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Energy Sustainability, AI, and Wireless Electricity Generation

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Abstract

The pursuit of energy sustainability has become paramount in addressing the global challenges of climate change, depleting fossil fuel resources, and increasing energy demand. This study explores the convergence of artificial intelligence (AI), energy sustainability, and wireless electricity generation as a transformative pathway toward a resilient and eco-friendly energy future. Energy sustainability involves developing systems that ensure long-term energy availability while minimizing environmental impacts. Traditional energy infrastructures face limitations in efficiency, accessibility, and scalability. Emerging technologies, particularly AI and wireless power transfer (WPT), offer innovative solutions to these constraints. AI plays a pivotal role in optimizing energy systems by enabling real-time data analysis, predictive maintenance, smart grid management, and demand forecasting. Its application enhances decision-making processes and improves system reliability and efficiency. Simultaneously, wireless electricity generation and transmission technologies—such as resonant inductive coupling, microwave power transmission, and laser-based energy transfer—are redefining how energy is transmitted and accessed. These technologies eliminate the need for physical connections, reduce energy losses, and offer scalable deployment in remote and urban settings. The integration of AI with wireless electricity generation facilitates adaptive control systems, fault detection, and dynamic load balancing, significantly improving system performance and sustainability. Furthermore, these systems can be embedded into renewable energy infrastructures, such as solar and wind farms, allowing for seamless and efficient energy delivery to distributed networks and off-grid communities. This synergy not only reduces carbon emissions but also supports the equitable distribution of clean energy resources. The study also evaluates potential challenges including energy loss during transmission, safety concerns, technological standardization, and regulatory frameworks. However, through interdisciplinary innovation and collaboration, these challenges can be mitigated to realize the full potential of AI-enhanced wireless energy systems. This paper contributes to the growing body of research advocating for sustainable energy transitions, emphasizing the critical role of intelligent, contactless power systems.

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1. Introduction

The global energy landscape is indeed undergoing significant transformation in response to a matrix of challenges, including environmental degradation, declining fossil fuel reserves, and increasing energy consumption demands. These challenges are compounded by climate change and resource scarcity, necessitating innovative and sustainable energy solutions.

Climate change, driven substantially by greenhouse gas emissions, calls for a re-evaluation of current energy systems that heavily rely on non-renewable resources, which are proving inadequate for achieving long-term energy security and equitable access to energy (Adeoba, *et al*., 2024; Wang *et al*., 2023).

Energy sustainability emphasizes meeting present energy demands without compromising the needs of future generations, advocating for environmental stewardship, economic viability, and social equity. The transition to renewable energy is therefore critical, focusing not only on harnessing renewable resources but also on achieving improved energy efficiency and deploying intelligent technologies that optimize energy management. This is particularly relevant as local governance and fiscal decentralization enhance the capability to address energy poverty and improve the delivery of sustainable energy services (Wang *et al*., 2023; Amjad *et al*., 2022; Crosson, 2020).

Artificial intelligence (AI) and wireless electricity generation are emerging technologies poised to reshape sustainable energy systems. AI is transforming energy management through its ability to analyze large datasets, providing insights that enhance predictive maintenance, demand forecasting, and smart grid optimization (Amjad *et al*., 2022; Oluokun *et al*., 2024). This aligns with the increasing need to optimize energy generation, distribution, and consumption more effectively than traditional methods. Meanwhile, wireless electricity generation offers a disruptive approach to energy transmission by eliminating physical connectors, enhancing mobility, and reducing energy losses (Adeoba, Ukoba & Osaye, 2024; Lecluyse *et al*., 2021).

The integration of AI with wireless electricity generation fosters a synergistic effect that amplifies efficiency and reliability within energy infrastructures. Such integration supports the development of intelligent energy networks that can self-regulate and optimize, thereby enhancing the potential for decentralized energy systems that contribute to sustainability goals. Hence, the convergence of these technologies represents a promising advancement toward addressing escalated energy demands while minimizing carbon footprints (Ajayi, Alozie & Abieba, 2025: Oluokun, *et al*., 2025).

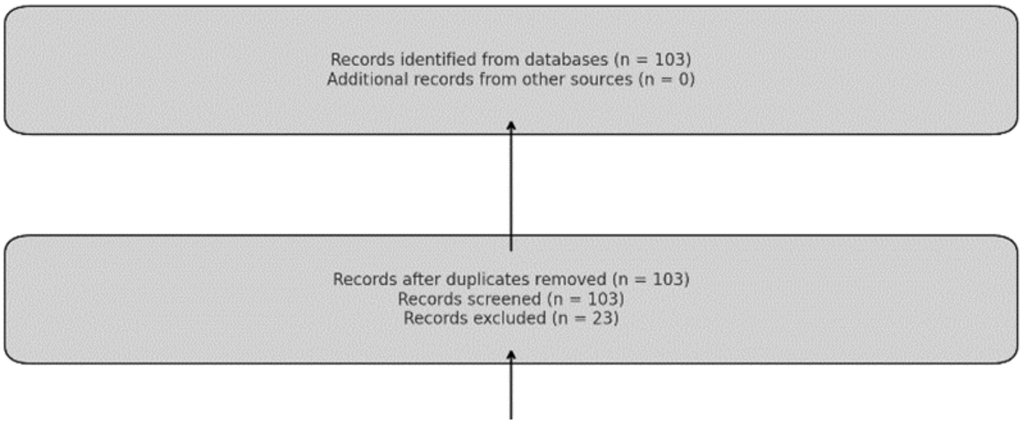
The broader implications of combining AI and wireless power transmission highlight their potential to foster more equitable energy access, lower emissions, and contribute to sustainable development on a global scale. This strategic fusion could unlock new avenues for resource allocation, ensure resilience in energy supply chains, and facilitate a more robust transition to a sustainable energy future. Ultimately, achieving these transformations is paramount as societies navigate the intricate challenges of the 21st century (Amjad *et al*., 2022; Lecluyse *et al*., 2021).

