, thereby enhancing the overall sustainability of renewable energy systems.

Despite these advancements, the integration of AI in renewable energy faces challenges, including data quality and availability, algorithmic complexity, and the need for interdisciplinary expertise. Future research should focus on developing more robust AI models that can handle incomplete or noisy data, as well as algorithms that can adapt to the rapidly evolving landscape of renewable energy technologies.

The fundamental principles of AI in renewable energy revolve around optimizing energy harvesting, enhancing efficiency through predictive analytics, and improving grid management and resource allocation. As the field evolves, AI will play an increasingly pivotal role in driving the efficiency and sustainability of renewable energy systems.

3.2. Overview of AI Applications in Solar Energy Systems

The integration of Artificial Intelligence (AI) in solar energy systems has revolutionized the way solar power is harnessed, managed, and utilized. AI applications in this domain range from optimizing sensor performance to enhancing energy harvesting and forecasting solar energy output. Rao et al. (2020) delve into the critical role of sensors in solar energy systems, emphasizing their importance in measuring system parameters and ensuring successful operation. AI plays a pivotal role in optimizing these sensors, enabling them to adapt to changing environmental conditions and improve the efficiency of solar power generation. By analyzing data from sensors, AI algorithms can make real-time adjustments to the solar system, ensuring maximum power output and system reliability.

Hao et al. (2022) provide a comprehensive review of solar energy harvesting technologies, particularly for photovoltaic (PV) self-powered applications. AI's contribution to this field is significant, particularly in the application of Maximum Power Point Tracking (MPPT) techniques. AI algorithms are capable of dynamically adjusting the operating point of PV systems to ensure that they always operate at their maximum power point, thus optimizing energy harvest even under fluctuating environmental conditions.

Zulkifly, Baharin, and Gan (2021) focused on the development of a ranking system to evaluate the performance of various machine learning models in forecasting PV power output. This research highlights the importance of selecting the right AI model for accurate solar energy forecasting. By evaluating different models like Support Vector Machine (SVM), Gaussian Process Regression (GPR), and Decision Trees, the study demonstrates how AI can be tailored to predict solar power output with high accuracy, which is crucial for grid stability and efficient energy management.

AI applications in solar energy systems are not limited to hardware optimization but also extend to the management of the energy produced. AI algorithms can predict energy consumption patterns and adjust the distribution of solar power accordingly. This not only improves the efficiency of solar systems but also ensures a more balanced and reliable energy supply to the grid.

Despite these advancements, challenges remain in the integration of AI in solar energy systems. Issues such as data quality, the complexity of AI algorithms, and the need for continuous improvement in AI models are areas that require further research and development. Future advancements in AI are expected to focus on enhancing the adaptability and accuracy of forecasting models, as well as improving the overall efficiency of solar energy systems. AI applications in solar energy systems have brought about significant improvements in sensor optimization, energy harvesting, and power output forecasting. As AI technology continues to evolve, its role in enhancing the efficiency and reliability of solar energy systems is expected to become even more prominent, driving the solar industry towards a more sustainable and efficient future.

3.3. AI-Driven Innovations in Wind Energy Optimization

The integration of Artificial Intelligence (AI) in wind energy optimization has led to significant advancements in the field, offering innovative solutions to enhance efficiency and performance. El Mokhi and Addaim (2021) present a groundbreaking approach to optimizing the design of cable layouts in offshore wind farms. Their study introduces an algorithm that combines the Firefly Algorithm and Minimum Spanning Tree, focusing on reducing the total cable length in the design phase of offshore wind farms. This innovation is particularly significant given the high investment costs and complex construction processes associated with offshore wind energy projects. The algorithm's ability to minimize cable lengths and associated power losses represents a substantial step forward in making offshore wind farms more economically viable and competitive with onshore alternatives. The study's findings are crucial for countries like Morocco, with extensive seafronts and potential for offshore wind energy development (El Mokhi & Addaim, 2021).

