Multidisciplinary Journal of TUM 4(1) 2025 81-92 https://doi.org/ 10.48039/mjtum.v4i1.91.g109 **Review Article**

Integrating Digital Transformation and Technological Innovation for Sustainable Renewable Energy Systems: The Role of AI, IoT, and Blockchain in Enhancing Efficiency and Grid Stability

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Abstract

Renewable energy and grid stability systems are transforming because of digital innovation and novel advancements. This necessitates studying advancements within the renewable energy sector through digital technologies, including artificial intelligence (AI), the Internet of Things (IoT), and blockchain. The advancements allow real-time monitoring, predictive maintenance, and decentralized energy management, thus increasing renewable energy systems' efficiency, sustainability, and dependability. This review was based on how AI integrated with IoT technology and blockchain improves the operational efficiency of renewable energy systems. The PRISMA 2020 guidelines were adopted in this systematic review, and 433 articles from databases such as IEEE Xplore, Science Direct, Google Scholar, and Springer Link were retrieved. After the inclusion and exclusion criteria, 10 (n=10) articles were selected. The quality assessment of the studies was done using the Critical Appraisal Skills Program (CASP) tool. Among the included studies, 70% *(n=7)* demonstrated that AI achieved efficiency improvements, IoT role optimization of grids was shown in 60% *(n=6)* of studies and blockchain impact on energy trading in 50% *(n=5)*. In addition, cost reductions were documented in 80% *(n=8)* of studies, while 90% (*n=9)* reported security and regulatory challenges during implementation. The findings revealed that the efficiency of renewable energy and grid stability was improved by adopting digital solutions such as AI, IoT, and Blockchain. However, the gaps demonstrated in the study prompt the need to develop policy interventions and conduct further research to reduce technological and regulatory barriers to a sustainable energy transition.

Key Words: Digital transformation, Renewable energy, Artificial Intelligence and IoT, Blockchain.

Introduction

In the last century, concerns have increased about humanity's energy consumption, especially fossil fuels such as coal and oil, and methane emissions, owing to their effects on climate change (Parmesan et al., 2022); (Welsby et al., 2021). Human energy use has increased by about 1.3°C (compared to pre-industrial levels) (Wang et al., 2023). Climate change currently poses changes in the occurrence and severity of extreme weather events, particularly heat waves, droughts, and floods, which threaten agricultural productivity and food and water security (Singh et al., 2025). In addition, it also influences the degradation of ecosystems, biodiversity loss, and economic inequalities, increasing global disparities (Marzouk, 2025). These growing challenges have prompted policymakers, researchers, and the public to contemplate shifts towards sustainable energy solutions. Recent progress in clean energy technologies offers a pathway toward a successful energy transition, but the remaining barriers are immense. For example, the climate action agenda set at COP28 2023 highlights significant reductions in wind power, solar energy, and electric vehicle costs (Wang et al., 2023). Therefore, experts have suggested an energy transformation pathway with widespread adoption of and electrification by renewable energy (Meinshausen et al., 2022). However, these goals will not be fully realized in the

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following decades due to unresolved technical and financial issues such as the intermittent nature of renewables, high infrastructure costs, and integrating electrification into existing grids (Levin et al., 2023).

There is also a transformation of the energy landscape in response to the urgency to decarbonize from climate change to achieve energy access and sustainability. Decentralized, renewable, and digitalized alternatives have challenged traditional centralized energy systems based on fossil fuels. The transformation is critical to achieving the United Nations Sustainable Development Goal 7 (SDG 7) for universal access to reliable, affordable, and sustainable energy by 2030 (Yang et al., 2024). Even with these ambitious goals, almost 733 million people worldwide remain without electricity, while millions more are confronted with unreliable supply, and what is needed is innovative and scalable solutions (Ou et al., 2024). Digital transformation (DT) is taking centre stage to address these challenges since it transforms energy production, distribution, and consumption and optimizes grid stability by enabling the integration of advanced technologies like artificial intelligence (AI), the Internet of Things (IoT), and Blockchain. They also allow the transition of a 3D energy system, decentralized, decarbonized, and digitalized (3D) (Groll, 2023), with improved efficiency, reliability, and resiliency (Yaan et al., 2024). These methods offer the energy management paradigm since they facilitate renewable energy integration and optimize system operations while improving grid stability.

