



Renewable Energy and Sustainability: A Critical Review of Technologies, Environmental Benefits, and Future Development Pathways

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How to Cite this Article:

Jena, M. C., Chakra, A., Bhanja, B., Swain, C. K., Satapathy, S., Sahu, S., Behera, S. K., Muduli, A., Maharana, M., Barik, P. M., Mahapatra, P. P. & Padhy, I. P. (2026). Renewable Energy and Sustainability: A Critical Review of Technologies, Environmental Benefits, and Future Development Pathways. International Journal of Creative and Open Research in Engineering and Management, <i>02</i>(6).
<https://doi.org/10.55041/ijcope.v2i6.332>

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<https://doi.org/10.55041/ijcope.v2i6.332>

Abstract

Renewable energy has emerged as a central pillar of global sustainability initiatives due to increasing concerns regarding climate change, environmental degradation, fossil fuel depletion, and energy security. The transition from conventional fossil-fuel-based energy systems toward renewable energy technologies is essential for achieving sustainable development goals and reducing greenhouse gas emissions. This review critically examines the role of renewable energy in promoting environmental, economic, and social sustainability. Major renewable energy technologies, including solar, wind, hydropower, and biomass systems, are evaluated in terms of their sustainability contributions, technological advancements, and implementation challenges. The review further explores the integration of Industry 4.0 technologies, artificial intelligence, circular economy principles, and sustainability assessment frameworks in enhancing renewable energy deployment. Current challenges, opportunities, and future research priorities are discussed to provide a comprehensive understanding of renewable energy's contribution toward a sustainable future.

Keywords: Renewable energy, sustainability, sustainable development, climate change, solar energy, circular economy, Industry 4.0, sustainable manufacturing.



1. Introduction

The global demand for energy has increased substantially over the past several decades as a result of industrialization, urbanization, technological advancement, and population growth. Although fossil fuels have historically supported economic development and industrial expansion, their continued exploitation has contributed significantly to greenhouse gas emissions, climate change, environmental degradation, and resource depletion [1–4]. According to the International Energy Agency, global energy consumption continues to rise despite improvements in energy efficiency, creating significant challenges for achieving long-term sustainability objectives [4]. Consequently, the transition toward renewable energy systems has become a critical priority for governments, industries, and international organizations seeking to establish sustainable development pathways [2,5].

The concept of sustainable development was formally articulated in the Brundtland Report, which defined sustainability as development that satisfies present needs without compromising the ability of future generations to meet their own needs [1]. Since then, sustainability has evolved into a multidimensional framework encompassing environmental protection, economic prosperity, and social well-being. This perspective was further strengthened through the Triple Bottom Line approach, which emphasizes the balanced integration of environmental, economic, and social dimensions of development [20]. More recently, the United Nations Sustainable Development Goals (SDGs) established a comprehensive framework for addressing global challenges related to climate change, clean energy, sustainable industrialization, and responsible resource utilization [2,5].

Renewable energy technologies have emerged as one of the most effective strategies for achieving sustainability objectives. Unlike conventional fossil fuels, renewable energy resources are naturally replenished and generate significantly lower environmental impacts during operation [7,8]. The increasing deployment of solar photovoltaics, wind farms, hydropower systems, biomass energy facilities, and emerging renewable technologies has transformed the global energy landscape over the past two decades [7,8]. According to REN21 and IRENA reports, renewable energy installations continue to expand rapidly, supported by declining technology costs, improved efficiencies, and favorable policy interventions [7,8].

Climate change remains one of the most significant drivers behind the renewable energy transition. The Intergovernmental Panel on Climate Change (IPCC) has repeatedly highlighted the necessity of reducing greenhouse gas emissions to limit global temperature rise and avoid severe environmental consequences [3]. Renewable energy technologies contribute directly to climate change mitigation by reducing carbon emissions associated with electricity generation and industrial activities [13]. Furthermore, the International Energy Agency's Net Zero Roadmap emphasizes renewable energy deployment as a fundamental requirement for achieving global carbon neutrality targets by mid-century [31].

