Renewable Energy and Industry 4.0: A Comprehensive Review

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DOI: https://dx.doi.org/10.51584/IJRIAS.2025.101100015

Received: 12 November 2025; Accepted: 20 November 2025; Published: 03 December 2025

ABSTRACT

The fast merging of Industry 4.0 (I4.0) technologies with Renewable Energy Systems (RES) is changing the world energy infrastructures into new digitalized, effective, and sustainable energy operations. This paper provides a comprehensive review based on the PRISMA framework in order to explore the role, challenges and opportunities of adopting the I4.0 technologies, including the Internet of Things (IoT), Artificial Intelligence (AI), Big Data analytics, Blockchain and Cyber-Physical Systems (CPS), in renewable energy applications. The review includes peer-reviewed articles published from 2015 to 2025 in academic database such as Scopus, IEEE Xplore, ScienceDirect, and Springer. The results indicate that I4.0 usage leads to improved effectiveness of renewable energy forecasting, predictive maintenance, smart grid management, and data-driven decision-making, resulting in increased efficiency in operations and reduction of emissions. Nevertheless, there are long-standing obstacles like cybersecurity weaknesses, interoperability, infrastructure constraints, and policy-mismatch, that have impeded mass adoption, especially in the developing economies. The paper presents research directions in open research that focus on AI-based optimization, secure IoT design, validation of digital twins, framework-based standardised data, and context-specific policy models. In general, this study highlights the transformative nature of I4.0 in hastening the process of energy transition in the world and meeting the United Nations Sustainable Development Goals (SDGs) by developing sustainable, intelligent, and resilient energy systems.

Keywords: Industry 4.0, Renewable Energy Systems, Artificial Intelligence (AI), Internet of things (IoT), Smart grid.

INTRODUCTION

The accelerated process of industrialization and population increase has added significant stress to the global energy needs and has overwhelmed the conventional fossil fuel sources and enhanced environmental issues like climate change and air pollution (Reddy and Assenza, 2023; Owusu and Asumadu-Sarkodie, 2016). The drawbacks of traditional energy systems, which are typified by inefficiency, depletion of resources and greenhouse gases, have led to a worldwide transition towards renewable energy sources (RES) including solar, wind, hydro and biomass (Panwar et al., 2011). Not only are these energy forms insufficient and unsustainable, they are also the main focus in meeting international climate goals such as the Paris Agreement and the United Nations Sustainable Development Goals (SDGs) especially Goal 7, which proposes affordable and clean energy. Nevertheless, renewable energy systems still have a problem of intermittency, high integration costs, and complicated management of operations (Nerini et al., 2018).

Digital transformation has overcome most of these limitations through the emergence of Industry 4.0 (I4.0), which is the Fourth Industrial Revolution. The Internet of Things (IoT), Artificial Intelligence (AI), Big Data analytics, Blockchain, and Cyber-Physical Systems (CPS) are some of the technologies that are changing the way energy is produced, stored, distributed and used (Shabur, 2024). Industry 4.0 will be able to achieve real-time monitoring and optimization of renewable energy infrastructure to allow it to be more efficient, resilient, and cost-effective through automation, predictive maintenance, and intelligent decision-making (Alsharif et al., 2022). Furthermore, digitalization provides the possibility to develop smart grids and virtual power plants and unite various renewable sources (or systems) into one coherent and evolving system (Zhang et al., 2022).