Predictive analytics, demand forecasting, and real-time optimization of energy flows are leading to a revolution in the energy sector through artificial intelligence (AI). AI-driven models analyze considerable datasets to improve grid stability and aid in integrating variable renewable energy resources like wind and solar. The AI algorithms have also been used to optimize surplus energy distribution among solar home systems interconnected via swarm electrification, making global energy efficiency and scalability possible (Liu & Liu, 2024). IoT complements AI-powered solutions by creating an interlinked network of smart devices that collect and transmit energy-related data. With smart meters, sensors, connected appliances, and other technologies, energy providers and consumers can gain real-time insights and maximize electricity use. The IoT-based system allows two-way communication between smart grids and energy-sharing communities. Especially in rural electrification projects, IoT is critical for the continuity of system operation and generating actionable information for the operators (Huang & Liu, 2024).

Blockchain opens secure, transparent, and decentralized peer-to-peer (P2P) energy trading in the energy markets. With the help of blockchain-based platforms, consumers can become prosumers by selling surplus renewable energy produced from sources like rooftop solar panels to other users. Decentralized trading platforms can potentially create scalable, democratized energy systems based on local energy autonomy (Yang et al., 2024). Swarm electrification introduced by Groll (2023) constitutes a promising model of decentralized energy expansion. This approach links Solar home systems (SHSs) to make them part of modular microgrids that can scale from small, standalone units to integrated national grids. The model has a four-phase evolution from individual SHS installations to interconnected local grids integrated into central energy grids. Such a flexible and scalable model is appropriate for electrification in marginalized regions (Karakurt & Aydin, 2023).

Related Studies

The innovations in digital technologies have revolutionized smart grids, renewable energy systems, and demand response. There have been several studies on the role played by artificial intelligence (AI), Blockchain, and the Internet of Things (IoT) in contemporary energy systems. Entezari et al. (2023) conducted a broad review of AI and ML-based energy management applications in ML and energy-related domains, and they demonstrated research gaps in the areas where ML can help energy systems. Li et al. (2023) also studied big data (BD) and AI applications in energy management and their links. In Zhang et al. (2022), AI in renewable energy is presented through a bibliometric analysis. Shareef et al. (2018) researched home energy management with demand response and schedule controllers based on AI. Demand response has also been extensively analyzed from the viewpoint of the role of AI. Wang et al. (2018) observed that multi-agent systems are considered in smart grids, and meter data analytics for demand response programs were investigated. Antonopoulos et al. (2020) reviewed AI techniques in demand response schemes and their role in power system operations. Ali and Choi (2020) determined AI's role in integrating renewable energy sources (RES), energy storage, and grid security, while Szczepaniuk and Szczepaniuk (2022) examined their respective applications in grid stability, fault detection and protection, cybersecurity, power loss minimization, and fault diagnosis. Widespread studies on IoT-enabled smart grids have also been done. Abir et al. (2021) stated that smart grids are reviewed in terms of IoT technologies' sensing, communication, and computing aspects. Qays et al. (2023) also provided a detailed analysis of IoT communication technologies and applications, while Ghasempour (2019) highlighted the relationship between IoT and energy management.

Methodology

This section covers the structured process of reviewing the impact of digitalization on the role of AI, IoT, and Blockchain in Enhancing Efficiency and Grid Stability. The PRISMA 2020 guidelines were followed to conduct the methodology systematically and transparently (Page et al., 2021). Several key phases were involved, including data retrieval, selection criteria, and a bibliometric analysis using advanced software tools (Kitchenham et al., 2009). The systematic review was conducted using a well-defined process. A structured search strategy was applied to perform a comprehensive literature search to acquire the relevant studies (Wang et al., 2025). After that, a filtering process was conducted according to specific inclusion and exclusion criteria to keep the review focused. An approach was taken to formulate research questions guided by the study, based on the relevant literature that had been identified. The findings were analyzed, and specific emphasis was on key contributions, research gaps, and challenges (Wang et al., 2025). Systematic synthesis and categorization of results from selected studies in terms of thematic areas covering the impact of digitalization on smart grids, renewable energy, and demand response were carried out.

Data Sources and Search Strategy

A literature search was conducted using IEEE Xplore, Science Direct, Google Scholar, Springer Link, and top databases for peer-reviewed academic research to verify cross-database search and ensure the review was as comprehensive and rounded as possible. This approach minimized the risk of failing to include relevant studies and considering a broad perspective. The search strategy involved formulated questions that captured studies on digitalization in energy systems. The keywords used in the search are related to digital technologies' applications in energy systems. A search was performed using the following terms: (Digitalization, OR Internet of Things OR IoT OR Artificial Intelligence OR AI OR Blockchain OR Digital Twin) AND (Grid Stability OR Renewable Energy OR Demand Response OR Smart Grid). Using these search terms to retrieve studies on various aspects of digital transformation in energy management demonstrates that the review considered studies covering the field's most relevant and impactful research.