Recent technological advancements have significantly enhanced the performance and economic viability of renewable energy systems. Solar photovoltaic technologies have experienced remarkable improvements in conversion efficiency and cost reduction, making solar energy one of the most competitive electricity generation options globally [9]. Research by Nayak et al. [10] demonstrated that advanced control strategies can improve power quality and energy efficiency in grid-connected photovoltaic systems, while Swain et al. [11] reported significant opportunities for enhancing photovoltaic system performance through optimization techniques. Similarly, developments in wind turbine design, biomass conversion technologies, and energy storage systems have improved renewable energy reliability and operational effectiveness [12,28,33].



The integration of digital technologies with renewable energy systems has further accelerated sustainability improvements. Industry 4.0 technologies, including artificial intelligence, machine learning, big data analytics, cloud computing, and the Internet of Things (IoT), enable intelligent energy management and optimization of renewable energy operations [6,16]. Jena et al. [6] highlighted the potential of integrating Industry 4.0 with environmental management systems to improve sustainability performance, while Jena et al. [16] demonstrated the contribution of Industry 4.0 technologies toward sustainable manufacturing practices. These digital technologies facilitate predictive maintenance, energy forecasting, operational optimization, and real-time monitoring, thereby enhancing the efficiency and reliability of renewable energy systems.

In addition to environmental benefits, renewable energy contributes significantly to economic development and industrial competitiveness. The transition toward renewable energy systems stimulates technological innovation, job creation, infrastructure development, and energy security [17]. Sustainable manufacturing initiatives increasingly incorporate renewable energy technologies to reduce environmental impacts and improve resource efficiency. Studies utilizing the Economic-Efficiency-Environment (EEE) Impact Model have demonstrated that renewable energy alternatives provide substantial environmental and economic advantages compared with conventional energy sources [14,15,18].

The growing emphasis on circular economy principles has further strengthened the relationship between renewable energy and sustainability. Circular economy frameworks promote resource efficiency, waste minimization, recycling, and sustainable production systems, thereby supporting long-term environmental sustainability [19,21]. Research on fly ash utilization, battery waste management, and industrial waste valorization has highlighted the importance of integrating renewable energy systems with circular economy strategies to maximize sustainability benefits [22–24].

Despite significant progress, renewable energy deployment continues to face several technical, economic, environmental, and policy-related challenges. Intermittency of renewable energy generation, energy storage limitations, infrastructure requirements, investment barriers, and regulatory uncertainties remain important constraints affecting large-scale implementation [28,30,31,33]. Addressing these challenges will require coordinated efforts involving technological innovation, supportive policy frameworks, industrial participation, and international collaboration.

Therefore, this review aims to critically examine the role of renewable energy in advancing sustainability by evaluating major renewable energy technologies, environmental benefits, digital transformation opportunities, circular economy integration, and future development pathways. Through a comprehensive synthesis of recent literature, this study seeks to identify emerging trends, research gaps, and strategic directions that can support the global transition toward sustainable energy systems.

2. Renewable Energy and Sustainable Development

Renewable energy has become a fundamental component of sustainable development strategies because it simultaneously addresses environmental protection, economic growth, and social well-being. The increasing dependence on fossil fuels has contributed to climate change, environmental degradation, and resource depletion, creating an urgent need for cleaner and more sustainable energy systems [1–5]. Renewable energy technologies offer a viable solution to these challenges by providing low-carbon energy alternatives that reduce greenhouse gas emissions while supporting long-term economic development [7,8,13].



The contribution of renewable energy to sustainability extends beyond environmental benefits. Renewable energy systems improve energy security by reducing dependence on imported fossil fuels and diversifying energy portfolios. In addition, the renewable energy sector has become an important driver of economic growth through investments in infrastructure, technological innovation, and employment generation [8,17]. The United Nations Sustainable Development Goals recognize affordable and clean energy as a critical enabler of sustainable development, highlighting its role in poverty reduction, industrial development, climate action, and environmental conservation [2,5].

The major renewable energy technologies and their sustainability contributions are summarized in Table 1.

