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Exploring the Latest Advances in Renewable Energy

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ABSTRACT

This paper reviews advanced and emerging research topics in renewable energy, synthesizes recent technological, systems-integration, and policy developments, and proposes future research directions to accelerate decarbonisation of electricity, heat, transport and industrial processes. Key topics covered include perovskite and tandem photovoltaics, floating and deep-water offshore wind, green hydrogen and Power-to-X pathways, next-generation energy storage (solid-state batteries, flow and pumped-hydro innovations), tidal and enhanced geothermal systems, bioenergy with sustainability constraints, and the role of artificial intelligence and digital twins in grid integration and operation. The paper draws on recent reviews, international agency reports and peer-reviewed literature to identify research gaps—particularly in long-term durability, materials sustainability, life-cycle impacts, system-level flexibility, and socio-technical policy design—and outlines a multi-disciplinary research agenda for doctoral and postdoctoral investigation.

Keywords: renewable energy, perovskite, floating offshore wind, green hydrogen, power-to-x, energy storage, solid-state battery, AI, grid integration, life-cycle assessment

INTRODUCTION

The global energy system is undergoing a fundamental transformation driven by the urgent need to mitigate climate change, enhance energy security, and achieve sustainable economic development. Fossil fuel–based energy systems are the largest contributors to anthropogenic greenhouse gas (GHG) emissions, accounting for the majority of carbon dioxide emissions responsible for global warming (IPCC, 2023). In response, renewable energy technologies—such as solar, wind, hydropower, geothermal, and bioenergy—have emerged as central pillars of the global decarbonisation strategy (IEA, 2024).

Over the past two decades, significant cost reductions and efficiency improvements have enabled large-scale deployment of renewable energy, particularly solar photovoltaics (PV) and wind power. However, achieving global net-zero emission targets by mid-century requires more than incremental improvements to existing technologies. It demands advanced research into next-generation renewable energy systems, long-duration energy storage, sector coupling, digitalised grids, and sustainable materials (IRENA, 2024). These advanced research topics form the focus of contemporary renewable energy scholarship and are critical to overcoming the technical, economic, and systemic barriers that still constrain full-scale energy transition.

Advanced renewable energy research is increasingly interdisciplinary, integrating materials science, electrical and mechanical engineering, environmental science, economics, artificial intelligence, and public policy. For example, innovations in perovskite-based solar cells promise higher efficiencies and lower manufacturing costs compared to conventional silicon PV, while floating offshore wind technology expands exploitable wind resources into deep-water regions previously inaccessible (Green et al., 2024; IRENA, 2024). Similarly, green hydrogen produced through renewable-powered electrolysis is gaining prominence as a solution for decarbonising hard-to-abate sectors such as steel, cement, aviation, and long-haul transport (IEA, 2024).

Despite these advances, major challenges remain, including intermittency of renewable energy supply, grid stability under high penetration levels, storage limitations, critical mineral dependencies, and lifecycle environmental impacts. These challenges necessitate sustained doctoral-level research focused on system integration, resilience, and sustainability assessment rather than isolated technology development (Sovacool et al., 2023). Consequently, a comprehensive academic examination of advanced research topics in renewable energy is both timely and necessary.

Statement of the Problem

While renewable energy deployment has accelerated globally, the current pace and technological maturity are insufficient to meet climate targets and energy demand growth simultaneously. Many renewable technologies face limitations related to efficiency ceilings, durability, scalability, and integration into existing energy infrastructures (IEA, 2024). For instance, conventional lithium-ion batteries, though dominant, are constrained by energy density, safety concerns, and resource availability, limiting their suitability for long-duration and grid-scale storage (Liu et al., 2024).

Additionally, renewable energy systems introduce new complexities, such as variable power generation, bidirectional electricity flows, and the need for advanced forecasting and control mechanisms. Power grids originally designed for centralized fossil-fuel generation struggle to accommodate high shares of decentralized and variable renewable energy without significant upgrades and intelligent management systems (Brown et al., 2023). Furthermore, the sustainability of renewable energy technologies themselves—considering land use, material extraction, recycling, and social acceptance—raises important questions that remain inadequately addressed in many deployment strategies (Sovacool et al., 2023).

In developing regions, including Africa, these challenges are compounded by weak infrastructure, limited research funding, policy inconsistencies, and technology transfer gaps. As a result, there is a critical need for advanced research that not only pushes technological frontiers but also contextualizes solutions within socio-economic and policy frameworks suitable for diverse regional conditions. Addressing these gaps forms the core problem that this study seeks to engage.

Aim and Objectives

The primary aim of this paper is to critically examine latest advanced research topics in renewable energy and evaluate their potential contributions to a sustainable, low-carbon energy future.

The specific objectives are to:

1. Investigate the trend of global energy transition and the emergence of renewable energy.
2. Review emerging and advanced renewable energy technologies and their current state of development.
3. Examine the effect of system integration, digitalization, and control system.
4. Explore the availability of materials, efficient manufacturing processes, and resilient supply chains.

Research Questions

This study is guided by the following research questions:

1. What is the trend of global energy transition and the emergence of renewable energy?
2. What are the emerging and advanced renewable energy technologies and their current state of development?
3. What are the effect of system integration, digitalization, and control system?
4. How can materials be accessed for manufacturing processes and in what ways can materials enhance supply chain?

Significance of the study

This study is significant in several respects. Academically, it contributes to the growing body of literature on advanced renewable energy research by synthesising recent developments across multiple disciplines. It provides a structured foundation for researchers seeking to identify impactful and policy-relevant research topics.

Practically, the findings offer insights for policymakers, energy planners, and industry stakeholders on emerging technologies and system-level solutions necessary for achieving energy transition goals. For developing economies, the study highlights pathways for leapfrogging carbon-intensive development trajectories through context-sensitive renewable energy innovation..