The inclusion and exclusion criteria were used to reduce the selection of studies in this review. The inclusion criteria were based on:

- Studies published in peer-reviewed journals and conference proceedings, written in English.
- Research was published between 2019 and 2025 to ensure the inclusion of recent developments in digitalization.
- Articles that examine digital technologies within the context of smart grids, renewable energy, and demand response.

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- Studies that discuss applications, case studies, and system integration of digital technologies in energy systems.

The exclusion criteria were based on:

- Opinion pieces, short articles, conference abstracts, and posters.
- Studies that focus on digital technologies without clear relevance to energy systems or demand response.
- Non-peer-reviewed or unpublished research.

Bibliometric Analysis

A bibliometric analysis was conducted to identify significant trends, research gaps, and influential studies in this domain (Wang et al., 2025). The data requested for this analysis and the research problem were downloaded in CSV format and contained article titles, abstracts, keywords, and citation information. The dataset was finalized to include pertinent studies, especially the most cited papers and those that best capture the recent developments in the digitalization of the energy sector. The systematic review ended with a comprehensive synthesis of selected research findings that were grouped into thematic areas of the impact of digitalization on smart grids, renewable energy, and demand response. This approach offered a clearer idea about what is happening in this field, its current applications, and its future. The quality assessment of studies was conducted using the critical appraisal skills programme (CASP) tool, as (Long et al. (2020) elaborated. Meta-analysis was conducted to determine the effect estimates of two or more studies and was typically based on calculating a weighted average (Bond et al., 2024). The Statistical Package for the Social Sciences (SPSS) version assisted in conducting a meta-analysis to interpret results adequately, especially for higher-order meta-analytical approaches (Thomas et al., 2023).

This present study investigated the elements of digitalization related to smart grid, renewable energy, and demand response through essential technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), and Blockchain. This review analyzes how these technologies benefit energy efficiency, reliability, and sustainability while highlighting key challenges, such as cybersecurity risks and integration complexities. These research questions were formulated according to Cummings et al. (2007 and 2013) to guide this investigation: how do AI, IoT, Blockchain, and Digital Twins improve smart grids, renewable energy, and demand response?; what challenges hinder the adoption of these technologies in energy systems?, and what emerging trends are shaping digitalization in the energy sector?

Results

Study Characteristics

From databases such as IEEE Xplore, ScienceDirect, Google Scholar, and Springer Link, the review retrieved 433 articles. After duplicates were removed, 320 articles remained and were screened, with 105 articles excluded based on relevance to titles and abstracts. A full-text review was performed using inclusion and exclusion criteria, and 32 studies were further selected. Once quality and alignment with the research scope had been assessed for all 39 papers, 10 were included in the systematic review (n=10 studies) (Figure 1).

