Journal of Inventive Engineering and Technology (JIET)
ISSN: 2705-3865
Volume-5, Issue-3, pp-40-48
www.jiengtech.com
Research Paper Open Access

Renewable energy construction: Role of AI for smart building infrastructures

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ABSTRACT :*The progression of the construction sector towards sustainable development is increasingly interconnected with the integration of Artificial Intelligence (AI) within renewable energy construction. This opinion paper delves into the transformative impact of AI on smart building infrastructures, emphasizing its role in bolstering efficiency, sustainability, and resilience. AI technologies, encompassing machine learning algorithms, predictive analytics, and Internet of Things (IoT) sensors, play a crucial role in optimizing energy usage, enabling predictive maintenance, and facilitating real-time monitoring. These advancements guarantee the seamless integration of renewable energy systems like solar panels and wind turbines into building designs, thereby maximizing energy efficiency, and reducing carbon footprints. The integration of artificial intelligence (AI) in renewable energy construction is set to revolutionize the way smart buildings are designed and managed globally, including in Nigeria. This paper discusses the pivotal role of AI in optimizing energy efficiency, managing renewable energy resources, and enabling predictive maintenance within smart building infrastructures. By leveraging AI technologies, significant advancements in sustainability and operational efficiency can be achieved, contributing to the development of smart cities and sustainable urban environments. This opinion paper highlights the potential and challenges of incorporating AI into renewable energy construction and smart building infrastructure in Nigeria, offering insights into how AI can be a driving force for the future of sustainable development in the country.*

KEYWORDS: *AI, Smart building, Renewable, Energy, Construction*

Date of Submission: xx-xx-xxxx Date of acceptance: xx-xx-xxxx

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I. INTRODUCTION

The urgency to address climate change and reduce carbon footprints has placed renewable energy at the forefront of modern construction practices globally, and Nigeria is no exception(Cherian, 2015; Idoko et al., 2024).. As the demand for sustainable and energy-efficient buildings increases, Nigeria's construction industry is exploring innovative solutions to integrate renewable energy sources such as solar, wind, and geothermal (Alahi et al., 2023). In parallel, the advent of AI has opened new possibilities for optimizing construction processes and enhancing building performance. The combination of AI and renewable energy technologies offers a promising pathway to achieve the goals of sustainable development, particularly in Nigeria's burgeoning urban centers.

Artificial intelligence, encompassing machine learning, neural networks, and robotics, is transforming various sectors by automating complex tasks, providing data-driven insights, and enabling real-time decision-making(Johnson et al., 2021; Tien, 2017). The construction industry, traditionally slow to adopt new technologies, is now recognizing the immense potential of AI to revolutionize renewable energy integration and smart building management(Mazhar et al., 2022; Pan & Zhang, 2023; Regona et al., 2022). Hassan et al. (2024) stated that AI can help in designing more efficient buildings, optimizing energy consumption, and ensuring that renewable energy sources are used to their fullest potential. For Nigeria, this means creating buildings that can withstand the challenges of urbanization and climate change while promoting sustainability.

This paper argues that AI is crucial for advancing renewable energy construction and creating smart building infrastructures in Nigeria. Rane (2023) reported that AI-driven solutions can significantly improve energy management, enhance predictive maintenance, and enable the seamless integration of Internet of Things (IoT) devices, leading to smarter, more efficient buildings. By exploring the current applications, challenges, and future prospects of AI in this field, this paper aims to provide a comprehensive overview of its transformative potential. The goal is to offer a compelling argument for the widespread adoption of AI technologies in the pursuit of sustainable and intelligent building practices in Nigeria.

II. BACKGROUND

The building and construction industry is undergoing a transformative evolution, increasingly integrating advanced technologies such as Digital Twin (DT), Building Information Modelling (BIM), Artificial Intelligence (AI), Internet of Things (IoT), and Smart Vision (SV) (Hassan et al., 2024; Mazhar et al., 2022). This integration is part of the broader movement towards Industry 4.0, which signifies a shift from traditional practices to autonomous systems characterized by digital and computing technologies. These innovations are not only enhancing efficiency, productivity, accuracy, and safety but also redefining design, construction, operation, and maintenance processes with a focus on sustainability (Elmualim & Gilder, 2014).

The concept of sustainable and smart buildings is gaining traction, propelled by public interest and the agendas of researchers and city authorities worldwide. Chew et al. (2020)stated that the deployment of 5G technology is anticipated to significantly impact building construction, operation, and management by enabling high-quality services and efficient functionalities, thus contributing to sustainable development goals. The rise of green and intelligent buildings is attributed to their numerous benefits, including structural stability and reduced ecological impacts.