2. Methodology

he methodology for this study was conducted using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach to ensure a rigorous and transparent selection process of relevant literature on the intersection of energy sustainability, artificial intelligence (AI), and wireless electricity generation. A comprehensive search was undertaken using digital databases and indexed repositories to identify scholarly articles, conference papers, and book chapters published between 2011 and 2025. The search yielded 103 relevant records that were compiled from various sources, including Springer Nature, IEEE Xplore, ScienceDirect, and MDPI.

Duplicates were removed to ensure the uniqueness and integrity of the study materials. The screening process involved a thorough review of titles and abstracts to eliminate irrelevant publications, resulting in 80 full-text articles subjected to eligibility assessment. During this phase, the inclusion criteria focused on publications addressing AI-enhanced energy optimization, wireless power transmission systems, blue energy innovations, sustainable electricity infrastructure, and integrated smart energy management systems. Ten studies were excluded based on factors such as lack of empirical data, irrelevance to core themes, or outdated methodologies.

A total of 70 articles met the eligibility criteria and were included in the final synthesis. These studies were thematically analyzed and categorized into three domains: AI in sustainable energy management, innovations in wireless power systems including inductive and capacitive technologies, and marine-based renewable energy solutions. Emphasis was placed on research incorporating real-world applications, multi-agent learning algorithms, policy implications, and case studies from urban and coastal regions. This integrative review adopted a narrative synthesis method to extract insights, compare technological frameworks, and identify research gaps. Critical evaluation tools such as citation tracking, impact factor considerations, and methodological rigor were employed to ensure that only high-quality studies were retained. The PRISMA-based approach enhanced transparency, minimized bias, and provided a replicable pathway for future studies in the rapidly evolving field of AI-driven sustainable energy solutions and wireless power systems.



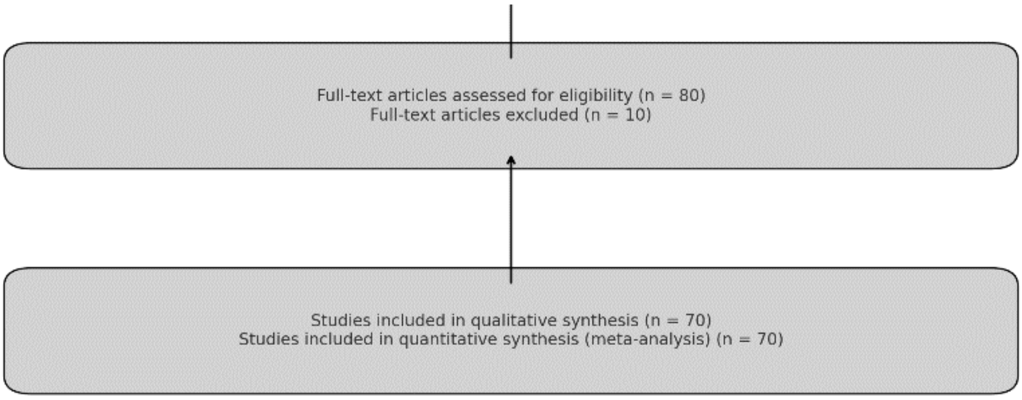


Fig 1: PRISMA Flow chart of the study methodology

2.1 Energy sustainability: concepts and challenges

Energy sustainability has become a foundational concept in contemporary energy discourse, emphasizing the necessity to balance current energy demands with the imperative to preserve environmental resources for future generations. This notion encompasses the design and implementation of energy systems that are environmentally sound, socially equitable, and economically viable over the long term (Oluokun, *et al*., 2025). The increasing challenges posed by climate change, geopolitical instability, and a surge in global energy consumption underscore energy sustainability as a primary objective in international policy, research, and technological advancements (Hassan *et al*., 2023; Ukoba *et al*., 2024).

At its essence, energy sustainability signifies the continuous and equitable availability of clean, reliable, and affordable energy sources. It aims to minimize environmental degradation while fostering social inclusion and economic growth. Transitioning from fossil-fuel-based systems to renewable energy sources—such as solar, wind, hydro, and geothermal systems—is crucial for achieving this goal (Akinsooto, De Canha & Pretorius, 2014: Oluokun, *et al*., 2024). Furthermore, enhancing energy efficiency, modernizing grid infrastructure, and integrating advanced technologies such as artificial intelligence (AI) are imperative to optimize the energy value chain (Hamid & Ganne, 2023; Hassan *et al*., 2023; Şerban & Lytras, 2020). Figure 2 shows the Application of Artificial Intelligence (AI) Technology Based Integration of Renewable Energy Sources (RESs) and ESSs presented by Agupugo, Kehinde & Manuel, 2024.