Table 1. Comparison of Major Renewable Energy Technologies and Sustainability Contributions

Renewable Energy Source	Primary Resource	Major Sustainability Benefits	Key Challenges
Solar Energy	Solar Radiation	Low emissions, abundant resource, decentralized generation	Intermittency, storage requirement
Wind Energy	Wind Flow	Low carbon footprint, large-scale electricity generation	Variability, site dependency
Hydropower	Water Resources	Reliable power generation, high efficiency	Ecological impacts
Biomass Energy	Organic Materials	Waste utilization, renewable resource	Feedstock management
Geothermal Energy	Earth's Heat	Continuous energy supply	High capital investment

As shown in Table 1, each renewable energy technology contributes differently toward sustainability objectives. Solar and wind energy are currently the fastest-growing renewable energy sectors due to declining technology costs and supportive policy measures, while hydropower continues to provide the largest share of renewable electricity generation globally [7,8,30]. Biomass energy offers additional sustainability benefits through waste utilization and resource recovery, supporting circular economy principles and sustainable resource management [12,19].

Renewable energy technologies are also essential for achieving international climate goals. The IPCC has emphasized that rapid decarbonization of energy systems is necessary to limit global warming and reduce climate-related risks [3]. Similarly, the International Energy Agency has identified renewable energy deployment as one of the most important strategies for achieving net-zero emission targets by 2050 [31]. Consequently, renewable energy expansion has become a central component of national and international sustainability policies.

3. Solar Energy and Sustainability

Solar energy has emerged as one of the most important renewable energy technologies due to its widespread availability, technological maturity, and declining installation costs [9]. Photovoltaic systems convert solar radiation directly into electricity without producing significant operational emissions, making them highly attractive for sustainable energy generation. Global solar photovoltaic capacity has expanded rapidly during the past decade and is expected to continue growing as governments pursue low-carbon development strategies [7,8].



The environmental benefits of solar energy are substantial. Unlike fossil-fuel-based power generation systems, photovoltaic technologies produce electricity without emitting carbon dioxide, sulfur oxides, nitrogen oxides, or particulate matter during operation. Consequently, solar energy contributes directly to climate change mitigation, improved air quality, and reduced environmental degradation [3,13].

Technological developments have significantly improved photovoltaic system performance. Advances in semiconductor materials, inverter technologies, and intelligent control systems have enhanced energy conversion efficiencies while reducing system costs [9]. Nayak et al. [10] reported that sliding mode control techniques can improve power quality and energy efficiency in grid-connected photovoltaic systems. Similarly, Swain et al. [11] demonstrated that optimization-based approaches can substantially increase photovoltaic power generation efficiency and enhance overall sustainability performance.

Despite these advantages, solar energy systems continue to face challenges related to intermittency and energy storage. Variations in solar irradiance influence electricity generation and create difficulties for grid integration. Consequently, significant research efforts are focused on developing advanced energy storage systems and intelligent energy management technologies to improve system reliability and operational stability [28,33].

4. Wind, Hydropower, and Biomass Energy Systems

Wind energy represents one of the most successful renewable energy technologies in terms of large-scale electricity generation. Technological improvements in turbine design, materials engineering, and aerodynamic optimization have significantly increased energy conversion efficiency and reduced electricity generation costs [8]. Wind power contributes substantially to greenhouse gas reduction and supports sustainable electricity generation across many regions worldwide.

Hydropower remains the largest source of renewable electricity generation globally due to its high efficiency, reliability, and ability to provide grid stability [8,30]. Hydroelectric facilities play an important role in balancing renewable energy systems and supporting electricity supply during periods of variable solar and wind generation. However, hydropower development may affect aquatic ecosystems, biodiversity, and water resource management, requiring careful environmental planning and monitoring.

Biomass energy provides unique sustainability benefits because it simultaneously addresses energy generation and waste management objectives. Agricultural residues, forestry waste, municipal solid waste, and industrial by-products can be converted into useful forms of energy through thermochemical and biochemical conversion processes [12]. Sustainable biomass utilization contributes to reduced waste disposal requirements while supporting renewable energy production and resource efficiency.