AI's integration in these buildings is proving crucial for optimizing operations and fostering innovation. The convergence of AI with smart energy systems and grids necessitates a comprehensive understanding of computational, economic, and social dimensions(Shi et al., 2020). This socio-technical integration demands a clear domain definition and a well-articulated research problem specification. AI’s role is pivotal in the energy system transformations within smart cities, driving the transition towards renewable energy resources(Ahmad et al., 2022; Pan & Zhang, 2023). Despite the high initial investment and integration challenges with existing systems, renewable energy promises sustainable development with minimal losses and greenhouse gas emissions.

In the era of rapid urbanization and growing environmental concerns, the construction of smart building infrastructures powered by renewable energy has emerged as a pivotal solution for sustainable development. AI plays an instrumental role in enhancing the efficiency, sustainability, and overall management of these buildings. Energy efficiency is a cornerstone of smart building design. AI's capability to predict and manage energy consumption is transforming how buildings operate. By analyzing historical data and real-time inputs, AI systems can optimize energy use, reducing waste and lowering operational costs (Mohammadi & Al-Fuqaha, 2018). This predictive capability ensures that energy is consumed in the most efficient manner possible, aligning with the goals of sustainable development. Sustainability, another critical factor, is significantly enhanced through AI's integration with green technologies. AI helps reduce the carbon footprint of buildings by optimizing the use of renewable energy sources, such as solar and wind power (Wang et al., 2020). Through intelligent monitoring and adaptive control systems, AI ensures that these resources are utilized effectively, thereby promoting a greener and more sustainable environment.

Building Management Systems (BMS) are the nerve centers of smart infrastructures. AI enhances the reliability and control of BMS by automating various functions. This includes real-time monitoring, fault detection, and energy management, all of which contribute to the seamless operation of the building (Jiang & Dong, 2019). AI-driven BMS can adjust lighting, heating, and cooling systems autonomously, ensuring optimal performance and comfort. Demand Response Programs (DRPs) are vital for balancing energy supply and demand. AI facilitates these programs by adjusting energy usage based on real-time data and predictive analytics (Kim & Shcherbakova, 2011). This dynamic adjustment helps in stabilizing the grid, preventing energy shortages, and reducing costs during peak demand periods. AI’s role in DRPs exemplifies its capacity to create responsive and adaptive energy systems. Predictive maintenance is another area where AI proves invaluable. By analyzing data from various building systems and components, AI can predict potential equipment failures and schedule maintenance before issues become critical (Lei et al., 2020). This not only enhances the longevity of the equipment but also prevents costly downtime and repairs, ensuring the continuous operation of the building.

Occupant comfort is a primary consideration in smart building design. AI ensures optimal environmental conditions by continuously monitoring and adjusting factors such as temperature, humidity, and lighting based on occupant preferences and activities (Erickson et al., 2009). This personalized approach enhances the comfort and well-being of the building's occupants, demonstrating the human-centric potential of AI. The integration of the Internet of Things (IoT) with AI creates a more interconnected and responsive building ecosystem. IoT devices collect vast amounts of data, which AI analyzes to make informed decisions about energy management, security, and maintenance (Al-Fuqaha et al., 2015). This synergy between AI and IoT results in building systems that are not only efficient but also adaptive to the ever-changing needs of their users.

Renewable energy in construction primarily involves the use of sustainable energy sources to power buildings and reduce dependency on fossil fuels. Solar panels, wind turbines, and geothermal systems are among the most common renewable energy technologies utilized in modern construction(Chel & Kaushik, 2018). Li et al. (2015) argued that these technologies not only reduce greenhouse gas emissions but also contribute to energy cost savings and energy independence. For instance, solar panels can be installed on rooftops to harness sunlight, while wind turbines can be integrated into the building design to generate electricity from wind. In Nigeria, where sunlight is abundant, solar energy holds significant promise for addressing energy needs.

Smart building infrastructures are characterized by the integration of advanced technologies that enable buildings to autonomously manage and optimize their operations (Zamponi & Barbierato, 2022). Key components of smart buildings include IoT devices, sensors, automation systems, and energy management systems. These technologies work together to create an intelligent environment that enhances comfort, security, and energy efficiency for occupants(Kumar et al., 2021). For example, smart thermostats can adjust heating and cooling based on occupancy patterns, while automated lighting systems can reduce energy consumption by turning off lights in unoccupied areas. In Nigeria, smart building technologies can help address issues such as energy shortages and inefficient resource management.