Khamharnphol et al. (2023) explore the optimization of a hybrid power generation system, combining solar, wind, diesel, and battery energy storage, for a distribution system in Koh Samui, Thailand. Their research aims to maximize renewable energy deployment while minimizing the levelized cost of energy (LCOE). The study employs a hybrid

renewable energy-based power generation system, including solar PV, wind turbines, and diesel generators, integrated with a bi-directional grid-tied charging inverter and a battery energy storage system (BESS). This comprehensive approach, utilizing AI and optimization techniques, demonstrates the potential for significant economic and environmental benefits. The study's outcomes are particularly relevant for island regions and contribute to the broader understanding of microgrid hybrid systems in renewable energy optimization (Khamharnphol et al., 2022).

Lukin et al. (2020) investigate the application of generative design in the mass optimization of wind energy systems, specifically focusing on an experimental wind generator based on the Magnus effect. Their study highlights the potential of generative design as a tool for optimizing electromechanical applications, despite the requirement for complex manufacturing techniques like additive manufacturing. The significant mass reduction achieved in the components of the wind turbine underscores the potential of AI-driven design approaches in enhancing the efficiency and performance of wind energy systems. This study provides valuable insights into the application of AI in the development of more efficient and sustainable wind energy technologies (Lukin et al., 2020).

These studies collectively illustrate the diverse and impactful ways in which AI is driving innovations in wind energy optimization. From the design of offshore wind farms to the optimization of hybrid power generation systems and the application of generative design in wind turbines, AI is playing a crucial role in advancing the field of wind energy. These developments not only enhance the efficiency and economic viability of wind energy systems but also contribute significantly to the broader goal of sustainable energy development.

3.4. Key Technological Advancements in AI for Renewable Energy

The integration of Artificial Intelligence (AI) in renewable energy has led to significant technological advancements, enhancing efficiency, reliability, and sustainability. Teekaraman et al. (2022) investigate the application of AI in smart grid systems, particularly using Support Vector Machines (SVM) for identifying regression losses in large-scale systems. Their study addresses the challenges in conventional smart grid systems, such as manual operation and delayed problem-solving, by implementing AI techniques. The introduction of automated procedures using AI significantly reduces operational risks and enhances efficiency. The two-stage process they propose involves fault identification and diagnosis, integrated with constant parameters to manage power flows effectively. This approach demonstrates a substantial improvement in smart grid operations, achieving an efficiency of 81% compared to existing methods. The study underscores the potential of AI in transforming smart grid systems, making them more responsive and efficient (Teekaraman et al., 2022).

Elavarasan (2020) provides a comprehensive review of India's progress in renewable energy technologies, comparing it with other countries. The study highlights the role of technological advancements, including AI, in optimizing the utilization of renewable resources. It focuses on identifying areas where India lags in renewable energy methods and suggests a redirection of efforts. The research emphasizes not only the technological aspects but also the challenges and policies needed to overcome these obstacles. This comparative analysis offers valuable insights into the global landscape of renewable energy advancements and the critical role of AI in driving these developments (Elavarasan, 2020).

Raihan and Voumik (2022) explore the impact of renewable energy, remittances, and technical innovation, including AI, on carbon dioxide emissions in China. Using the autoregressive distributed lag (ARDL) model, their study reveals a significant relationship between these factors and CO₂ emissions. The findings indicate that while economic development increases emissions, the use of renewable energy and technological advancements, such as AI, contribute to reducing them. The study provides empirical evidence of the potential of AI and renewable energy in mitigating environmental impacts, offering policy recommendations for sustainable development (Raihan & Voumik, 2022).

These studies collectively highlight the transformative impact of AI in the renewable energy sector. From enhancing smart grid systems to fostering growth in renewable energy technologies and reducing carbon emissions, AI is proving to be a crucial driver of innovation and sustainability. As the world increasingly turns towards renewable energy sources, the role of AI in optimizing these resources and mitigating environmental impacts becomes more vital, paving the way for a more sustainable and efficient energy future.

3.5. State-of-the-Art Data Science Techniques in Energy Optimization

The integration of data science techniques in renewable energy optimization has been pivotal in enhancing the efficiency and sustainability of energy systems. Testasecca et al. (2023) provide a comprehensive overview of the recent advances in data-driven services for smart energy systems optimization and proactive management. They emphasize

the significance of optimization in various domains, including electric vehicles charging, district heating networks, and energy districts, highlighting the role of machine learning algorithms and scientific models in these advancements.