The environmental and operational characteristics of renewable energy systems vary considerably. Therefore, integrated energy strategies that combine multiple renewable technologies are increasingly being adopted to improve energy security and system reliability while maximizing sustainability benefits [8,28].

5. Environmental Benefits of Renewable Energy

The environmental benefits associated with renewable energy deployment extend far beyond greenhouse gas emission reduction. Renewable energy technologies contribute to reduced air pollution, lower water consumption, enhanced resource conservation, and decreased ecological impacts compared with conventional fossil-fuel-based energy systems [3,13].



A comparison of key sustainability indicators associated with conventional and renewable energy systems is presented in Table 2.

Table 2. Environmental Benefits of Renewable Energy Compared with Conventional Energy Sources

Sustainability Indicator	Fossil Fuel Systems	Renewable Energy Systems
Greenhouse Gas Emissions	High	Very Low
Air Pollution	High	Low
Water Consumption	High	Low
Resource Depletion	High	Low
Climate Change Impact	Significant	Minimal
Long-Term Sustainability	Limited	High

Table 2 clearly illustrates the environmental advantages of renewable energy systems. Fossil fuel-based electricity generation contributes significantly to climate change, environmental pollution, and resource depletion, whereas renewable energy technologies offer cleaner alternatives capable of supporting long-term sustainability objectives [3,4,13].

Several studies have demonstrated the environmental benefits of renewable energy adoption in industrial applications. Jena et al. [14] evaluated alternative energy sources using the Economic-Efficiency-Environment (EEE) Impact Model and reported significant reductions in environmental impacts through renewable energy implementation. Similar findings were reported by Jena et al. [15,18], who demonstrated that renewable energy sourcing can improve sustainability performance while maintaining economic viability.

The environmental advantages of renewable energy become increasingly important as nations seek to achieve carbon neutrality targets and comply with international climate commitments. Consequently, renewable energy deployment is expected to remain a primary strategy for addressing climate change and promoting sustainable development during the coming decades.

6. Artificial Intelligence and Industry 4.0 in Renewable Energy

Digital transformation is rapidly reshaping renewable energy systems through the integration of artificial intelligence (AI), Industry 4.0 technologies, big data analytics, cloud computing, and the Internet of Things (IoT). These technologies enhance renewable energy performance by improving forecasting accuracy, operational efficiency, system reliability, and decision-making capabilities [6,16].

Artificial intelligence enables advanced energy forecasting by analyzing large datasets related to weather conditions, energy demand, and system performance. Accurate forecasting improves renewable energy scheduling and facilitates better integration with electricity grids. AI-based predictive maintenance systems also reduce equipment failures and operational downtime by identifying potential faults before they occur.

The major applications of AI and Industry 4.0 technologies in renewable energy systems are summarized in Table 3.

**Table 3. Applications of Artificial Intelligence and Industry 4.0 in Renewable Energy Systems**

Technology	Application Area	Sustainability Contribution
Artificial Intelligence	Energy forecasting	Improved energy planning
Machine Learning	Predictive maintenance	Reduced downtime and resource waste
Internet of Things (IoT)	Real-time monitoring	Enhanced operational efficiency
Big Data Analytics	Energy optimization	Improved decision making
Digital Twin	System simulation	Reduced operational risks
Smart Grid	Energy management	Improved renewable integration

As shown in Table 3, digital technologies contribute significantly to improving renewable energy efficiency and sustainability. Jena et al. [6] demonstrated that integrating Industry 4.0 technologies with environmental management systems can enhance environmental sustainability through intelligent monitoring and optimized resource utilization. Similarly, Jena et al. [16] highlighted the role of Industry 4.0 in supporting sustainable manufacturing and energy-efficient industrial operations.

The convergence of renewable energy systems with AI and Industry 4.0 technologies is expected to accelerate the development of smart energy systems capable of achieving higher efficiency, reliability, and sustainability performance. Consequently, digitalization is likely to become a critical component of future renewable energy strategies.