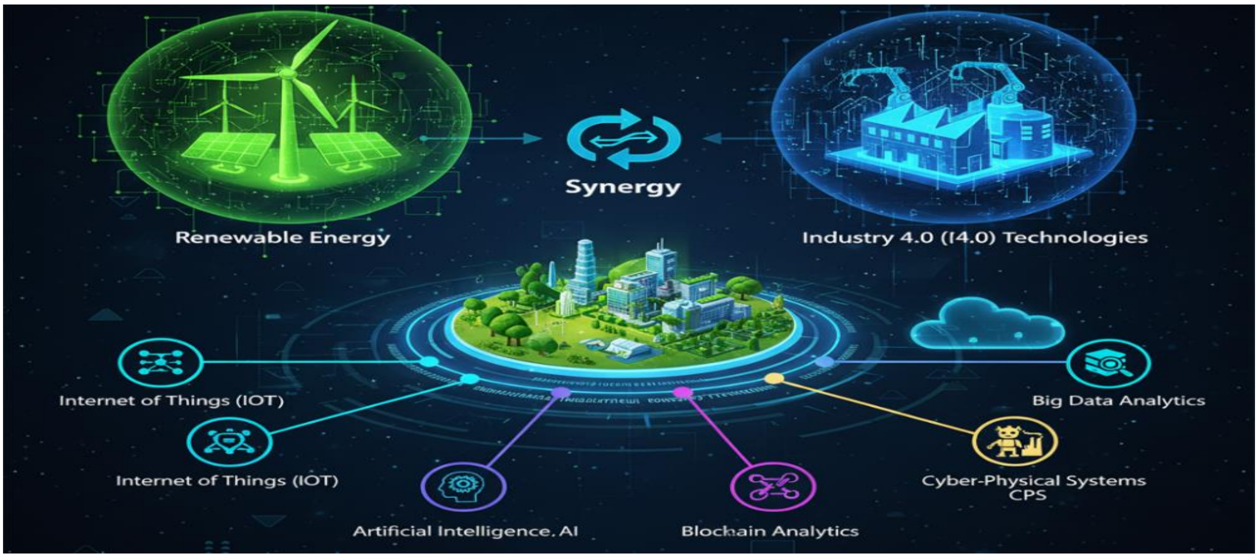
The use of the Industry 4.0 technology in renewable energy has demonstrated some encouraging outcomes globally in enhancing the accuracy of energy forecasting, carbon reduction, and decentralised generation of power. Research has shown that predictive models based on AI lead to optimal energy yield, whereas sensors on IoT devices can be used to pre-empt faults and manage energy on the demand side (Panda et al., 2025). Digital twins and automation technologies have simplified workflows and minimised the use of energy in the industrial environment, making the industrial processes more sustainable. In spite of such developments, the adoption rate is uneven in different regions, and among the developing countries, the lack of digital infrastructure, financial capabilities, and policy gaps are some of the issues that impede extensive implementation of Industry 4.0 in the renewable energy industry (Pandey et al., 2025).

Thus, this study seeks to cognitively discuss the overlap between renewable energy and Industry 4.0 and the role of digital technologies in increasing the pace of migration into the intelligent and sustainable energy infrastructure. The study aims to summarise available material, find patterns, as well as point out useful models that reveal the disruptive potential of Industry 4.0 in developing renewable energies. Moreover, it seeks to resolve the existing issues and give strategic recommendations on how to effectively integrate I4.0 into renewable energy systems especially in the emerging economies. Conclusively, the research paper has added to the increasing research on digital-energy convergence, which provides informed insights on policymakers, researchers, and other industry players interested in enhancing sustainability of global energy through technological advancement.

LITERATURE REVIEW

The literature review investigates the nexus between Renewable Energy and Industry 4.0 (I4.0) technologies, and how they can be used in support of sustainable industrial development and energy transition. It discusses how the digital innovations, including the Internet of Things (IoT), Artificial Intelligence (AI), Big Data analytics, Blockchain, and Cyber-Physical Systems (CPS) transform the production, delivery, and control of renewable energy where their connexions are depicted in Figure 1.

Figure 1: Concept Diagram of Literature Review.



The section provides the synthesis of the discoveries of global and regional researches covering renewable energy forecasting, smart grid integration, digital transformation, and reduction of carbon emissions. It also covers theoretical models and practise applications that evoke the disruptive effect of I4.0 on energy efficiency and sustainability and provides current research gaps and challenges, including cybersecurity, policy preparedness, and infrastructure constraints, which inform the direction to a digitally enabled clean energy future.