Cai (2014) delves into the application of data mining and analysis techniques for renewable energy network design and optimization. This approach is particularly effective in managing the complexity of energy networks, which encompass energy generation, transformation, transportation, and consumption. Data mining and analysis stand out for their ability to handle imprecision and uncertainty, offering robust and cost-effective solutions for agile energy dispatching, especially in extreme events causing local energy shortages.

Jalli et al. (2023) investigate the intersection of data science and renewable energy, focusing on how big data analytics can revolutionize the renewable energy industry. They discuss the potential of data science in managing and analyzing diverse datasets generated by renewable sources, weather patterns, energy consumption, and grid operations. The paper highlights key data science techniques such as machine learning, time-series analysis, and optimization algorithms, and their application in demand-side management, smart grid optimization, real-time forecasting of renewable energy generation, and predictive maintenance for renewable energy infrastructure.

The integration of these data science techniques in renewable energy optimization has led to significant improvements in efficiency, reliability, and sustainability. For instance, the use of machine learning algorithms in predicting renewable energy generation and consumption has been instrumental in enhancing grid management and energy efficiency. This is particularly evident in the work of Testasecca et al. (2023), where they discuss the novel European project, DigiBUILD, which employs various data-driven models for optimizing electric vehicle charging management and building energy and comfort management. Furthermore, the application of data mining and analysis in renewable energy network design, as discussed by Cai (2014), demonstrates the capability of these techniques in handling restoration during extreme and emergency situations with uncertain parameters. This approach not only ensures energy efficiency but also contributes to the resilience of the energy network.

Jalli et al. (2023) also shed light on the challenges that need to be addressed for the widespread adoption of data science applications in renewable energy. These include data privacy concerns, data quality issues, and scalability challenges. However, the benefits, such as increased use of renewable energy sources, decreased carbon emissions, and mitigated climate change impacts, make these challenges worth tackling. The state-of-the-art data science techniques in energy optimization have significantly contributed to the advancement of renewable energy systems. The integration of machine learning algorithms, data mining, and big data analytics has not only enhanced the efficiency and sustainability of these systems but also paved the way for innovative solutions in energy management and optimization. As these technologies continue to evolve, they hold great promise for the future of renewable energy optimization.

3.6. Emerging Trends in AI for Renewable Energy

The renewable energy sector is undergoing a transformative phase with the integration of Artificial Intelligence (AI), leading to emerging trends that are reshaping the landscape of energy production and management. AlShafeey and Csáki (2022) conducted a tech mining analysis to understand the evolution of scientific studies in renewable energy forecasting using AI technologies. Their research, which analyzed over 25,000 articles, revealed an exponential growth in this topic over the past decade. The findings underscore the increasing reliance on AI for accurate and efficient forecasting in renewable energy. This trend is particularly prevalent in Asian countries, with China leading in both publications and citations. The study highlights the growing importance of AI in enhancing the predictability and reliability of renewable energy sources, thereby facilitating better planning and management (AlShafeey & Csáki, 2022).

Singh et al. (2021) explore AI-based renewable energy with a focus on emerging applications. Their study reviews critical techniques in photovoltaic (PV) forecast using machine learning techniques. The variability in environmental conditions poses significant challenges to the stability and reliability of renewable energy systems. AI applications, particularly in machine learning, are instrumental in overcoming these challenges by providing more accurate predictions of energy production. This research not only summarizes the various renewable energy sources and their merits but also demonstrates the key challenges and AI applications in real-life scenarios, offering a comprehensive view of the potential of AI in revolutionizing renewable energy systems (Singh et al., 2021).

Xue, Fan, and Yue (2020) investigate the emerging trends of risk management in renewable energy projects. Their study, utilizing Citespace software, systematically summarizes the research hotspots and frontiers in this field. The results indicate a shift from traditional risk management practices to technology-driven integration systems in renewable energy. This trend reflects the increasing complexity and long life cycles of renewable energy projects, where AI plays a crucial role in managing these complexities and uncertainties. The study provides insights into the evolving nature of

risk management in renewable energy, emphasizing the importance of AI in ensuring the success and sustainability of these projects (Xue, Fan, & Yue, 2020).