7. Sustainable Manufacturing and Renewable Energy Integration

The manufacturing sector is one of the largest consumers of energy and a significant contributor to greenhouse gas emissions, environmental pollution, and resource depletion. As governments and industries pursue sustainability objectives, the integration of renewable energy technologies into manufacturing systems has emerged as an important strategy for reducing environmental impacts while maintaining economic competitiveness [17]. Renewable energy-powered manufacturing facilities contribute to lower carbon emissions, reduced dependence on fossil fuels, improved energy security, and enhanced environmental performance.

The concept of sustainable manufacturing emphasizes the production of goods through economically viable processes that minimize environmental impacts and conserve resources throughout the product life cycle [20]. Renewable energy technologies support this objective by providing cleaner energy alternatives for industrial operations. Solar photovoltaic systems, biomass energy plants, and renewable electricity procurement mechanisms are increasingly being adopted across manufacturing industries to reduce environmental footprints and improve sustainability indicators [7,8].

Several studies have highlighted the importance of renewable energy in advancing sustainable manufacturing. Jena et al. [14] evaluated alternative energy sources using Madhab's Economic-Efficiency-Environment (EEE) Impact Model and reported that renewable energy systems provide superior environmental performance compared with conventional fossil-fuel-based energy sources. Similarly, Jena et al. [15] demonstrated that fuel selection based on environmental, economic, and efficiency considerations can significantly improve sustainability outcomes in industrial applications. Renewable energy sourcing strategies examined by Jena et al. [18] further confirmed the potential of renewable energy technologies to support sustainable industrial development while reducing environmental impacts.



The integration of Industry 4.0 technologies with renewable energy systems has further strengthened sustainable manufacturing initiatives. Intelligent manufacturing systems utilize real-time monitoring, predictive analytics, artificial intelligence, and digital communication technologies to optimize energy utilization and improve operational efficiency [6,16]. Such integrated approaches enable industries to simultaneously achieve productivity improvements and environmental sustainability objectives.

8. Circular Economy and Resource Efficiency

The transition toward a circular economy has become an important strategy for achieving sustainable development and resource conservation. Unlike the traditional linear economic model, which follows a pattern of extraction, production, consumption, and disposal, the circular economy emphasizes resource recovery, reuse, recycling, and regeneration [19,21]. Renewable energy technologies support circular economy objectives by reducing dependence on non-renewable resources and facilitating cleaner production systems.

Resource efficiency plays a critical role in improving sustainability performance across industrial sectors. Renewable energy systems contribute to resource conservation by reducing fossil fuel consumption and minimizing environmental degradation associated with energy production. Furthermore, renewable energy technologies can be integrated with waste management systems to promote resource recovery and waste-to-energy applications [12].

Several studies have demonstrated the potential of industrial by-products and waste materials to support sustainable manufacturing and circular economy objectives. Jena et al. [22] investigated the utilization of fly ash and ground granulated blast furnace slag (GGBS) in fiber cement sheet manufacturing and reported significant environmental benefits through waste valorization and resource conservation. Such approaches reduce landfill requirements while promoting sustainable material utilization.

Battery waste management has emerged as an increasingly important sustainability challenge due to the rapid expansion of renewable energy systems and energy storage technologies. The widespread adoption of photovoltaic systems, electric vehicles, and battery-based storage systems is expected to generate substantial quantities of end-of-life batteries in the coming years. Jena et al. [23,24] highlighted the environmental risks associated with battery waste and emphasized the need for sustainable recycling, recovery, and disposal strategies. Effective battery waste management will be essential for ensuring the long-term sustainability of renewable energy systems.

9. ESG, Sustainability Reporting, and Environmental Accountability

Environmental, Social, and Governance (ESG) frameworks have become important instruments for evaluating organizational sustainability performance. Investors, policymakers, regulators, and stakeholders increasingly rely on ESG indicators to assess environmental responsibility, social impact, and governance effectiveness [25]. Renewable energy adoption contributes positively to ESG performance by reducing carbon emissions, enhancing resource efficiency, and supporting sustainable business practices.