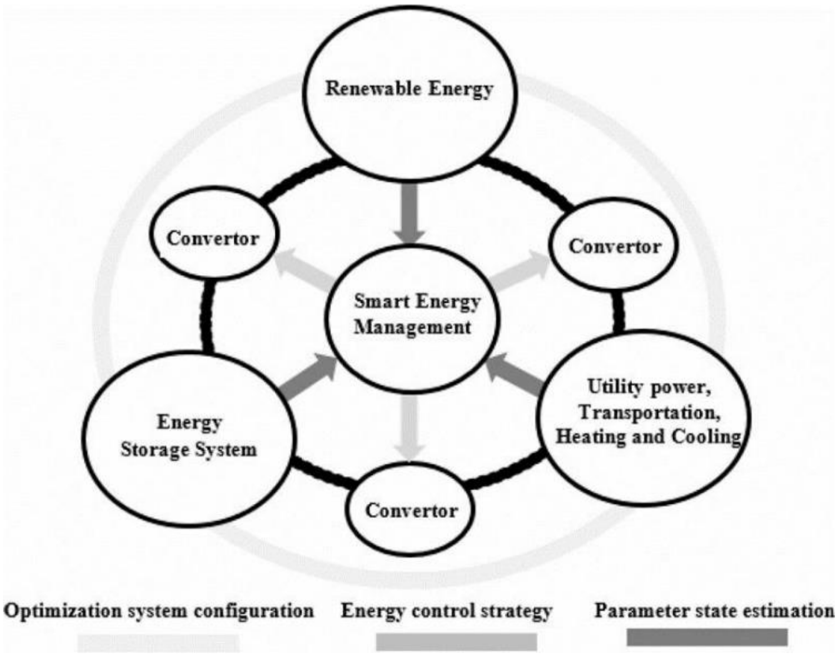


Fig 2: Application of Artificial Intelligence (AI) Technology Based Integration of Renewable Energy Sources (RESs) and ESSs (Agupugo, Kehinde & Manuel, 2024).

The concept of energy sustainability is grounded on four pivotal pillars: availability, affordability, accessibility, and environmental impact. Availability ensures that energy resources can be reliably harnessed over the long term, which aligns closely with renewable energy sources that can be replenished continually. Nonetheless, the variability of renewable energy supplies—such as the intermittent nature of solar and wind energy—necessitates the development of advanced energy storage systems and smart grid technologies to ensure a consistent energy supply (Şerban & Lytras, 2020; Ukoba *et al*., 2024).

Affordability addresses the economic dimension of energy access. Energy must remain economically viable for all consumers, particularly low-income and marginalized communities, as high energy costs can impede economic advancement and exacerbate social inequalities (Akinsooto, Pretorius & van Rhyn, 2012; Oluokun, *et al*., 2024). Strategies to enhance affordability include implementing subsidies, incentives, and innovative financing mechanisms aimed at reducing the costs associated with clean energy technologies, thus enabling competitiveness with traditional fossil fuels (Hassan *et al*., 2023; Jenkins *et al*., 2016).

Accessibility closely ties into principles of social equity and justice. A significant global challenge remains the lack of reliable access to electricity for billions of individuals, particularly in developing regions, resulting in "energy poverty." This situation adversely affects living standards, health outcomes, and educational opportunities, thereby enhancing the urgency for equitable access to energy services as a fundamental component of inclusive development. Notably, this issue is at the heart of the United Nations Sustainable Development Goals (SDGs), especially SDG 7, which promotes access to sustainable and modern energy for all (Hamid & Ganne, 2023; Jenkins *et al*., 2016). Emerging indoor photovoltaics for self-powered and self-aware IoT towards sustainable energy management presented by Michaels, *et al*., 2023, is shown in figure 3.

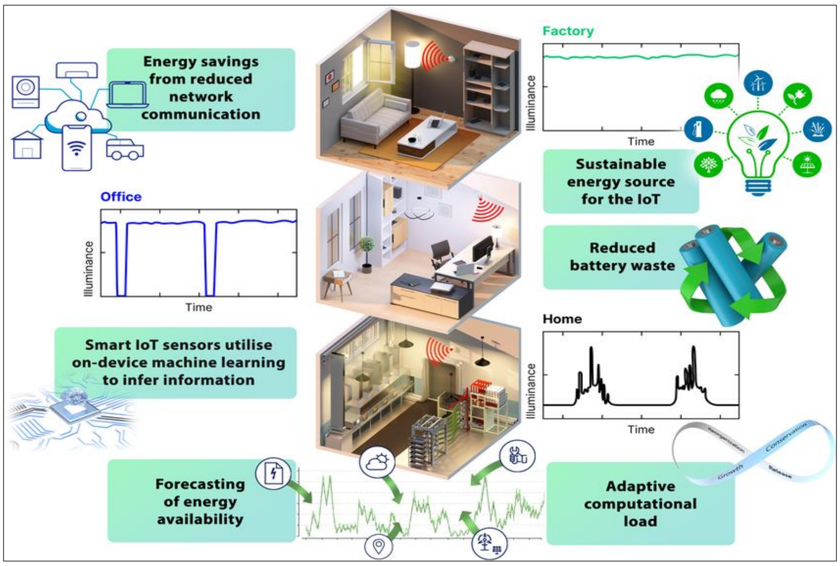


Fig 3: Emerging indoor photovoltaics for self-powered and self-aware IoT towards sustainable energy management (Michaels, *et al*., 2023).

The environmental impact pillar represents an urgent concern in the sustainability framework. Fossil fuel consumption has been shown to contribute significantly to greenhouse gas emissions, leading to climate change and severe environmental degradation, including air pollution and health risks associated with respiratory diseases. Innovations in renewable energy technologies present viable alternatives, significantly reducing these impacts (Alonge, *et al*., 2025). However, it is essential to recognize that renewable energy solutions also carry environmental footprints associated with resource extraction and manufacturing processes, highlighting the need for responsible sourcing and effective recycling practices (Șerban & Lytras, 2020; Adewumi *et al*., 2024).