Therefore, the emerging trends in AI for renewable energy are marked by significant advancements in forecasting, application development, and risk management. These trends highlight the growing importance of AI in enhancing the efficiency, reliability, and sustainability of renewable energy systems. As the sector continues to evolve, AI is expected to play an increasingly vital role in addressing the challenges and harnessing the full potential of renewable energy sources.

3.6.1. Novel AI Algorithms for Energy Efficiency

The integration of Artificial Intelligence (AI) in renewable energy systems has led to the development of novel algorithms aimed at enhancing energy efficiency. Bagheri et al. (2021) investigated the use of AI algorithms in different building typologies to achieve energy efficiency, particularly in the context of smart buildings. Their study focused on the application of AI in controlling heating systems across various building types. The research demonstrated that AI algorithms could lead to significant energy savings, ranging from 20% to 40%, regardless of the building typology or the type of heating system used. This was achieved through a corporate server that controlled the heating systems in a unified energy-saving platform, showcasing the potential of AI in optimizing energy consumption in buildings (Bagheri et al., 2021).

Abdel-Razek et al. (2022) explored energy efficiency through the implementation of an AI model to predict room occupancy based on thermal comfort parameters. Their study utilized machine learning algorithms, such as K-nearest neighbors (KNN) and decision trees (DT), to predict room occupancy using data on temperature, humidity, lighting, and CO₂ levels. The research found that KNN performed better than DT in occupancy recognition, with a 99.5% accuracy rate. This approach demonstrates how AI can be used to optimize energy use in buildings by adjusting environmental conditions based on occupancy, contributing to energy savings and improved user comfort (Abdel-Razek et al., 2022).

Abualigah et al. (2022) conducted a comprehensive survey of advanced machine learning and deep learning techniques applied to wind, solar, and photovoltaic renewable energy systems. Their study covered a range of learning-based modeling methods, including deep learning (DL) and machine learning (ML) algorithms, for precise forecasting in renewable power sources. The research highlighted the effectiveness of these techniques in handling large datasets and complex parameters, emphasizing the superiority of hybrid learning methods that combine different algorithms for more accurate forecasting. This study underscores the potential of novel AI algorithms in optimizing the generation and management of renewable energy (Abualigah et al., 2022).

The development of novel AI algorithms is playing a crucial role in enhancing energy efficiency in various sectors. From smart building management to renewable energy forecasting, these advancements are paving the way for more sustainable and efficient energy systems. As AI continues to evolve, its application in energy efficiency is expected to yield even more significant improvements, contributing to the global effort in energy conservation and sustainability.

3.6.2. Integration of AI in Renewable Energy Grids

The integration of Artificial Intelligence (AI) in renewable energy grids is a pivotal development in the energy sector, enhancing the efficiency and reliability of energy systems. Rai, Chanda, and De (2021) presented an efficient integration algorithm and methodology for incorporating solar and wind energy sources into modern power systems. Their study aimed at revamping the standard of electric power supply at minimal cost and highest reliability in smart grid infrastructure. The research modeled the costing *characteristics of solar and wind units using data from NASA Surface Metrology and Solar Energy. This approach enabled the integration of these clean energy sources into the optimal power flow program with a Pareto optimal objective function, ensuring the welfare of all participants. The methodology demonstrated the ability to sustain reliable and standard operating conditions in the presence of renewable energy sources, highlighting the efficacy of AI in optimizing smart grid operations (Rai, Chanda, & De, 2021).*

Nithara et al. (2022) reviewed the role of power electronics in the integration of renewable energy sources with microgrids. Their study focused on various power electronic configurations and topologies and their role in the conversion and control of electric energy. The paper emphasized the significance of power electronic devices and technologies in integrating wind and solar energy into the electric grid. This integration is crucial for meeting future energy demands and addressing global environmental concerns, such as CO₂ emissions. The research underlined the importance of power electronics in facilitating the seamless integration of renewable energy sources into microgrids, thereby enhancing the overall efficiency and reliability of the power system (Nithara et al., 2022).