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue XI November 2025

Renewable Energy Development and Forecasting

The study by Firlej and Stanuch (2022) is a forecasting research that analyses how the Visegrad Group (V4) countries, including Poland, Hungary, Czech Republic, and Slovakia, develop Renewable Energy Source (RES) in comparison to the context of the European Union energy transition agenda. Based on EUROSTAT data (2004 to 2020) and two econometric models, including HOLT-Winters exponential smoothing, and autoregressive (AR), they forecasted the share of RES in gross final energy consumption until 2024. In their results, their analysis showed that 19 of the 27 EU Member States, two of which were the V4 countries, were in danger of not reaching their 2022 RES targets. The Holt-Winters model predicted a 1.49% annual growth, aligning with the EU's 2030 goal of 40% RES share, while the AR model predicted a slower 0.58% growth. Slovakia had the best growth potential among other V4 whereas Hungary underperformed.

He and Ni (2022) explored the historical connection between energy transitions and industrial revolutions with coal, oil, and nuclear being used to fuel the previous revolutions, and the Fourth Industrial Revolution (4IR) making more use of renewable energy sources like wind and solar. Based on the world statistics of IEA and BP, they found that the adoption of renewable power sources has increased significantly, as the growth of solar electricity has increased by 20 percent and the wind energy sources have given the greatest portion to the renewable growth. The authors inferred that 4IR technologies, especially AI and digital technologies are speeding up the transformation into clean and efficient and sustainable systems of energy.

Industry 4.0 and Renewable Energy Integration

Onu et al. (2023) carried out a transdisciplinary review of how I4.0 technologies, including IoT, AI, and advanced manufacturing, can be useful in managing renewable energy. Their thematic analysis shows that due to I4.0, it is possible to collect data in real-time and make predictive analytics and smart decisions that are essential to optimize energy systems. Nevertheless, there were other difficulties, including the lack of standardization and regulatory limitations, that were found to inhibit mass adoption.

Borowski (2021) has explored the concept of combining digital twins, blockchain, and digitization in management of the energy sector. It was found that digital twins led to real-time optimization and simulation, blockchain to transparent energy trade and digitization of operations led to up to 30 reduction in operational costs. These results indicate the relevance of digital innovation to the realization of sustainability and decarbonization in the energy industry. Scharl and Praktiknjo (2019) also applied the case study approach and examined how Industry 4.0 facilitates integration of renewable using digital transformation by using Germany as a case study. Their qualitative interviews were able to identify three fundamental capabilities of I4.0, which included enhancing transparency with the help of digital twins, facilitating demand-side flexibility, and enhancing energy efficiency with the help of smart analytics. Another crucial point identified by the research was the need to have industrial goodwill and favourable policy regimes to ensure the implementation process is successful.

Digital Transformation, Smart Grids, and Energy Management

Medojevic et al. (2018) provided the basis review of the energy management in Industry 4.0 with a special focus on Intelligent Energy Management Systems (IEMS). Their suggested model includes the equipment connectivity, data integration, and smart services based on big data analytics. The authors came to the conclusion that the combination of IoT and Manufacturing Execution Systems (MES) and ERP systems can transform the process of energy optimization and decision-making in factories.

Apata et al. (2021) examined the intersection of 4IR and Renewable Energy Systems (RES) via smart grid. They showed that IoT, cloud computing, and blockchain can be used to facilitate the bi-directional movement of energy and data, predictive maintenance, and the combination of Virtual Power Plants (VPPs) using reinforcement learning in causal transformer-based controllers. Their results revealed that 4IR technologies can improve stability of the grid, flexibility of operations and market presence in renewable energy systems. Monye et al. (2024) also established a conceptual framework of the IoT adoption in smart grids on the basis of Technology-Organization-Environment model, which is the Technology-Organization-Environment (TOE).