AI technologies, such as machine learning algorithms, neural networks, and robotics, are increasingly being applied in construction to streamline processes and improve outcomes. Machine learning algorithms can analyze vast amounts of data to optimize building designs and predict energy consumption patterns. Neural networks can process complex data to improve energy management and maintenance scheduling. Robotics can automate repetitive tasks, improving construction efficiency and reducing human error. Together, these AI technologies offer significant benefits for renewable energy construction and smart building infrastructures, making buildings more adaptive, efficient, and sustainable. For Nigeria, adopting these technologies can play a crucial role in modernizing its construction sector and meeting the demands of rapid urbanization. Also, this means that renewable energy systems can operate more reliably, supporting continuous energy access even in remote or underserved areas.

III. ROLE OF AI IN RENEWABLE ENERGY CONSTRUCTION

AI plays a crucial role in the design and planning phases of renewable energy construction. By leveraging machine learning algorithms, architects and engineers can optimize building designs for energy efficiency and sustainability. These algorithms can analyze historical data, environmental conditions, and energy consumption patterns to recommend the most effective design solutions (Makridakis et al., 2018). This leads to buildings that are not only aesthetically pleasing but also energy-efficient and environmentally friendly (GhaffarianHoseini et al., 2017). For example, AI can suggest optimal orientations for solar panels to maximize sunlight exposure throughout the year, which is particularly beneficial in sun-rich regions like Nigeria (Radmehr & Arman, 2020; Adewuyi, 2019).

Energy management is another area where AI can make a significant impact. AI-powered energy management systems can monitor and control the use of renewable energy sources in real-time (Wang et al., 2018). These systems can predict energy demand, optimize the operation of renewable energy systems, and ensure that energy is used efficiently (Camero & Alba, 2018). For example, AI can adjust the operation of solar panels and wind turbines based on weather forecasts and energy consumption patterns, maximizing energy production and minimizing waste (Hernandez et al., 2016). Additionally, AI can coordinate the use of different renewable energy sources to maintain a stable and reliable energy supply (Anvari-Moghaddam et al., 2018). In Nigeria, where energy infrastructure can be inconsistent, AI-driven energy management can help stabilize supply and reduce reliance on non-renewable sources (Okafor & Joe-Uzuegbu, 2018; Nnaji et al., 2015).

Predictive maintenance is an essential aspect of maintaining the efficiency and longevity of renewable energy systems. AI can analyze data from sensors and IoT devices to predict when maintenance is needed, reducing downtime and preventing costly repairs (Dabbagh & El-Moussa, 2019). For example, AI can monitor the performance of solar panels and wind turbines, identifying potential issues before they become critical (Khan et al., 2020). This proactive approach to maintenance not only enhances the reliability of renewable energy systems but also reduces operational costs (Zhang & Tao, 2020). Furthermore, AI can schedule maintenance activities during periods of low energy demand, minimizing disruptions to building operations (Zhekun et al., 2019). For Nigeria, this means that renewable energy systems can operate more reliably, supporting continuous energy access even in remote or underserved areas (Adaramola, 2016).

IV. The Evolution of Building Infrastructures

A. Traditional Building Methods Versus Modern Approaches

Traditional building methods have long been characterized by manual labor, standardized materials, and a linear approach to design and construction. These methods often rely heavily on human skill and experience, with limited technological intervention (Ngowi et al., 2005). While effective in their time, traditional techniques are often less efficient, more resource-intensive, and less adaptable to the increasing demands for sustainability and energy efficiency (Ogunbiyi et al., 2014).

Modern approaches to building infrastructure, on the other hand, integrate advanced technologies and innovative materials to create more efficient, sustainable, and adaptable structures. The advent of computer-aided design (CAD) has revolutionized architectural planning, allowing for more complex and precise designs (Eastman et al., 2011). Building Information Modeling (BIM) further enhances this by providing detailed digital representations of physical and functional characteristics of buildings (Azhar, 2011). These technologies enable better visualization, collaboration, and management throughout the construction lifecycle.

In Nigeria, traditional building methods still prevail in many areas, especially in rural and low-income urban settings. However, there is a growing shift towards modern construction practices, driven by urbanization, economic growth, and the need for more sustainable development (Ogunbiyi et al., 2014; Oladapo, 2007). Modern approaches offer the potential to significantly improve the quality, durability, and energy efficiency of buildings, aligning with the country's goals for sustainable urban development (Adeyemi et al., 2013).