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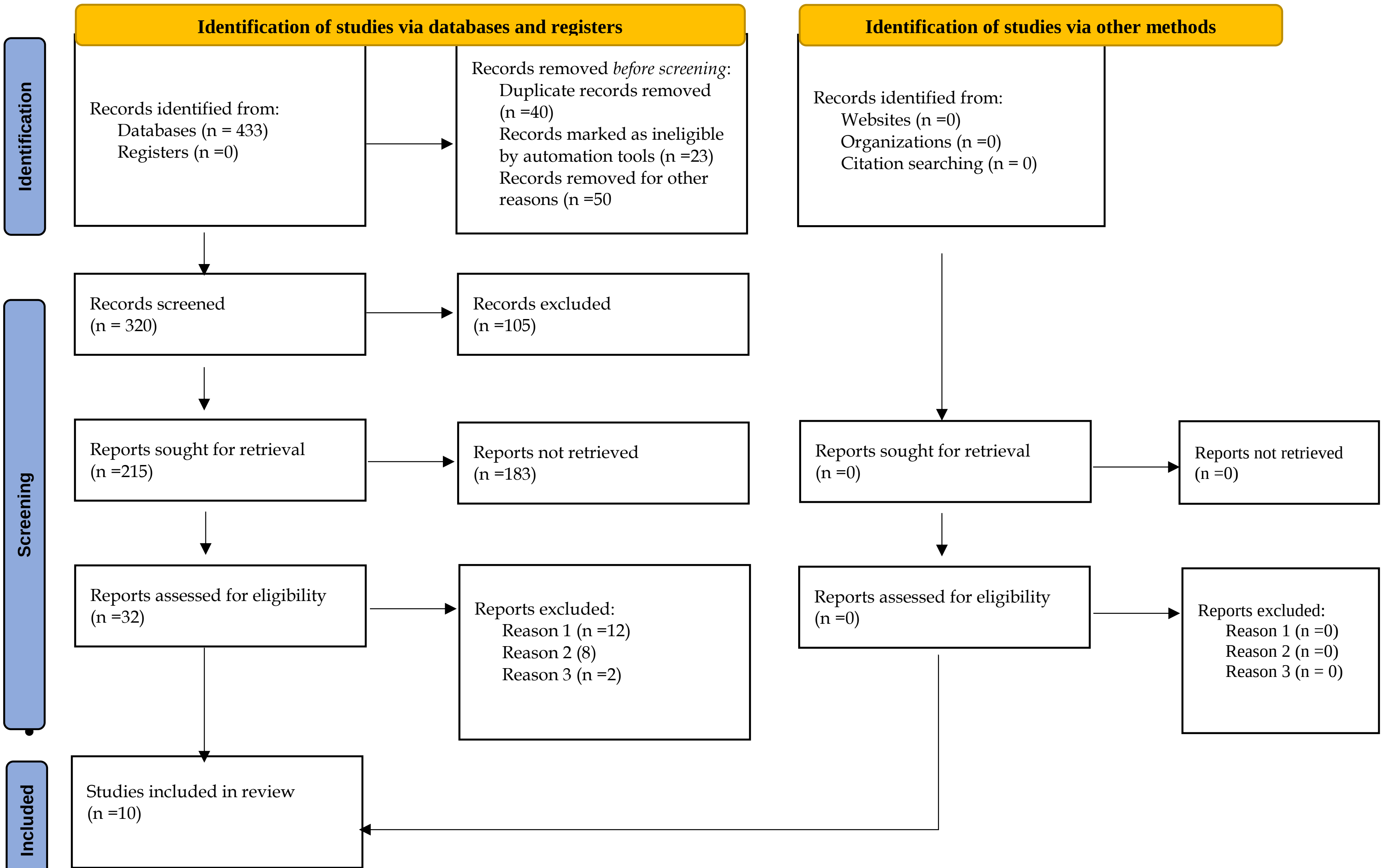

Figure 1. PRISMA 2020 Diagram (Included Studies) Page et al., (2020)

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Study Narrative

Among the included studies, 70% (n=7) demonstrated that AI achieved efficiency improvements, and IoT role optimization of grids was shown in 60% (n=6) of studies, with blockchain impact on energy trading in 50% (n=5). In addition, cost reductions were documented in 80% (n=8) of studies, while 90% *(n=9)* reported security and regulatory challenges during implementation (Table 1).

Table 1. Included reviewed literature

Study	Authors and Year	Objectives	Study Design	Key Findings	Limitations
Climate change 2022: Impacts, adaptation and vulnerability	Parmesan, C., Morecroft, M. D., & Trisurat, Y. (2022)	To examine climate change impacts, adaptation strategies, and vulnerabilities	Literature review	Highlights significant climate risks and adaptation measures across regions.	Limited to available data, no primary research
Integrating artificial intelligence in energy transition: A comprehensive review	Wang, Q., Li, Y., & Li, R. (2025)	Investigating AI's role in optimizing energy transitions	Systematic review	AI enhances energy efficiency, forecasting, and grid stability	Focuses on existing AI applications, lacks empirical validation
Climate change impacts plant pathogens, food security, and paths forward.	Singh, B. K., et al. (2023)	Assess the effects of climate change on plant pathogens and food security	Review and synthesis of research	Climate change alters pathogen dynamics, affecting food production	Limited real-world testing of proposed solutions.
Accelerating the energy transition towards photovoltaic and wind in China	Wang, Y., et al. (2023)	Analyze the role of photovoltaic and wind energy in China's transition	Empirical and modelling study	China can significantly reduce emissions through renewables	Assumes current policies remain unchanged
Realization of Paris Agreement pledges may limit warming just below 2°C.	Meinshausen, M., et al. (2022)	Assess the impact of Paris Agreement pledges on global warming	Climate modelling study	Current commitments could limit warming to just below 2°C	Uncertainty in policy implementation
Energy storage solutions to decarbonize electricity through enhanced capacity expansion modelling	Levin, T., et al. (2023)	Investigate energy storage solutions for decarbonization.	Modeling study	Storage solutions improve grid reliability and decarbonization	High infrastructure costs and policy uncertainty
Applying separate treatment of fuel- and air-borne nitrogen to enhance understanding of in-cylinder nitrogen-based pollutants formation	Yang, R., et al. (2024)	Explore nitrogen-based pollutant formation in ammonia-diesel engines	Experimental study	Identifies mechanisms of pollutant formation for emissions control	Limited to specific fuel combinations