The framework was dealing with interoperability, infrastructure preparedness, and cybersecurity-providing a channel of integration of the IoT in energy systems on a sustainable basis.

Industry 4.0 Applications and Case Studies

Coban (2019) explored the potential of I4.0 technologies to transform the hydropower generation. The paper revealed the effectiveness of digitalization in hydropower performance, stability, and efficiency through the use of intelligent control systems that combine IoT and AI to achieve climate objectives.

Dulaimi et al. (2022) have presented a practical case study of Hubgrade 4.0- the smart energy city digital

platform based on a digital twin. The system, which compromised the energy optimization with the use of IoT and AI, saved 254 million kWh of energy and 138 million AED of operation costs in five years, demonstrating the potential of digital twins in urban energy management on a large scale. Tymoshenko et al. (2023) investigated how Industry 4.0 influences the development of energy futures in the developing economies with references to the energy transformation in Ukraine. The paper has pointed out a 11.5-fold rise in the use of renewable energy (2007, 2020) and estimated greater efficiency in energy consumption with a combination with the European power systems.

The article by Voitko et al. (2022) compared the efficiency of renewable energy use in Ukraine and Turkey (2016-2020) and revealed that solar and wind performance had been high in Turkey because the environmental conditions were favorable. They found out that the implementation of Industry 4.0 technologies can increase efficiency and energy security in the two countries.

Technological Frameworks and Synergistic Models

Nemomsa et al. (2025) suggested a four-layered architecture of digital-clean synergy framework, Digital-Clean Synergy Framework (DCSF), consisting of sensing, analytics, control and governance layers to integrate clean energy systems with both Industry 4.0 technologies. The framework revealed the measurable advantages: IoT and AI attained 24% energy efficiency, digital twins decreased the downtime by 30 percent, and CPS-improved microgrids enhanced the renewable presence up to 52 percent. The paper recognized the necessity of empirical testing by pilot implementations.

Peer et al. (2025) have overviewed the implementation of nanofluids and Industry 4.0 in CSP systems. They found out that hybrid nanofluids was able to reach a thermal efficiency of as high as 70.54 percent, and digital twins and AI led to better predictive maintenance and optimization of the system. Labaran and Masood (2023) analyzed the place of Industry 4.0 in the Green Supply Chain Management (GSCM) in renewable energy sectors. The systematic review of 215 studies conducted by them revealed blockchain, IoT, and AI as key enablers of transparency, reduction of waste, and sustainable logistics management.

Regional and Sectoral Perspectives

Bhagwan and Evans (2022) made comparisons between the 4IR use of energy in South Africa, Germany, and China. The survey revealed that there was a high interest in Big Real-Time Data (BRTD) analytics and IoT, but South African companies were low in AI and robotics because it was expensive. In their study, Ukoba et al. (2023) examined the concept of renewable energy and its integration with 4IR in Africa and emphasized that the continent could jump into sustainable industrialization. The research paper has determined solar and wind as the most robust renewable resources in Africa and has highlighted that the 4IR technologies have the potential to enhance inclusive development and energy equality. In their study, Mughele et al. (2022) examined the 4IR adoption in Africa and determined that the adoption of digital enablers, such as IoT and AI, can be used to change energy access and sustainability. The lack of infrastructural support and policy failures are however the key barriers to widespread adoption.

Environmental Sustainability and Carbon Emission Reduction

Khan et al. (2025) used panel econometric models to examine the impact of AI on the emission of carbon in 21 countries. Their findings showed that a greater rate of AI patent had a significant effect in decreasing CO 2 emissions particularly in the economies that were major emitters. Renewable electricity and human capital were also discovered to enhance the emission reduction, which confirms the Environmental Kuznets Curve hypothesis.