Mbungu et al. (2020) provided an overview of the integration of renewable energy resources in the urban sector, particularly for commercial building applications. The study addressed the challenges of global energy demand and growth, focusing on solar photovoltaic (PV) and battery energy storage systems (BESS). It developed the concept of PV energy storage integration in commercial building applications, considering the variability of common renewable energy resources like wind and solar. The research highlighted the benefits of integrating distributed energy resources (DERs) connected to the grid, especially when PV and energy storage systems are smartly combined with the utility grid. This integration assists in improving the dynamic performance of electrical networks operating in commercial buildings, demonstrating the potential of AI in designing dynamic behavior for energy management (Mbungu et al. 2020). From smart grid operations to microgrid management and commercial building applications, AI plays a crucial role in enhancing the efficiency and sustainability of renewable energy integration. As the energy sector continues to evolve, AI-driven solutions are expected to become increasingly vital in addressing the complexities of integrating renewable energy sources into power grids.

4. Discussion and Analysis

4.1. Evaluating the Impact of AI on Renewable Energy Systems

The integration of Artificial Intelligence (AI) in renewable energy systems has been a transformative development, offering new avenues for optimizing energy production and distribution. Gernaat et al. (2021) conducted a comprehensive study on the impact of climate change on renewable energy supply. Their research utilized climate and integrated assessment models to estimate the effects on various renewable energy technologies, including solar and wind energy. The study revealed that while solar power's impact was minor, the effects on wind energy varied significantly, with some regions experiencing declines and others seeing increases in potential. This variability underscores the importance of AI in adapting renewable energy systems to changing climatic conditions. AI algorithms can predict and manage these fluctuations, ensuring a stable and efficient energy supply (Gernaat et al., 2021).

Tawfiq et al. (2020) analyzed the impact of integrating wind farms into electrical power generation systems. Their study employed block diagrams and Markov chain techniques to assess the reliability of generation systems with wind farms. The findings indicated that the connection of wind farms enhances system reliability, reducing congestion and improving voltage stability. AI plays a crucial role in this context by optimizing the operation and maintenance of wind farms, thereby enhancing the overall reliability of the power system. AI-driven predictive maintenance and real-time monitoring can significantly reduce downtime and improve the efficiency of wind energy systems (Tawfiq et al., 2020).

Zhang et al. (2022) conducted a regional comprehensive environmental impact assessment of renewable energy systems in California. Their study, which included a life cycle assessment (LCA), showed that renewable energy systems, particularly solar energy and biomass, have significant environmental impacts. AI can mitigate these impacts by optimizing the design and operation of renewable energy systems. For instance, AI algorithms can enhance the efficiency of solar panels and biomass energy conversion, reducing the overall environmental footprint. Additionally, AI can aid in the strategic planning of renewable energy deployment, ensuring minimal ecological disruption (Zhang et al., 2022). AI enhances the adaptability of renewable energy systems to climate change, improves the reliability of wind farms in power systems, and aids in reducing the environmental impact of renewable energy. As the renewable energy sector continues to evolve, AI will play an increasingly vital role in ensuring the sustainability and efficiency of energy systems.

4.1.1. Technological, Economic, and Environmental Impacts

The integration of Artificial Intelligence (AI) in renewable energy systems has profound technological, economic, and environmental impacts.

Technological Impact: The study by Solarin, Bello, and Tiwari (2022) highlights the significant role of technological innovation in renewable energy production. They emphasize that technological advancements, particularly in AI, have greatly enhanced the efficiency and output of renewable energy systems. AI algorithms have improved forecasting, grid management, and energy storage, leading to more reliable and efficient renewable energy production. This technological leap is crucial for countries with varying levels of renewable energy production, as AI can tailor solutions to specific needs and capacities (Solarin, Bello, & Tiwari, 2022).

Economic Impact: Wen et al. (2022) discuss the economic implications of renewable energy, emphasizing the role of technological innovation, including AI, in shaping economic growth. They argue that renewable energy, supported by AI advancements, contributes to sustainable economic development by reducing dependency on non-renewable

resources and mitigating the costs associated with environmental degradation. AI-driven renewable energy systems can lead to job creation, new market opportunities, and overall economic resilience, especially in developing countries (Wen et al., 2022).