Effect of ammonia reaction kinetics on the two-stage ignition mechanism of dimethyl ether	Ou, J., et al. (2024)	Investigate ammonia's reaction kinetics in ignition mechanisms	Experimental study	Ammonia impacts ignition delay and combustion characteristics	Requires further real-world validation
Can climate change be avoided? Vision of a hydrogen-electricity energy economy	Groll, M. (2023)	Explore the hydrogen-electricity economy as a climate solution	Conceptual analysis	A hydrogen economy could reduce reliance on fossil fuels	High costs and infrastructure challenges
Internet of things in smart grid: Architecture, applications, services, key technologies, and challenges	Ghasempour, A. (2019)	Discuss IoT applications in smart grids	Literature review	IoT improves grid efficiency and real-time monitoring	Cybersecurity and data privacy concerns

Risk of Bias

The Critical Appraisal Skills Programme (CASP) tool ensured methodological rigor and reliability as it assessed the risk of bias. The criteria for judging studies were research design, collection methods, and possible conflicts of interest. The inclusion and exclusion criteria were applied to minimize selection bias. Multiple databases were used to source literature and address publication bias. However, some of the studies were unclear in methodology, which might result in a potential risk of bias in interpretation and generalizability of findings (Table 2).

Table 2. Risk of Bias in the reviewed literature

Authors & Year	**Selection Bias**	**Performance Bias**	**Detection Bias**	**Attrition Bias**	**Overall Risk of Bias**
Parmesan et al. (2022)	Moderate	Moderate	Low	Low	Moderate
Wang et al. (2025)	High	Moderate	Moderate	Low	Low
Singh et al. (2023)	Moderate	Low	Low	Low	Low
Wang et al. (2023)	Low	Low	Moderate	Low	Low
Meinshausen et al. (2022)	Moderate	Moderate	High	Low	Moderate
Levin et al. (2023)	Low	Low	Moderate	Low	Low
Yang et al. (2024)	Low	Low	Low	Low	Low
Ou et al. (2024)	Low	Low	Low	Low	Low
Groll (2023)	High	High	High	Moderate	High
Ghasempour (2019)	Moderate	Moderate	Moderate	Low	Moderate

Discussion

Digital technologies have played a continuous and evolving role in the evolution of changing energy management and demand response, enhancing efficiency and smart grid stability strategies. However, combined with these technologies, these advantages provide unique advantages, collectively improving energy efficiency, reliability, and scalability (Wang et al., 2025). Integrating these tools well can allow grids to develop more adaptive, secure, and scalable frameworks to cope with the key challenges.

Artificial Intelligence (AI) and the Internet of Things (IoT) are the biggest combinations. IoT devices like smart meters or sensors can gather real-time data on energy consumption and environmental factors (Rind et al., 2023). This

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data is AI processed to apply predictive analytics, detect anomalies, and facilitate real-time decision-making for improving energy efficiency. IoT devices are always in play in residential and commercial settings to measure energy usage, which AI algorithms analyze to predict future demand and detect consumption patterns. This synergy benefits smart grids, as the AI-driven IoT allows dynamic load balancing to stabilize the grid and prevent overload (Wang et al., 2025). Moreover, IoT data drives AI-powered demand response mechanisms to predict and respond to energy demand fluctuations to optimize resource distribution. These technologies help reduce waste by aligning production with real-time demand, lowering AES operational costs.