Shabur (2024) has performed a Meta-analysis of 207 Industry 4.0 and environmental sustainability manuscripts. In the study, 18 main applications of Industry 4.0, such as smart metering, drone-based monitoring, and predictive analytics, were identified that minimize waste of resources and improve the efficiency of the operations. It also found that I4.0 promotes a sustainable production paradigm in line with the global decarbonization ambitions. Bildirici et al. (2023) examined the impact of Industry 4.0 on the renewable energy production in G20 countries (20002021). Through cointegration and causality tests, they observed a reciprocal causality between Industry 4.0 and renewable generation in the sense that digital transformation improves renewable output up to 8-52% and at the same time, the latter.

RESEARCH METHODOLOGY

In this paper, an approach that is applied is a Systematic Literature Review (SLR) which aims to analyze the interface between Renewable Energy and Industry 4.0 technologies. The methodology is based on the PRISMA guidelines of Preferred Reporting Items of Systematic Reviews and Meta-Analyses, which provides transparency, replicability, and scientific rigour of the review. The relevant peer-reviewed journal articles, conference papers, and technical reports published since 2015 and pertaining to the keywords like Renewable Energy, Industry 4.0, IoT in energy, AI in renewable systems, and smart grids were found in such reputable academic databases as ScienceDirect, IEEE Xplore, SpringerLink, Scopus, and Google Scholar. The inclusion and exclusion criteria were based on publication dealing with the topics of digital integration, smart energy management, and sustainability effects, and non-English, non-peer-reviewed, and non-energy-related publications were excluded. Systematic codes were used in the extraction, coding, and synthesis of data to develop core themes, emerging technologies, implementation models, and gaps in research. The SLR design therefore offers a systematic basis of knowledge in the transformation of renewable energy systems towards increased efficiency, resiliency, and sustainability as a result of Industry 4.0 innovations.

The Concept of Renewable Energy

Renewable energy is defined as energy that is generated through natural processes which are constantly replenished, e.g. sunlight, wind, rain, tides, geothermal heat and biomass. As opposed to fossil fuels which are depletable and release greenhouse gases, renewable sources of energy are renewable, cleaner, and important in the reduction of climate change. The main principle is the exploitation of the natural phenomena to generate types of energy that can be used without exhausting the resources of the planet (Ersoy, 2024). An example of this is the use of solar PV systems that change the light energy of the sun to electricity, wind turbines which use kinetic energy of the atmosphere to produce electrical energy, and hydropower plants which use flowing water to produce mechanical and electrical energy.

Classification of Renewable Energy Sources

There are five broad categories of renewable energy according to their natural sources and conversion methods that are demonstrated in Table 1 (Rêgo, 2021).

Table 1: Classification of Renewable Energy Sources

Type of Renewable Energy	Source/Origin	Conversion Mechanism	Key Applications	Notable Advantages
Solar Energy	Sun’s radiation	PV cells convert	Electricity	Abundant,

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue XI November 2025

		sunlight directly to electricity; CSP systems use mirrors to generate heat for turbines.	generation, water heating, solar drying, and industrial process heat.	sustainable, and zero greenhouse gas emissions during operation.
Wind Energy	Movement of air masses (wind)	Wind turbines convert kinetic energy from wind into mechanical and then electrical energy.	Power generation for residential, commercial, and grid-scale applications.	Clean, cost-effective, and scalable for onshore and offshore installations.
Hydropower	Flowing or falling water in rivers and dams	Turbines and generators convert the mechanical energy of moving water into electricity.	Electricity generation, water pumping, and flood control.	High conversion efficiency and reliable base-load power source.
Biomass Energy	Organic materials (plants, agricultural residues, animal waste)	Combustion, anaerobic digestion, or fermentation to produce biofuels, heat, or electricity.	Power generation, heating, and transportation (bioethanol and biodiesel).	Converts waste to energy, reduces landfill use, and supports rural economies.
Geothermal Energy	Heat from beneath the Earth's crust	Steam or hot water extracted from geothermal reservoirs drives turbines or provides direct heating.	Electricity generation, district heating, greenhouse farming, and industrial heating.	Continuous and reliable energy source with minim

All these sources in Table 1 contribute to the level of energy diversification and the decrease in the reliance on fossil energy since each will have its specific role in the global energy mix (Dunlap, 2024).