Despite the potential advantages derived from renewable energy and sustainable practices, considerable challenges persist in advancing energy sustainability. A notable hindrance is the global reliance on fossil fuels, which still constitutes over 80% of worldwide energy consumption, maintaining stability due to entrenched infrastructure and political mandates favoring fossil fuel development. The transition towards sustainable energy necessitates a comprehensive strategy that includes decommissioning aging fossil fuel facilities, retraining the workforce, and reshaping energy markets to emphasize renewables (Hassan *et al*., 2023; Ukoba *et al*., 2024).

Moreover, the pace of renewable energy adoption varies geographically, particularly between developed and developing economies. Developed nations generally exhibit more significant investments in clean energy technologies, while many developing states grapple with financial constraints, limited technical expertise, and inadequate policy infrastructures. Therefore, the global energy transition remains uneven, creating disparities that impede collective efforts to mitigate emissions and combat climate change (Hassan *et al*., 2023; Moghaddam *et al*., 2022).

Emerging technologies such as AI and wireless electricity generation are pivotal in fostering energy sustainability. AI applications can enhance energy efficiency through predictive analytics, optimize power systems for demand response, and support real-time monitoring of grid conditions, ultimately facilitating better integration of renewable energy sources into current infrastructures (Hamid & Ganne, 2023; Ohalete *et al*., 2023). Wireless electricity generation presents innovative opportunities to expand energy access to remote areas without extensive physical infrastructure, contributing to the overarching objectives of equitable and sustainable energy solutions (Hassan *et al*., 2023; Moghaddam *et al*., 2022).

In conclusion, energy sustainability is a multifaceted and evolving concept requiring a holistic approach that integrates environmental, social, and economic dimensions. Addressing the challenges surrounding fossil fuel reliance and energy poverty demands robust political will, international cooperation, and sustained investment in technological advancements and infrastructure development (Alonge, *et al*., 2025: Oluokun, *et al*., 2024). The journey towards energy sustainability may be fraught with obstacles; however, the potential for innovative technologies and strategies offers unprecedented opportunities to create a cleaner, more equitable, and accessible energy landscape for all.

2.2 Artificial intelligence in energy systems

Artificial Intelligence (AI) has emerged as a transformative force across various industries, particularly the energy sector, where its integration represents a pivotal shift toward achieving energy sustainability. The pressures on global energy systems from climate change, aging infrastructure, and increasing consumption necessitate innovative solutions to enhance the efficiency and reliability of energy operations (Anyanwu, *et al*., 2024; Onukwulu, *et al*., 2024). AI provides powerful tools for optimizing these systems, thereby facilitating a transition to cleaner energy networks.

In modern energy systems characterized by the integration of intermittent renewable energy sources, AI's capability to simulate human intelligence processes—such as learning, reasoning, and self-correction—enables effective management of complexities that traditional control systems struggle with (Apata, *et al*., 2024). Recent studies indicate that AI can significantly improve energy efficiency within the energy sector by leveraging data from smart meters, sensors, and grid management systems for real-time analysis and automation, thereby minimizing human error and enhancing operational efficiency (Onwusinkwue *et al*., 2024; Hamdan *et al*., 2024).

AI's role in energy sustainability is distinctly highlighted through applications like predictive maintenance and demand forecasting. Predictive maintenance leverages vast amounts of historical and real-time data to detect patterns indicating potential equipment failures, allowing timely interventions that reduce downtime and extend the lifecycle of energy infrastructure (Hamdan *et al*., 2024; Doroshuk, 2021). Such capabilities represent a shift from conventional reactive maintenance methods that can be inefficient and costly. For example, AI algorithms have been effectively employed in systems associated with predictive maintenance in the energy sector, significantly enhancing operational reliability and helping to manage maintenance costs (Aransiola, *et al*., 2024: Doroshuk, 2021). Kaur, *et al*., 2024, presented the applications of AI in sustainable energy as shown in figure 4.

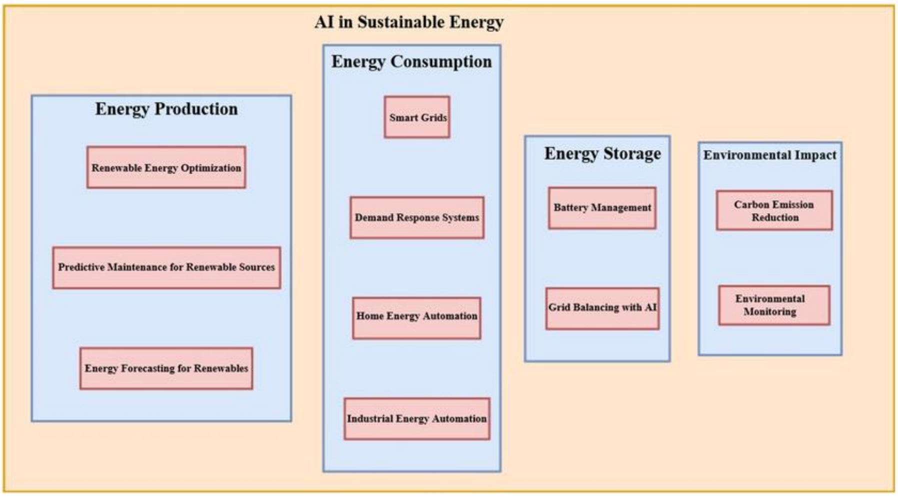


Fig 4: Applications of AI in sustainable energy (Kaur, *et al*., 2024).