The growing emphasis on sustainability reporting has encouraged organizations to disclose environmental performance indicators and sustainability initiatives. The Global Reporting Initiative (GRI) provides internationally recognized sustainability reporting standards that facilitate transparency and comparability across industries [25]. Similarly, Life Cycle Assessment (LCA) methodologies based on ISO 14040 standards provide structured approaches for evaluating environmental impacts throughout the life cycle of products and technologies [27].



Despite the increasing popularity of ESG frameworks, concerns regarding greenwashing and symbolic sustainability reporting remain significant. Patyrykin et. al. [26] critically examined ESG ratings and environmental accountability within the insurance sector and identified substantial inconsistencies in sustainability assessment methodologies. Their findings suggest that organizations may sometimes emphasize sustainability reporting without achieving meaningful environmental improvements. Consequently, the development of more transparent and standardized sustainability assessment frameworks remains an important research priority.

Renewable energy projects increasingly incorporate ESG considerations into planning and evaluation processes. Environmental impact assessments, carbon footprint analyses, and sustainability performance indicators are now commonly used to assess the environmental effectiveness of renewable energy investments. Such approaches support evidence-based decision-making and enhance accountability within sustainability initiatives.

10. Challenges and Future Research Priorities

Despite substantial technological progress and increasing global adoption, renewable energy systems continue to face numerous technical, economic, environmental, and policy-related challenges that hinder their large-scale implementation and long-term sustainability. Addressing these challenges is essential for achieving global decarbonization targets and supporting the transition toward sustainable energy systems [3,8,28,30,31].

One of the most significant technical challenges associated with renewable energy systems is the intermittent and variable nature of energy generation. Solar and wind energy technologies are highly dependent on weather conditions, seasonal variations, and geographical factors, resulting in fluctuations in electricity production. These variations can create operational difficulties for power systems, particularly when renewable energy penetration levels are high. Maintaining grid stability under such conditions requires increased flexibility within energy systems, improved forecasting capabilities, demand-side management strategies, and enhanced grid infrastructure [28,31,34]. Furthermore, the integration of variable renewable energy sources necessitates the development of advanced smart grids capable of balancing electricity supply and demand in real time.

Energy storage remains another critical challenge for renewable energy deployment. Although battery technologies have experienced significant improvements in performance and cost reduction, current storage systems still face limitations related to energy density, lifespan, resource availability, and economic feasibility [33,35,36,37]. Large-scale deployment of renewable energy systems requires reliable and cost-effective storage solutions capable of compensating for generation variability and ensuring continuous power supply. Emerging technologies such as solid-state batteries, hydrogen-based storage systems, pumped hydro storage, and hybrid energy storage systems offer promising opportunities for overcoming existing limitations; however, further technological advancement and cost reduction are necessary before widespread implementation can be achieved [35–37].

Economic barriers continue to influence renewable energy adoption, particularly in developing economies. Although the levelized cost of electricity generated from solar and wind technologies has declined considerably over the past decade, high initial capital investment requirements remain a significant obstacle for many projects [8,30]. Financial risks, inadequate infrastructure, limited access to funding, and uncertainty regarding future policy support can reduce investor confidence and slow renewable energy deployment [39]. In many developing regions, additional challenges related to grid connectivity, technology transfer, and institutional capacity further complicate renewable energy implementation. Consequently, innovative financing



mechanisms, public-private partnerships, and supportive policy frameworks are essential for accelerating investment in renewable energy infrastructure.

Environmental concerns associated with renewable energy technologies must also be carefully considered. While renewable energy systems generally produce substantially lower emissions than conventional fossil-fuel-based energy systems, they are not entirely free from environmental impacts [13]. Large-scale hydropower projects may alter river ecosystems, affect biodiversity, and influence water resource availability. Similarly, extensive solar and wind energy installations may require significant land areas and potentially affect local ecosystems and wildlife habitats [38]. The environmental implications of renewable energy infrastructure therefore require comprehensive assessment to ensure that sustainability benefits outweigh potential ecological impacts.