Global Trends and Technological Advancements

Over the past several decades, the technology of renewable energy has experienced some exceptional development that has enhanced their effectiveness, affordability, and capacity (Kumar and Pal, 2025). Recent advances in solar PV cells, design of wind turbine blades and power storage have made the deployment of large scale renewable deployment much more feasible. The addition of smart grids and sophisticated metering infrastructure (AMI) has also enhanced reliability and grid stability due to the ability to monitor the grid in real-time, automatically control, and send energy in both directions. The International Energy Agency (IEA) estimates that by 2023 over 30 percent of overall electricity production is produced by renewable energy, the fastest-growing energy sector in the world (International Energy Agency, 2023). Such developments show the transition of paradigm toward decentralized technology-driven energy systems by abandoning the centralized fossil-fuel-based systems.

Industry 4.0

The 4IR or Industry 4.0 is the latest stage of industrial transformation that implies the combination of digital, physical, and biological technologies. It is a continuation of previous industrial revolutions the initial one powered by mechanization and steam engines, the second one by electricity and mass production, and the third one by automation and information technology. Industry 4.0 was first conceived as a strategic move in Germany in 2011 (Raj et al., 2024) with the idea to make manufacturing more efficient, flexible, and intelligent by means of digitalization. It is no longer limited to manufacturing today, but is used in energy systems, healthcare, transportation and agriculture to transform the system operation, interaction and real-time self-optimization.

Core Technologies of Industry 4.0

Industry 4.0 incorporates a collection of interconnected and sophisticated technologies, which allow making operations intelligent and data-driven (Azizi and Barenji, 2023). Table 2 presents the core technologies (Thames and Schaefer, 2017).

Table 2: Principles and Characteristics of Industry 4.0

Principle/Characteristic	**Description**	**Key Impact/Benefit**
Interconnectivity	Ensures seamless communication and data exchange among machines, humans, and systems via IoT and networked infrastructures.	Enables system-wide integration, interoperability, and smart coordination of industrial operations.
Information Transparency	Provides real-time visibility of production and operational data across all stages of the value chain.	Enhances decision-making accuracy, monitoring efficiency, and process optimization.
Decentralized Decision-Making	Allows intelligent systems and machines to make autonomous decisions without direct human control.	Increases flexibility, reduces downtime, and accelerates response to operational changes.
Technical Assistance	Machines and systems support humans by providing data-driven insights, automation, and decision recommendations.	Improves safety, efficiency, and productivity by reducing human workload.
Virtualization	Creates digital replicas (digital twins) of physical assets and processes for analysis, simulation, and optimization.	Enables predictive maintenance, operational optimization, and scenario testing.
Real-Time Capability	Facilitates immediate processing and response to data inputs for agile operations and adaptive control.	Enhances responsiveness, predictive maintenance, and operational reliability.

Applications of Industry 4.0 in Energy Systems

The introduction of industry 4.0 solutions in the energy sector has altered the way energy is produced, distributed as well as consumed. With the IoT and AI-powered smart grids, real-time monitoring, demand forecasting, and automated control are achieved, which makes grids more reliable and energy-efficient. Blockchain enables peer to peer trading of energy which offers transparency and traceability of renewable energy markets. On the same note, digital twins and CPS are available to give predictive data on the performance of energy assets (Prasad et al., 2023), minimizing down time and engineering expenses. Industry 4.0 also helps achieve renewable power integration, distributed generation, and sustainable energy management, and the future of smart and decentralized energy ecosystems (Shabur, 2024).

c. Benefits and Opportunities of Industry 4.0

The implementation of Industry 4.0 has a broad gamut of economic, operational and environmental advantages as indicated in Figure 2.