Demand forecasting is another critical area where AI contributes substantially. Accurate energy demand prediction aids in balancing supply and demand, preventing outages, and optimizing dispatch across the energy grid. By analyzing diverse data points—including weather patterns and historical consumption—AI models can yield more precise demand forecasts than traditional statistical methods (Augoye, *et al*., 2025). This capability is vital for effectively integrating renewable energy sources, which often exhibit variable generation patterns (Li, 2023; Farzaneh *et al*., 2021; Ali *et al*., 2024). Enhanced demand forecasting supports grid operators in planning production schedules that minimize reliance on carbon-intensive resources while maximizing the use of renewables (Onwusinkwue *et al*., 2024; Doroshuk, 2021).

Moreover, AI technologies enable superior smart grid management, providing real-time insights into load balancing, outage detection, and the management of distributed energy resources. Smart grids equipped with AI can leverage reinforcement learning to optimize energy distribution based on real-time data, ensuring swift responses to fluctuations in demand and supply (Kuzlu *et al*., 2020; Farzaneh *et al*., 2021). Such flexibility is crucial for the modern energy landscape, which increasingly depends on decentralized and intelligent grid systems (Onwusinkwue *et al*., 2024; Li, 2023).

AI also plays a transformative role in optimizing energy consumption across various settings. For instance, AI integrated into building energy management systems can analyze usage patterns and automate controls to enhance energy efficiency. Commercial and residential AI-powered applications can learn user habits and adjust operations—resulting in significant energy savings (Ali *et al*., 2024: Cihan, 2023). In industrial contexts, AI can time production processes to align with lower energy costs during off-peak hours or when renewable energy availability is high, thereby contributing to sustainability objectives (Farzaneh *et al*., 2021; Ali *et al*., 2024; Pu, *et al*., 2021).

Real-world applications underscore AI's transformative potential in the energy sector. Noteworthy examples include Google's implementation of AI within its data centers, which resulted in a significant reduction in energy consumption for cooling through optimized management based on sensor data (Famoti, *et al*., 2025; Onukwulu, *et al*., 2025). Similarly, Xcel Energy has utilized AI for accurate wind energy production forecasting, enhancing scheduling efficiency and reducing carbon emissions (Hamdan *et al*., 2024; Doroshuk, 202). Companies such as Enel and Tata Power have also leveraged AI technologies for predictive maintenance and enhanced customer service capabilities, respectively, showcasing the practical impacts of AI on operational efficiency (Hamdan *et al*., 2024; Doroshuk, 2021; Cihan, 2023).

In conclusion, AI stands as a strategic enabler of energy sustainability through its applications in predictive maintenance, demand forecasting, smart grid management, and energy consumption optimization. The evidence presented through various case studies reaffirms the significant benefits AI can deliver in reducing environmental impacts while enhancing operational efficiencies (Odunaiya, Soyombo & Ogunsola, 2021). As energy systems transition toward a data-intensive future, addressing challenges related to data privacy, algorithm transparency, and workforce development will be crucial for realizing AI's full potential in this field (Rajamallaiah, *et al*., 2024).

2.3 Wireless electricity generation and transmission

Wireless electricity generation and transmission represent a transformative approach to energy delivery, providing innovative solutions that challenge conventional wired infrastructure. As the global community strives for sustainable and flexible energy systems, wireless power technologies have emerged as promising innovations capable of revolutionizing energy accessibility, particularly in remote or underserved regions (Rajitha & Ram, 2024). This aligns with broader sustainability goals aimed at minimizing environmental impacts and enhancing energy equity, which are crucial for advancing technologies such as artificial intelligence (AI) and the Internet of Things (IoT) (Nnamdi & Asianuba, 2023; Ahmed *et al*., 2015).

The concept of wireless electricity transmission has historical roots tracing back to pioneers such as Nikola Tesla, whose experiments with devices like the Tesla coil laid foundational principles for modern wireless power transfer technologies. Tesla's vision of transmitting energy without wires foresaw reduced dependency on extensive grid systems, a vision limited by contemporary technological constraints (Oladipo, Dienagha & Digitemie, 2025: Rathor & Saxena, 2020). Recent advancements in materials science, electronics, and communication technologies have revitalized this field, making it feasible to explore previously theoretical concepts of wireless energy transfer (Ahmed *et al*., 2015; Triviño-Cabrera *et al*., 2018).

Among the key technologies in wireless power transmission is resonant inductive coupling, which operates on the principle of electromagnetic resonance between two tuned coils, enabling efficient energy transfer for applications ranging from consumer electronics to electric vehicles (EVs) (Rui, *et al*., 2019). This method serves as a practical solution for various applications, including wireless charging in mobile devices and electric vehicles. Research indicates this technology's maturity in the context of EV charging, where it enhances user convenience and safety by eliminating the need for physical connections (Triviño-Cabrera *et al*., 2018; Hatchavanich *et al*., 2020; Liu & Zhang, 2023).

Another innovative approach is microwave power transmission, utilizing microwave radiation beamed to a rectenna to convert microwave energy back into electricity. This method promises long-range energy delivery, making it attractive for applications that require power in hard-to-reach areas or during emergencies when traditional services are disrupted. Limited field deployments of microwave power transmission have shown promise, and future developments may enable energy distribution across significant distances, including potential applications involving space-based solar power (Ko & Jang, 2013).

Laser-based energy transfer is yet another method that employs directed beams of light for energy transmission. Although this technology can achieve high energy density and is suited for applications requiring line-of-sight power delivery (such as UAVs), it faces challenges such as alignment sensitivity and atmospheric interference, which are critical for safe and effective operation (Saeed, *et al*., 2021; Sama *et al*., 2012). Collectively, these technologies reflect a significant shift in energy paradigms, offering promise in contexts where traditional infrastructure is either insufficient or impractical.