An emerging environmental challenge relates to the management of end-of-life renewable energy components. The rapid expansion of photovoltaic systems, battery storage technologies, and electronic control systems is expected to generate substantial quantities of waste materials in the coming decades. Photovoltaic panels contain valuable materials that require efficient recovery and recycling, while battery systems present additional challenges related to hazardous material management and resource recovery [23,24,36,38]. Developing effective recycling technologies and circular economy strategies will be essential for minimizing environmental impacts and supporting sustainable resource utilization throughout the life cycle of renewable energy systems.

Social and policy-related factors also play a significant role in renewable energy deployment. Public acceptance, stakeholder engagement, land acquisition challenges, and regulatory uncertainties can influence the success of renewable energy projects [40]. In some regions, opposition to renewable energy developments may arise due to concerns regarding visual impacts, land use changes, or perceived environmental consequences. Effective stakeholder communication, transparent decision-making processes, and community participation are therefore important for improving social acceptance and facilitating project implementation.

Future research priorities associated with renewable energy and sustainability are summarized in Table 4.

Table 4. Key Sustainability Challenges and Future Research Priorities in Renewable Energy

Sustainability Challenge	Current Impact	Future Research Focus
Renewable Energy Intermittency	Grid instability and power fluctuations	Smart grids and hybrid energy systems
Energy Storage Limitations	Reduced reliability and flexibility	Advanced battery and hydrogen technologies
High Capital Investment	Slower adoption in developing regions	Cost reduction and innovative financing
Battery Waste Generation	Environmental management concerns	Circular economy and recycling systems
Grid Integration Complexity	Operational challenges	AI-enabled energy management
Policy and Regulatory Uncertainty	Reduced investor confidence	Stable long-term policy frameworks

As shown in Table 4, future research should focus on developing integrated solutions that combine renewable energy technologies, artificial intelligence, advanced energy storage systems, smart grid infrastructures, circular economy principles, and sustainability assessment frameworks [34–40]. Artificial intelligence and



machine learning technologies offer considerable potential for improving renewable energy forecasting, grid management, predictive maintenance, and operational optimization. Similarly, advances in energy storage technologies will be critical for addressing intermittency challenges and supporting higher levels of renewable energy penetration.

Future studies should also investigate the integration of renewable energy systems with circular economy frameworks to improve resource efficiency and reduce waste generation throughout the technology life cycle. In addition, greater attention should be directed toward developing comprehensive sustainability assessment methodologies that simultaneously evaluate environmental, economic, social, and technological dimensions of renewable energy systems. Such integrated approaches will support evidence-based decision-making and contribute to the development of resilient, low-carbon, and sustainable energy systems capable of meeting future global energy demands [3,8,31,38–40].

11. Conclusion

Renewable energy has emerged as a cornerstone of global sustainability efforts and plays a critical role in addressing climate change, environmental degradation, resource depletion, and energy security challenges. The increasing deployment of solar, wind, hydropower, and biomass technologies has significantly improved opportunities for achieving sustainable development goals while reducing dependence on fossil fuels [2,7,8].

This review demonstrates that renewable energy technologies contribute substantially to environmental sustainability through greenhouse gas emission reduction, improved resource efficiency, pollution prevention, and support for circular economy initiatives. Advances in artificial intelligence, Industry 4.0 technologies, and smart energy systems have further enhanced the operational performance and sustainability potential of renewable energy applications [6,16].

The integration of renewable energy systems with sustainable manufacturing, circular economy principles, and ESG frameworks provides a comprehensive pathway toward long-term sustainability. However, challenges associated with intermittency, energy storage, financing, policy uncertainty, and end-of-life waste management continue to influence large-scale deployment [26,28,31,33]. Addressing these challenges through technological innovation, supportive policy interventions, and interdisciplinary research will be essential for accelerating the global transition toward sustainable energy systems.

Future sustainability strategies should emphasize the development of intelligent, resilient, and resource-efficient energy systems that integrate renewable energy technologies with digital transformation and circular economy principles. Such an approach will support environmental protection, economic development, and social well-being while contributing to global sustainability and carbon neutrality objectives.

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