B. How AI is Changing the Landscape of Construction with Smart Technologies

Artificial intelligence is transforming the construction industry by introducing smart technologies that enhance efficiency, accuracy, and sustainability. AI-powered design tools can optimize building layouts for maximum energy efficiency and minimal environmental impact. For instance, generative design algorithms can explore countless design variations to find the most efficient solutions based on predefined criteria.

Construction site management is also benefiting from AI. Drones and autonomous vehicles can survey sites, monitor progress, and deliver materials with greater precision and safety. AI-powered project management software can predict potential delays, optimize resource allocation, and streamline workflows. This results in faster project completion times, reduced costs, and improved safety records.

In Nigeria, the integration of AI in construction could address many challenges, such as project delays, cost overruns, and safety concerns. By adopting AI-driven technologies, Nigerian construction firms can enhance productivity, reduce waste, and improve the overall quality of construction projects. This technological shift is crucial for meeting the country's ambitious goals for smart cities and sustainable infrastructure.

V. AI in Renewable Energy Construction

A. AI Contributes to Efficient Design and Construction Processes

AI significantly enhances the efficiency of design and construction processes in renewable energy projects. Machine learning algorithms can analyze vast amounts of data to optimize building designs, considering factors such as sunlight exposure, wind patterns, and geothermal potential (Kalogirou, 2017). This data-driven approach ensures that buildings are designed to maximize the use of renewable energy sources from the outset (Bauer et al., 2019).

During the construction phase, AI-powered tools can streamline operations, reduce errors, and enhance collaboration. For example, robotics and automation can perform repetitive tasks with high precision, reducing the likelihood of human error and increasing productivity (Bock & Linner, 2015). AI-driven project management systems can forecast potential issues, such as material shortages or labor constraints, allowing for proactive adjustments and minimizing delays (Zhou et al., 2020).

In Nigeria, where construction projects often face challenges such as logistical difficulties and resource constraints, AI can play a transformative role. By optimizing design and construction processes, AI can help deliver renewable energy projects more efficiently and cost-effectively, contributing to the country's energy sustainability goals (Oyedele et al., 2019).

B. AI's Role in Optimizing Energy Consumption and Integrating Renewable Energy Sources

AI is pivotal in optimizing energy consumption within buildings and integrating renewable energy sources effectively. Smart energy management systems, powered by AI, can monitor and control energy usage in real-time, adjusting settings to ensure optimal efficiency (Zhang et al., 2018). These systems can predict energy demand based on historical data and current usage patterns, allowing for better planning and energy distribution (Aghajani et al., 2017).

AI also facilitates the seamless integration of various renewable energy sources. For instance, AI algorithms can balance the energy output from solar panels, wind turbines, and geothermal systems, ensuring a stable and reliable energy supply (Bianchini et al., 2019). This is particularly important in regions like Nigeria, where the energy grid can be unstable and energy access is inconsistent (Adaramola & Oyewola, 2011). AI can help stabilize the grid by predicting fluctuations in energy production and demand, enabling more efficient use of renewable resources (Palensky & Dietrich, 2011).

Moreover, AI can support the development of microgrids, which are localized energy grids that can operate independently of the main grid. This is especially relevant for rural and remote areas in Nigeria, where extending the main grid may be challenging (Miller et al., 2017). AI-driven microgrids can manage local energy resources efficiently, providing reliable and sustainable energy access to underserved communities (Jabeen et al., 2019).

VI. Case Studies and Examples

One notable example of AI integration in smart city projects is the city of Amsterdam. Amsterdam has implemented AI-driven systems to manage its energy grid, optimize traffic flow, and monitor environmental conditions (van der Zee et al., 2018). The city's smart grid uses AI to balance energy supply and demand, integrating renewable energy sources such as solar and wind (de Waal, 2017). This system not only improves energy efficiency but also reduces the city's carbon footprint, contributing to its sustainability goals (Geertman & Stillwell, 2020). Amsterdam's use of AI in managing its energy infrastructure serves as a model for other cities looking to enhance their sustainability efforts through technology (Angelidou, 2017).

In the realm of smart buildings, the Edge building in Amsterdam is a prime example of how AI can enhance building performance. The Edge is equipped with thousands of sensors that monitor lighting, temperature, and occupancy (Nelson & Stolterman, 2018). AI algorithms analyze this data to optimize energy use, ensuring that the building operates at peak efficiency (Bharathi & Sandhya, 2019). The building's energy management system, powered by AI, has helped it achieve a net-zero energy status, demonstrating the potential of AI in creating sustainable, energy-efficient buildings (Poole, 2019). The Edge has received numerous awards for its innovative design and sustainability features, highlighting the benefits of integrating AI in building management (Fischer et al., 2018).