The advantages of wireless electricity generation and transmission are manifold, primarily characterized by reduced infrastructural dependency and lower installation costs. This is particularly advantageous for rural and remote regions where extensive grid networks are economically unfeasible (Sahoo & Kishore, 2020). Wireless systems afford flexibility, enabling devices to operate without cords and facilitating applications such as dynamic vehicle charging while in motion or powering healthcare devices directly (Hatchavanich *et al*., 2020; Liu & Zhang, 2023).

However, the widespread implementation of wireless power technologies faces several challenges. Key among these is the issue of energy loss during transmission, particularly affecting the efficiency of microwave and laser-based systems over longer distances. Safety concerns related to human exposure to high-frequency electromagnetic fields and lasers necessitate well-defined regulatory standards and robust safety protocols (Takahashi *et al*., 2013; Olukotun *et al*., 2019). Additionally, the costs of technology deployment and the need for standardized protocols across different manufacturers are significant hurdles that must be addressed for broader market applicability (Hsieh *et al*., 2017; Sergeev & Матренин, 2023).

Finally, the reliability of wireless power systems can be significantly influenced by environmental conditions and the presence of other electronic devices. Innovations in control systems, particularly those leveraging AI, offer promising avenues for enhancing the operation and safety of wireless power systems by adapting to real-time conditions and improving operational efficiency (Nnamdi & Asianuba, 2023; Ahmed *et al*., 2015). As research and development advance, addressing these barriers will be crucial for facilitating the transition toward a more wireless energy future, bridging the gap between aspiration and operational reality.

In conclusion, the evolution of wireless electricity generation and transmission technologies is reshaping energy distribution, offering flexible and sustainable alternatives to traditional wired systems. By addressing the challenges of efficiency, safety, and standardization, stakeholders can pave the way for a future where wireless power significantly contributes to global energy sustainability efforts (Shaban, *et al*., 2021).

2.4 Synergy between AI and wireless power systems

The integration of Artificial Intelligence (AI) and wireless electricity systems is a transformative trend in the realm of sustainable energy solutions. This advancement is pivotal in addressing the evolving demands of energy systems that increasingly lean towards decentralization, digitization, and dynamic capabilities. AI enhances the intelligence and adaptability of wireless power transmission systems, leading to improved performance, reliability, and scalability (Shafiullah, *et al*., 2022). For instance, in the integration of electric vehicles with wireless technology, AI utilizes sensor data to optimize performance and automate decision-making processes in real-time. Such advancements signify substantial improvements in energy systems, particularly as they adapt to the complexities associated with non-contact power delivery systems where real-time decision-making is crucial (Srinivas *et al*., 2023).

AI's role in providing real-time monitoring and adaptive control is indispensable, especially in systems prone to variability and interference. Methods such as resonant inductive coupling and microwave transmission necessitate precision for optimal energy transfer. AI algorithms can analyze performance metrics from various sources, thereby facilitating dynamic optimization and efficient power management (Kumar *et al*., 2023; Sharma, *et al*., 2019). For example, in resonant inductive systems, real-time monitoring allows adjustments in coil alignment and load changes, which ensures that the system sustains resonance and optimizes energy transfer. Similar adjustments are required in microwave-based transmission systems to adapt to environmental changes, which is essential for applications involving electric vehicles where static configurations prove impractical (Srinivas *et al*., 2023).

The incorporation of AI with the Internet of Things (IoT) creates an intelligent energy ecosystem, enhancing how devices communicate and manage power distribution. AI acts as a central coordinator, analyzing real-time data from interconnected devices to ensure seamless energy flow. For example, in smart homes, AI can dynamically control energy delivery based on real-time occupancy and usage patterns, optimizing energy conservation and reducing costs (Rosati *et al*., 2022; Shukla, *et al*., 2024). Urban infrastructure also benefits from this synergy; AI can work alongside smart traffic management systems to prioritize power delivery to electric public transport during peak hours, thus maintaining a balance between energy supply and demand without overwhelming the existing infrastructure.

Moreover, AI is critical in optimizing power delivery and load balancing across wireless electricity systems, especially in settings where multiple receivers share energy resources. By analyzing real-time demand and adjusting energy allocation dynamically, AI can prevent overloads and improve efficiency (Moutsinas & Guo, 2020; Soares, *et al*., 2018). Predictive diagnostics empower AI to forecast and manage faults in wireless energy systems more effectively than traditional methods. Machine learning algorithms can detect anomalies by scrutinizing sensor data, allowing for proactive maintenance and resource allocation during critical demand periods, thereby extending the life of system components (Bai *et al*., 2018; Sinsel, Riemke & Hoffmann, 2020).

Furthermore, the ability of AI to monitor environmental conditions is particularly beneficial in contexts such as laser or microwave-based transmission systems, where safety concerns are paramount. By tracking potential obstacles and adjusting energy beams in real-time, AI systems ensure compliance with safety regulations, enhancing public trust in wireless power technologies (Sumarmad, *et al*., 2022; Zeng *et al*., 2019). In industrial applications, where automation is key, AI facilitates uninterrupted wireless charging of equipment, aligning with the objectives of Industry 4.0 to enhance productivity and minimize downtime (Guo *et al*., 2020).

Lastly, the interplay between AI and wireless power systems aligns with broader sustainability goals by improving energy efficiency, reducing dependence on physical infrastructure, and facilitating renewable energy deployment, especially in remote areas. By ensuring that energy generated from renewable sources is utilized effectively, AI contributes significantly to optimizing energy management and minimizing operational losses (Kou, 2022; Touma, *et al*., 2021). As demand for intelligent energy solutions escalates, the integration of AI and wireless electricity systems is on the cusp of becoming a foundational element of sustainable energy infrastructures worldwide.