Environmental Impact: Majeed et al. (2022) explore the environmental benefits of integrating AI in renewable energy consumption. Their study indicates that AI, coupled with environmental innovations, can significantly reduce the ecological footprint of energy production. AI can optimize energy consumption patterns, enhance the efficiency of renewable energy sources, and contribute to achieving climate goals. This is particularly relevant in the context of the Paris Climate Agreement, where AI-driven renewable energy solutions can play a pivotal role in reducing greenhouse gas emissions and promoting cleaner production (Majeed et al., 2022).

Technologically, it enhances the efficiency and reliability of renewable energy production. Economically, it fosters sustainable development and opens new avenues for growth. Environmentally, it contributes to cleaner production and reduced ecological impacts. As the renewable energy sector continues to evolve, the role of AI in shaping its trajectory will be increasingly significant.

4.1.2. Challenges and Solutions in AI Applications for Renewable Energy

Adenle (2020) discuss the economic challenges in renewable energy, particularly in the context of solar energy. They highlight that while AI offers promising solutions, its integration faces hurdles such as high initial costs, lack of skilled personnel, and technological complexities. These challenges are more pronounced in developing countries, where resources are limited and the technological infrastructure is not fully developed (Adenle, 2020).

Alam et al. (2020) focus on the challenges of integrating high-level renewable energy sources (RESs) into the grid. They note that the intermittent nature of renewable sources like solar and wind energy introduces issues such as low fault ride through capability and power quality concerns. AI can help in addressing these challenges by optimizing grid operations and enhancing predictive maintenance. However, the integration of AI itself is complex, requiring sophisticated algorithms and robust data analytics capabilities (Alam et al., 2020).

Siddique et al. (2021) explore the role of the Internet of Things (IoT) in the renewable energy sector of Bangladesh. They argue that IoT, a key component of AI applications, can facilitate the integration of renewable energy sources into the power grid. However, challenges such as data security, network reliability, and interoperability must be addressed to fully leverage IoT in renewable energy applications. The authors suggest that overcoming these challenges requires a collaborative approach involving government, industry, and academia (Siddique et al., 2021).

While AI offers transformative potential in renewable energy, its integration is not without challenges. Economic constraints, grid integration complexities, and the need for advanced IoT infrastructure are key hurdles. Addressing these challenges requires a multi-faceted approach, involving technological innovation, policy support, and capacity building. As the renewable energy sector continues to evolve, AI and IoT will play a crucial role in overcoming these challenges and unlocking the full potential of renewable energy sources.

4.1.3. Trends and Future Directions in AI for Solar and Wind Energy

The renewable energy sector, particularly solar and wind energy, is undergoing a transformative phase with the integration of Artificial Intelligence (AI). Abualigah et al. (2022) provide a comprehensive survey of advanced machine learning (ML) and deep learning (DL) techniques applied in wind, solar, and photovoltaic renewable energy systems. They emphasize the effectiveness of these techniques in handling large datasets and complex parameters inherent in renewable energy systems. The study suggests that hybrid learning methods, which combine different AI techniques, show promise in enhancing the accuracy and efficiency of renewable energy forecasts and optimizations (Abualigah et al., 2022).

Dias and Morais (2020) utilize text mining to analyze trends in wind and solar energy, based on patent documents and academic papers. Their findings indicate a significant investment in technical solutions and scientific discoveries in these fields. The study highlights the growing importance of AI in fostering innovative approaches to renewable energy development, suggesting a trend towards more AI-driven research and development in the sector (Dias & Morais, 2020).

Kumar et al. (2021) focus on the assessment of solar energy potential in Hungary and the Visegrád countries. Their study, which combines geographical mapping, technical regression analysis, and temperature distribution profiles, underscores the importance of AI in evaluating and optimizing solar energy potential. The research points towards a

future where AI-driven assessments could play a crucial role in the sustainable development of solar energy across different regions (Kumar et al., 2021).

The integration of AI in solar and wind energy is marked by advancements in machine learning and deep learning techniques, a growing trend in AI-driven research and development, and the application of AI in geographical and technical assessments. These trends indicate a future where AI not only enhances the efficiency and accuracy of renewable energy systems but also drives innovation and sustainable development in the sector.