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue XI November 2025

Figure 2: Benefits of Industry 4.0, Shabur, M. A. (2024)

Industry 4.0, as it is observable in Figure 2, improves productivity and resource efficiency and energy optimization, by automation and smart analytics. It helps in the energy sector move towards low-carbon economies through facilitating flexible integration of renewable energy, smart storage of energy management, and lower carbon footprints. Additionally, Industry 4.0 promotes innovativeness, competitiveness, and resilience in industries through the provision of flexible instruments of quick reaction to market and environment shifts. Digitalization-sustainability synergy is therefore a driver towards realizing the global energy and climate targets.

Open Research Directions

It can be noted that the reviewed literature shows that the merging of I4.0 technologies with RES has been achieved significantly, although many research opportunities still exist. Such open directions are the result of consistent issues that were found on the forecasting, integration, digital transformation, sustainability evaluation, and local implementation. They are critical to ensuring the full potential of Industry 4.0 is achieved in hastening renewable energy transitions in the world.

Advanced Renewable Energy Forecasting and Optimization

Despite other studies like Firlej and Stanuch (2022) and He and Ni (2022) proving the ability of econometric and AI-based models to improve renewable energy forecasts, predictive accuracy is limited to the variability of data, climatic uncertainty, and model generalization. The development of hybrid AI-statistical prediction schemes, deep learning architectures and real-time data fusion methods should be pursued by future studies blending meteorological, market and grid level data. It can be of great importance to develop adaptive learning systems that could modify the predictions depending on the environmental dynamics to increase the optimization of the renewable energy yield.

Intelligent Integration of Industry 4.0 Technologies

Although Onu et al. (2023), Borowski (2021) and Scharl and Praktiknjo (2019) identified the beneficial impact of IoT, digital twins, and blockchain in energy management, the interoperability and system scalability have not been addressed. The direction of open research needs to be the creation of integrated digital energy, communication protocols, and multi-agent control systems that will allow seamless integration of IoT devices, CPS, and renewable assets. Moreover, AI-enabled decision-support systems may be implemented in order to organize the distributed renewable energy assets in smart grids and microgrids and optimize them in real-time.

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue XI November 2025

Smart Grids, IoT Security, and Interoperability

Apata et al. (2021) and Monye et al. (2024) demonstrated that smart grids increase flexibility and reliability due to the control based on the IoT, but the problem of cybersecurity and interoperability remains. The following research questions need to be explored in the future: secure-by-design IoT architectures, blockchain-based trust model, and AI-assisted anomaly detection in smart grid settings. Furthermore, cross-platform interoperability models are required to make sure that the heterogeneous IoT systems are capable of communicating effectively in multi-vendor energy ecosystems.

Digital Twin Validation and Real-World Deployment

Although Dulaimi et al. (2022) and Borowski (2021) have shown the usefulness of digital twins in energy efficiency and predictive maintenance, the empirical validation is only done in pilot-scale case studies. Future research must look at scalable digital twin systems that can be used to model a complete energy network, that include real-time sensor feedback and machine-learning-based fault prediction. There should also be studies in terms of data synchronization, model calibration and uncertainty quantification of twin based renewable systems to improve reliability and deployment preparedness.

Regional Adaptation and Policy Frameworks

Comparative research, including Bhagwan and Evans (2022), Ukoba et al. (2023), and Mughele et al. (2022), found that there were digital energy disparities between regions, especially in the developing economies. It is necessary to conduct research on localized models of implementation, making the I4.0 technologies relevant to the regional infrastructure, policy, and socioeconomic contexts. Research ought to assess the policy-based incentives, the collaborations between the government and the private sector, and the capacity-building initiatives that can support the fair access to digital technologies and the sustainable energy solutions in various regions.