2.5 Sustainable applications and future opportunities

The integration of wireless electricity generation, artificial intelligence (AI), and renewable energy technologies signifies a transformative shift in the global energy landscape. These technologies align closely with the global movement towards low-carbon development, enhancing the efficiency, accessibility, and adaptability of energy systems across various sectors (Twaisan & Barışçı, 2022). Wireless electricity systems can play a critical role in reducing reliance on fossil fuels, particularly when integrated with AI algorithms that optimize energy distribution and consumption patterns. Advancements in wireless power transfer (WPT) can facilitate the charging of electric vehicles (EVs) and smart appliances in homes, thereby promoting energy efficiency and reducing carbon footprints (Awaar *et al*., 2023; Mohamed *et al*., 2022; (Ahmad *et al*., 2018).

One promising aspect of wireless electricity is its potential to enhance renewables' integration into power grids. Traditional power transmission often struggles with the inherent variability of renewable sources such as solar and wind energy, which are typically situated far from consumption centers. Wireless electricity generation technologies offer a solution by enabling efficient energy transfer without extensive physical infrastructure. AI enhances this capability by applying real-time data analytics and predictive forecasting to manage energy loads dynamically (Rayan *et al*., 2023; Gao, 2023; Hanashi *et al*., 2011). For instance, wireless systems utilizing solar energy can provide power directly to nearby buildings, with AI regulating the supply in response to weather changes and demand fluctuations, which is essential for managing the intermittent nature of renewable energy sources (Awaar *et al*., 2023; Gao, 2023).

In urban contexts, wireless electricity generation can enhance the functionality of smart homes and EVs. Equipping homes with wireless power capabilities, coupled with AI-driven smart energy management systems, can optimize energy consumption based on occupant behavior and instantaneous energy availability (Ahmad *et al*., 2018; (Cruz *et al*., 2023). Furthermore, wireless charging solutions for EVs, which can be integrated into roadways or parking spaces, facilitate charging without the need for cables and ensure that vehicles can recharge during off-peak periods or when renewable energy is abundant (Doan *et al*., 2018; Amjad *et al*., 2022). Such systems enhance convenience for users and promote the efficient use of renewable resources.

The healthcare sector also stands to gain from these advancements in wireless electricity and AI. Medical devices that typically rely on batteries for power, such as wearable health monitors and implantable sensors, can benefit from wireless charging systems, reducing the need for regular battery replacement and invasive procedures (Alam *et al*., 2019). AI can continuously monitor the operational status of these devices to ensure effective functioning and alert caregivers in real-time, thus improving patient care. Hospitals, utilizing wireless power systems, can ensure a consistent power supply to critical medical equipment, especially during emergencies, showcasing another layer of reliability vital in high-stakes environments (Alam *et al*., 2019).

In terms of rural electrification, wireless electricity generation can provide a much-needed solution to underserved populations. Many rural areas lack access to reliable electricity due to infrastructure challenges and high costs associated with extending traditional power lines (Cruz *et al*., 2023. By deploying localized renewable energy systems, like solar microgrids that operate wirelessly, sustainable energy access can be achieved efficiently and at a lower cost. AI plays a pivotal role in managing these decentralized systems, optimizing performance, forecasting demand, and scheduling maintenance (Hanashi *et al*., 2011). For example, a community can harness energy from a localized solar installation, with AI systems ensuring equitable energy distribution to homes, schools, and clinics (Cruz *et al*., 2023)

In disaster response scenarios, wireless electricity presents a promising avenue for delivering essential services when conventional infrastructure is compromised. Portable wireless power systems can be deployed rapidly to restore power to critical services during emergencies, with AI resources intelligently prioritizing energy distribution based on demand scenarios (Shin *et al*., 2014; Sultana *et al*., 2016). For instance, energy can be allocated effectively to field hospitals for life-support systems while directing power to less critical applications intermittently, ensuring that the most urgent needs are addressed first.

Looking to the future, the decentralization of energy through wireless systems, supported by AI, is likely to foster new energy paradigms. The evolution towards microgrids and decentralized networks can enable peer-to-peer energy transactions, with homes equipped to trade excess renewable energy with neighbors, maximizing efficiency and reducing reliance on traditional grids (Cruz *et al*., 2023; Hanashi *et al*., 2011). In off-grid settings, these systems can deliver clean, sustainable electricity for various applications while adapting to the dynamic needs of users, showcasing an inherent resilience that can respond effectively to challenges such as geographic barriers or natural disasters (Cao *et al*., 2018; Hanashi *et al*., 2011).

In summary, the combination of wireless electricity generation, AI, and renewable technologies not only facilitates a transition to cleaner energy sources but also enhances efficiency, resilience, and inclusivity in energy access. By addressing critical challenges in urban environments, rural electrification, healthcare, and disaster response, these innovations promise to significantly reshape how energy is produced, managed, and consumed globally.

2.6 Challenges and considerations

As the global energy landscape shifts towards sustainable systems enhanced by artificial intelligence (AI) and wireless electricity generation, it is crucial to address various challenges inherent to this technological convergence. Wireless power transfer (WPT) technologies exhibit expansive potential to improve energy management, access, and efficiency, yet they also bring significant barriers to large-scale implementation. Key issues include energy efficiency and transmission losses, health and safety concerns, lack of standardized practices, complex regulatory frameworks, and vulnerabilities in data security and AI reliability.