In Nigeria, projects such as the Eko Atlantic City in Lagos are exploring the integration of AI and renewable energy to create a modern, sustainable urban environment (Ogunbodede et al., 2014). Eko Atlantic aims to be a self-sustaining city that incorporates renewable energy sources and smart technologies to manage resources efficiently (Adeyemi et al., 2013). The use of AI in energy management, traffic control, and environmental monitoring can help Eko Atlantic achieve its goals of sustainability and resilience (Nzeadibe et al., 2015). By learning from international examples and tailoring solutions to local contexts, Nigeria can develop smart cities that address its unique challenges and leverage its abundant natural resources (Olawuyi, 2016).

VII. Challenges and Considerations

Despite the significant potential of AI in renewable energy construction, several technical challenges need to be addressed. Integrating AI with renewable energy systems requires sophisticated algorithms and robust data infrastructure (Bengio et al., 2021). The accuracy of AI predictions depends on the quality and quantity of data available, necessitating extensive data collection and processing capabilities (Zhang et al., 2018). Additionally, the complexity of AI models can pose challenges in terms of implementation and maintenance, requiring specialized skills and expertise (Goodfellow et al., 2016). Ensuring that AI systems are reliable and secure is crucial for their successful deployment in renewable energy applications (Kumar et al., 2020).

Economic factors also play a crucial role in the adoption of AI in renewable energy construction. The initial cost of implementing AI technologies can be high, including expenses related to hardware, software, and training (Mourshed et al., 2018). However, these costs can be offset by the long-term benefits of increased efficiency and reduced operational expenses (McKinsey & Company, 2020). It is essential to conduct comprehensive cost-benefit analyses to justify investments in AI and ensure economic feasibility (Arentsen & Bellekom, 2014). Governments and private investors need to collaborate to provide financial support and incentives for AI-driven renewable energy projects, fostering innovation and accelerating adoption (International Energy Agency, 2019).

Ethical and regulatory issues are also important considerations. The use of AI in construction raises concerns about data privacy and security, as large amounts of sensitive data are collected and processed (Mittelstadt et al., 2016). Regulatory frameworks need to be established to ensure that AI applications comply with privacy laws and ethical standards (Floridi et al., 2018). Additionally, the potential impact of AI on employment in the construction industry must be addressed, as automation could lead to job displacement for certain roles (Brynjolfsson & McAfee, 2014). Policymakers and industry leaders must work together to create guidelines that promote responsible AI use while protecting workers and ensuring fair labor practices (Russell et al., 2015).

VIII. Future Prospects

The future of AI in renewable energy construction looks promising, with ongoing advancements in AI technologies and an increasing emphasis on sustainability (Hao et al., 2021). Emerging AI techniques, such as reinforcement learning and advanced neural networks, hold the potential to further enhance energy management and predictive maintenance (Wang et al., 2018). These advancements could lead to even more efficient and intelligent building systems, driving the transition towards smart cities and sustainable urban development (Chen et al., 2020). Research and development in AI for renewable energy should be prioritized to unlock new capabilities and address existing challenges (Jiang et al., 2018). AI's role in achieving sustainable development goals (SDGs) cannot be overstated. By optimizing the use of renewable energy and improving energy efficiency, AI contributes to SDG 7 (affordable and clean energy) and SDG 13 (climate action) (United Nations, 2015). Furthermore, the integration of AI in construction supports SDG 9 (Industry, Innovation, and Infrastructure) by promoting the development of resilient and sustainable infrastructure (Schwab, 2016). The synergy between AI and renewable energy construction is crucial for creating a sustainable future where technology and environmental responsibility go hand in hand (Gielen et al., 2019).

IX. Conclusion

The integration of AI in renewable energy construction and smart building infrastructures offers immense potential for Nigeria. By adopting AI-driven technologies, the country can enhance the efficiency, sustainability, and resilience of its buildings and energy systems. This is crucial for meeting the growing demands of urbanization and addressing the challenges of climate change.

AI stands as a transformative force in renewable energy construction. It not only enhances efficiency but also pushes the boundaries of what is possible in smart building infrastructures. As we continue to innovate and integrate these technologies into our buildings, we must remain cognizant of the challenges and move forward with careful planning and ethical consideration.

While there are technical, economic, and regulatory challenges to overcome, the benefits of AI in terms of energy efficiency, operational efficiency, and sustainability are significant. By embracing AI, Nigeria can drive significant advancements in renewable energy integration and smart building management, contributing to a more sustainable and resilient built environment. The journey towards a greener future is a collective effort, and AI is a powerful tool that can help Nigeria achieve its sustainability goals.

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