4.2. Implications for Stakeholders in the Renewable Energy Sector

The renewable energy sector's evolution, particularly with the integration of AI and other advanced technologies, has profound implications for various stakeholders. Schick, Klempf, and Hufendiek (2022) explore the role of prosumers – individuals or entities that both produce and consume energy – in a sector-integrated energy system with high renewable shares. Their research highlights the potential of distributed battery storage systems as a source of flexibility in nearly 100% renewable energy systems. However, they note that the operation mode of these systems can either serve individual profit maximization or benefit the system as a whole. This dichotomy underscores the need for policies that balance individual benefits with the overall system optimum, considering both system cost changes and distributional effects for certain stakeholder groups (Schick, Klempf, & Hufendiek, 2022).

Pathirana (2022) addresses the conflicts of interest in formulating policies on renewable energy, which can affect the efficiency of these policies in driving sustainable development. The study reveals a disconnection between stakeholders' and voters' positions, with the public being sensitive to justice in procedures and distribution, and stakeholders focusing on energy autonomy and renewable energy as a solution to climate issues. This disparity suggests the need for harmonizing the interests of both parties to formulate feasible and publicly acceptable policies (Pathirana, 2022).

Vaidy (2020) examines the effectiveness of renewable energy subsidies in Nepal, particularly focusing on the biogas subsidy. The study reveals that the effectiveness of these subsidies is influenced by various factors, including users' awareness of renewable energy technology (RET) benefits, government policy, cost-effectiveness of the technology, and long-term access to RETs. Interestingly, the research indicates that subsidies have primarily benefited better-off households rather than low-income populations. This finding highlights the need for more equitable subsidy distribution and financial intermediation to ensure broader access to renewable energy technologies, especially for poorer farmers (Vaidy, 2020).

The implications for stakeholders in the renewable energy sector are multifaceted, involving considerations of policy formulation, subsidy distribution, and the role of prosumers. Balancing individual and collective benefits, ensuring equitable access to technology, and harmonizing conflicting interests are crucial for the sustainable development of the renewable energy sector.

5. Conclusion

Artificial Intelligence (AI) has emerged as a pivotal force in the renewable energy sector, particularly in solar and wind energy optimization. AI's role encompasses the enhancement of predictive maintenance, optimization of energy production, and integration of renewable sources into the power grid. Advanced machine learning and deep learning techniques have been instrumental in handling large datasets and complex parameters, leading to more efficient and reliable renewable energy systems. The integration of AI has not only improved operational efficiency but also facilitated innovative approaches to energy management and distribution.

The future landscape of AI in solar and wind energy optimization is poised for significant growth and innovation. The trend towards hybrid learning methods and the increasing use of AI in geographical and technical assessments indicate a future where AI-driven solutions will be integral to the sustainable development of renewable energy. The integration of IoT and other advanced technologies is expected to further enhance the efficiency and accuracy of renewable energy systems. As AI technologies continue to evolve, they will play a crucial role in addressing the intermittent nature of renewable sources and in optimizing grid operations.

For industry leaders and policymakers, it is essential to foster an environment conducive to the growth and integration of AI in renewable energy. This includes investing in research and development, providing training and resources to develop skilled personnel, and formulating policies that balance individual benefits with the overall system optimum. Equitable subsidy distribution and financial intermediation are crucial to ensure broader access to renewable energy

technologies. Additionally, harmonizing the interests of various stakeholders, including prosumers, is vital for the formulation of feasible and publicly acceptable policies.

Future research in AI-driven renewable energy solutions should focus on addressing the challenges of AI integration, such as economic constraints, grid integration complexities, and the need for advanced IoT infrastructure. Exploring novel AI algorithms for energy efficiency and the integration of AI in renewable energy grids will be key areas of focus. Research should also aim to understand the socio-economic impacts of AI integration in renewable energy and develop strategies to mitigate any adverse effects. The continuous evolution of AI technologies presents an opportunity for groundbreaking research that can further revolutionize the renewable energy sector. AI's role in renewable energy is transformative, offering numerous opportunities for optimization, innovation, and sustainable development. The future of renewable energy is inextricably linked with the advancements in AI, necessitating a collaborative and forward-thinking approach from all stakeholders involved.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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