One prominent challenge in wireless electricity generation involves the inherent energy inefficiencies and transmission losses. Unlike conventional wired systems that maintain high efficiency over short to medium distances, wireless systems can suffer significant power loss, particularly over greater distances or misaligned coils. Studies show that resonant inductive coupling, commonly utilized for WPT, requires precise alignment between coils to optimize energy transfer; any misalignment can lead to considerable efficiency losses (Zeng *et al*., 2017), (Jiang *et al*., 2021). Moreover, in radiofrequency and microwave transmission systems, energy conversion processes introduce additional stages of inefficiency as electricity is transformed into electromagnetic waves and back again. Jiang *et al*. emphasize that such energy losses render wireless power methods less competitive with traditional transmission methods, especially for high-power or long-distance applications (Jiang *et al*., 2021).

In addition to energy losses, environmental interference poses significant barriers to the applicability of wireless electricity. Various conditions—such as rain, fog, or obstacles like metal objects—can distort electromagnetic fields, further diminishing system efficiency (Wang & Lu, 2016). Zeng *et al*. highlight how advancements in communication and signal processing might mitigate these challenges but underscore those fundamental constraints posed by physics, particularly at greater distances, remain critical factors requiring ongoing research and innovation (Zeng *et al*., 2017).

Health and safety issues are paramount in the deployment of wireless electricity systems. High-frequency electromagnetic fields generated during power transmission could pose risks to human health, potentially causing burns or damage to biological tissues if not carefully managed (Lokhande, 2022; Gao *et al*., 2015). Systems employing microwave or laser-based methods are particularly sensitive, as safety protocols must be stringently observed to prevent accidental exposure in densely populated environments. Furthermore, there exists the risk of electromagnetic interference impacting sensitive medical devices and communication systems. To ensure public safety, designers of WPT systems must implement robust safety mechanisms, informed by real-time environmental sensing and AI capabilities, to adjust or shut down systems when humans or objects enter transmission fields (Lu *et al*., 2016).

The lack of universal standardization and the complexity of regulatory environments also hinder the widespread adoption of wireless electricity generation. Current standards are fragmented due to the nascent stage of wireless power technology, resulting in a marketplace where devices from different manufacturers may not be compatible (Niotaki *et al*., 2023). The development of comprehensive standards, supported by organizations like the Wireless Power Consortium and IEEE, is essential for promoting interoperability and facilitating the growth of wireless systems (Lu *et al*., 2016). Additionally, existing regulations may not sufficiently address the nuances of modern technologies, requiring updates to ensure the safe and effective deployment of WPT systems.

From a cybersecurity perspective, the increasing reliance on AI for optimizing power management in these systems presents another layer of complexity. The need for real-time data processing opens pathways for potential cyber threats, where malicious actors could disrupt energy delivery or compromise system integrity (Yue *et al*., 2023). Strengthening data security involves end-to-end encryption, secure authentication protocols, and continuous monitoring to detect and react swiftly to intrusions. However, transparency and reliability of AI systems remain pressing concerns. AI algorithms, often characterized as "black boxes," can yield unpredictable outputs if not appropriately managed. Establishing norms for ethical AI use in energy applications, alongside rigorous validation processes, is crucial for mitigating risks associated with AI-driven systems (Bocan & Sejdić, 2016).

In summary, while the integration of AI and wireless power technologies holds immense potential to reshape energy access and efficiency, it necessitates careful consideration of various critical challenges. These challenges include transmission inefficiencies, health and safety risks, the lack of standardized practices, and concerns related to data security and AI reliability. Addressing these barriers will require collaborative efforts across research, industry, and regulatory bodies, aiming for a safe and efficient transition to intelligent energy systems that will revolutionize power management in the contemporary world.

3. Conclusion

The integration of energy sustainability, artificial intelligence (AI), and wireless electricity generation presents a transformative opportunity to redefine how energy is produced, transmitted, and consumed in the modern era. Throughout this exploration, it has become clear that these three domains, when combined, form a powerful framework capable of addressing some of the most pressing energy challenges of our time. AI enhances the intelligence and responsiveness of energy systems, enabling predictive maintenance, smart grid management, demand forecasting, and consumption optimization. Wireless electricity generation introduces flexibility and mobility in energy transmission, offering new ways to deliver power without the constraints of physical infrastructure. When these technologies are anchored in sustainable principles—prioritizing environmental responsibility, energy access, and long-term efficiency—the result is a holistic solution poised to accelerate the global energy transition.

The potential impact of this synergy on global sustainability goals is profound. Energy is central to achieving many of the United Nations Sustainable Development Goals (SDGs), especially SDG 7, which seeks to ensure access to affordable, reliable, sustainable, and modern energy for all. By combining AI and wireless power with renewable energy sources, we can extend clean energy access to underserved communities, reduce dependence on fossil fuels, and support climate action efforts aligned with SDG 13. These technologies also support innovations in healthcare, education, transportation, and industry, contributing to broader social and economic development. Furthermore, the creation of decentralized and intelligent energy systems enhances resilience, empowers local communities, and fosters inclusive growth, which are all critical components of a sustainable future.

To realize these benefits at scale, targeted actions must be taken. Policymakers should prioritize the development of regulatory frameworks that promote innovation while ensuring safety, equity, and environmental protection. Investments in research and development are essential to improve the efficiency, scalability, and affordability of AI and wireless power technologies. Academic institutions, industry leaders, and governments must collaborate across disciplines to bridge knowledge gaps, build public trust, and create integrated solutions that reflect real-world complexities. By fostering such interdisciplinary cooperation and forward-thinking policy, we can harness the full potential of these technologies to create a cleaner, smarter, and more sustainable world.

4. References

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