Sustainable Digitalization and Carbon Footprint Analysis

Although Khan et al. (2025) and Shabur (2024) confirmed the existence of a correlation between AI and

digitalization and the reduction of emissions, the environmental footprint of digital infrastructures, including data centers and IoT devices, has not been quantified in many studies. To determine the net sustainability impact of I4.0 technologies in energy systems, future studies should use the life cycle assessment (LCA) and energy audit approaches. The creation of eco-friendly digital platforms which will be based on renewable energy and energy conscious computing structures will see the digital transformation become geared towards the global objectives of decarbonization.

Toward Industry 5.0 and Human-Centric Energy Systems

New paradigms, such as Industry 5.0, have a chance of human-machine cooperation in the management of sustainable energy. Continuing on Nemomsa et al. (2025) and Peer et al. (2025), the way cognitive robotics, augmented reality, and AI-assisted decision support could help empower operators and increase energy resilience should be researched in the future. It is necessary to focus more on human-centric digital ecosystems that are automated and sustainable in both ethical, social, and environmental aspects.

The literature review synthesis highlights the fact that the implementation of Industry 4.0 and renewable energy is currently in the phase of conceptualization, rather than actual, mass-scale implementation. The demand to have adaptive AI models, secure IoT systems, validated digital twins, and context-specific policies is highlighted in open research directions that support the overall progress of digital-energy convergence. Such gaps will be resolved to achieve intelligent, secure, and sustainable energy ecosystems that are in accordance with the global climate and industrial transformation objectives.

CONCLUSION

This paper has analyzed the overlap of the RES and I4.0 technologies critically and how the digital transformation is transforming energy production, distribution, and management across the world. The previous is a synthesis of research data concerning emerging trends, the most significant technologies, and implementation issues that occurred in the nexus of digitalization and clean energy through 2015 to 2025 (SLR, 2018). The results showed that I4.0 technologies and especially the IoT, AI, Big Data analytics, Blockchain, and CPS have a transformational role in optimizing renewable energy systems. These technologies can be used to improve accuracy of forecasts, make smart automation, and conduct real-time monitoring, predictive maintenance, and smarter grid control. Quantitative research showed that renewable infrastructures could be further enhanced through the incorporation of digital tools to increase energy use, operational stability, and carbon emission. Furthermore, AI-based analytics and digital twins have turned into potent facilitators of the decision-making process and optimization of the system in industrial and urban environments.

Nevertheless, the review also found that there are still a number of underlying issues acting as impediments to large scale implementation particularly those related to cybersecurity risks, interoperability, lack of digital infrastructure, and misalignment of policies. Inequality in regions particularly the developed and developing economies is not going to fade away because there is a difference in financial capacity, technological preparedness and human capital development. Moreover, the positive impact of I4.0 on the environment is evident, whereas the indirect energy expenses of data centers and communication networks should be evaluated further to provide comprehensive sustainability.

In order to mitigate these constraints, the research provided main open research opportunities that included AI-based optimization, secure IoT and blockchain, digital twin validation, smart grid protocol standardization, and context-sensitive policy frameworks. These guidelines note that multidisciplinary teams should be involved in the process of engineers, policymakers, data scientists, and sustainability experts to realize the fully-digitized and decarbonized energy ecosystem.

To sum up, the meeting of Industry 4.0 and renewable energy is not only a simple technological development but a complete paradigm shift to sustainable industrialization. Through digital intelligence, automation, and real-time analytics, countries will be able to jumpstart their effort to achieve global climate and energy security. Future studies and policy changes ought to aim at creating inclusive, resilience, and humanized energy systems that are inclined to balance between innovation and environmental care. In conclusion, the digital-energy nexus has the power to reshape the future of energy systems the world over- making them intelligent, adaptive, and sustainable and according to the agenda of Industry 5.0 and the United Nations Sustainable Development Goals (SDGs).

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