Blockchain technology is vital for building an IoT-based application. IoT networks collect increasing amounts of sensitive data; therefore, ensuring secure and transparent data exchange is required. Blockchain's tamper-proof energy transaction ledger technology gives users trust in IoT data sharing. Blockchain can verify the energy flow within smart grids between producers and consumers and reduce manipulation and transparency risks. Blockchain is also used in energy trading with peer-to-peer (P2P) markets, facilitating the trading of excess energy by consumers from those who produce it (Wang et al., 2025). By automating the agreements and eliminating intermediaries, smart contracts streamline these transactions and reach an efficient and transparent energy exchange. Therefore, Blockchain is essential for modelling the city-wide energy consumption between buildings, transportation, and infrastructure on a larger scale. These insights help frame policies for sustainable energy investment and policy development (Mazzetto, 2024). When integrated with AI and IoT, Blockchain enables a holistic view of energy systems that fuel efficient and sustainable energy management. Modern smart grids include multiple energy sources like electricity, gas, and heat as a multi-vector system. Combining AI, IoT, and Blockchain is particularly valuable in these complex environments. The real-time IoT data is used by AI to optimize energy flows across different vectors and to optimize a balanced supply and demand (Kumar et al., 2020). Similarly, Blockchain increases transparency by hashing away energy transaction records. Finally, DTs can improve system management by simulating multi-vector energy interaction under different conditions, such as peak demand or changes in renewable energy availability (Song et al., 2023). This integration allows for more efficient energy resource use and ensures the system is stable and resilient.

While there are advantages, integrating these digital technologies has some challenges. While IoT devices are necessary for gathering data, cyber threats are common. Blockchain security improves over data. However, its high energy consumption is limited, specifically in large-scale deployments. Researchers are developing energy-efficient Blockchain protocols and hybrid security models to alleviate these concerns (Fernández-Caramés & Fraga-Lamas, 2024). Another challenge is scalability, as AI and IoT-based systems produce immense amounts of data that need heavy computation. Edge computing, which processes data near the source, is becoming a potential solution to reduce latency and lighten central servers. Another important issue concerns interoperability, as renewable energy usually involves legacy and new digital systems (Ntafalias et al., 2022). Standardized protocols and cross-platform compatibility are still in progress and do not guarantee seamless integration. Industry-led initiatives are working to bridge the gaps in IoT and Blockchain for energy system standards. These challenges must be addressed to establish a secure and efficient AES infrastructure.

Digitalization is also essential in improving day-ahead energy markets by improving demand forecasting and prediction of renewable energy (Ukoba et al., 2024). Market participants can more accurately pre-empt energy consumption patterns, weather conditions, and renewable energy availability through advanced data analytics and AI-driven models (Singh et al., 2025). The improved forecasting thus allows energy aggregators to optimize their bidding strategies with a better supply and demand balance and maximize efficiency. For example, these sophisticated software tools in Europe enable aggregators to submit real-time bids that

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reflect market conditions (Wang et al., 2025). This ensures that energy resources are deployed correctly. Digitalization is even more necessary in energy markets, transitioning from daily training to intraday trading. Intraday markets enable the participants to optimize energy allocations concerning current developments, like unexpected outages or weather conditions (Cramton et al., 2024). Rapid data exchange and continuous monitoring of energy assets are possible through digital platforms, which enable market players to make decisions quickly. The improved energy market agility facilitates market efficiency, enabling consumers and businesses to engage in energy trading and actively keep the economy sustainable.

Limitations

Due to the evolving nature of digital transformation in renewable energy systems, it is challenging to capture emerging trends in this study. Regulatory policies across regions are uneconomical for generalizing the findings. Furthermore, although AI, IoT, and Blockchain have been explored, the other emerging technologies, quantum computing and 6G networks, have not been thoroughly investigated. Bibliometric analysis can also take qualitative insights from real-world implementations for granted. Scalability issues in integrating digital technologies into existing grid infrastructure must be empirically validated through large-scale pilot projects.

Future Studies

Future work should build such systems on integrating AI, IoT, and Blockchain to increase the efficiency and stability of renewable energy systems. Energy forecasting can be optimized using AI-driven predictive models, and the smart grids with IoT enabled are improved in real-time monitoring and response. With Blockchain facilitating peer-to-peer energy trading, there is still work to do to secure the process. The studies should also investigate these technologies' scalability in large-scale renewable energy networks. Comparative analyses of digital transformation based on regulatory frameworks also offer insights into market-driven digital transformation. Edge computing and quantum technologies should be explored as they can address the computational demands of AI and Blockchain applications.

Conclusion

With AI, IoT, and Blockchain integration, renewable energy systems are transformed into more efficient, stable, and sustainable. AI makes energy forecasting possible, IoT is used for real-time grid monitoring, and Blockchain makes for secure, decentralized energy transactions. Unfortunately, there are challenges like cybersecurity risks, scalability, and regulatory barriers to adoption. There is a need for future advancements in edge computing, AI-driven automation, and blockchain optimization. Digital transformation can create a more resilient, adaptive, and sustainable energy ecosystem by leveraging technological innovation that enables the smooth, decentralized, intelligent transition to a renewable energy grid.

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