Scope and Limitations of the Study

Scopes

The scope of this study covers advanced research topics in renewable energy, including next-generation solar and wind technologies, energy storage systems, green hydrogen and Power-to-X pathways, digitalisation and artificial intelligence in energy systems, and sustainability considerations. While global in perspective, the discussion incorporates implications for developing regions where renewable energy deployment faces unique structural challenges.

Limitations

1. The study does not employ statistical meta-analysis.
2. The selection of literature may also be influenced by publication bias and the availability of English-language sources.

3. Given the fast pace of innovation in renewable energy, some findings may become outdated as new technologies and data emerge.

LITERATURE REVIEW

Global Energy Transition and the Emergence of Renewable Energy

The global energy landscape is undergoing an unprecedented transformation as nations respond to climate change, resource depletion, and growing energy demand. Historically, economic development has relied heavily on fossil fuels, resulting in significant environmental degradation and greenhouse gas emissions. The energy sector alone accounts for approximately three-quarters of global anthropogenic carbon dioxide emissions, making it the single most important sector for climate mitigation (IPCC, 2023). This reality has positioned renewable energy at the core of international climate agreements, including the Paris Agreement, which seeks to limit global temperature rise to well below 2°C above pre-industrial levels.

Renewable energy technologies—solar, wind, hydropower, geothermal, and bioenergy—offer a pathway to decarbonisation by harnessing naturally replenishing energy sources with minimal direct emissions. Over the last decade, rapid technological progress and economies of scale have significantly reduced the cost of renewable electricity, with solar photovoltaic and onshore wind now among the cheapest sources of new power generation in many regions (IEA, 2024). Despite these gains, the transition from fossil-dominated systems to renewable-dominated systems remains complex and incomplete, necessitating deeper scientific and technological inquiry.

Limitations of Conventional Renewable Energy Technologies

While first-generation renewable technologies have proven technically viable and economically competitive, they exhibit inherent limitations that constrain their ability to fully replace fossil fuels. A primary challenge is variability and intermittency, particularly for solar and wind resources, which depend on weather and diurnal cycles. High penetration of variable renewable energy can lead to grid instability, curtailment, and increased balancing costs if not supported by adequate storage, transmission, and demand-side flexibility (Brown et al., 2023).

Furthermore, conventional renewable systems face efficiency and land-use constraints. Silicon-based photovoltaic cells are approaching theoretical efficiency limits, prompting the need for next-generation materials such as perovskite and tandem solar cells (Green et al., 2024). Similarly, onshore wind energy faces spatial limitations, social acceptance challenges, and diminishing returns in saturated regions, underscoring the need for offshore and floating wind innovations (IRENA, 2024).

These limitations demonstrate that existing renewable technologies alone are insufficient to meet long-term decarbonisation goals without significant technological evolution and system-level innovation.

Energy Storage, Flexibility, and System Integration

One of the most critical rationales for advanced renewable research is the need for effective energy storage and system flexibility. As renewable penetration increases, energy systems must manage temporal mismatches between energy supply and demand. Short-term solutions such as lithium-ion batteries are effective for frequency regulation and short-duration storage but are inadequate for long-duration and seasonal storage needs (Liu et al., 2024).

Advanced storage technologies—including solid-state batteries, redox flow batteries, pumped hydro innovations, compressed air energy storage, and hydrogen-based storage—are therefore receiving increasing research attention. These technologies are essential not only for grid stability but also for enhancing energy security and resilience against extreme weather events, which are becoming more frequent due to climate change (IPCC, 2023).

Equally important is the integration of digital technologies, such as artificial intelligence, smart grids, and digital twins, to enable real-time monitoring, forecasting, and optimisation of renewable energy systems. Without such integration, high-renewable energy systems risk inefficiency, reliability issues, and increased system costs (Algburi et al., 2024).

Sustainability, Materials, and Lifecycle Considerations

Although renewable energy technologies are low-carbon during operation, their full lifecycle impacts must be carefully considered. The extraction and processing of materials such as lithium, cobalt, nickel, rare earth elements, and silver raise environmental and social concerns, including ecosystem degradation and human rights issues in mining regions (Sovacool et al., 2023). Additionally, end-of-life management of solar panels, wind turbine blades, and batteries presents growing waste challenges.

Advanced research is therefore required to develop sustainable materials, recycling technologies, and circular economy approaches that minimise environmental footprints while ensuring long-term resource availability. Lifecycle assessment (LCA) and techno-economic analysis (TEA) have become essential tools in evaluating the true sustainability of advanced renewable technologies and guiding policy and investment decisions (IRENA, 2024).

Relevance to Developing Economies and Global Equity

The rationale for advanced renewable energy research is particularly compelling in developing regions, including Africa, where energy access deficits coexist with abundant renewable resources. Decentralised renewable systems, hybrid microgrids, and renewable-based industrialisation offer opportunities for economic development while avoiding carbon-intensive pathways (IEA, 2024). However, limited research infrastructure, financing barriers, and weak policy frameworks often hinder the adoption of advanced technologies in these contexts.

Context-specific research is therefore essential to adapt advanced renewable innovations to local socio-economic realities, climatic conditions, and institutional capacities. Addressing these disparities aligns with global sustainability goals and ensures that the energy transition is both inclusive and equitable.

TECHNOLOGICAL FRONTIERS

Technological innovation lies at the core of the global transition toward renewable energy–dominated systems. While first-generation renewable technologies have achieved significant market penetration, achieving deep decarbonisation requires breakthroughs that extend beyond incremental efficiency gains. Advanced renewable energy technologies are being developed to overcome limitations related to intermittency, scalability, material sustainability, and system integration (IEA, 2024). This section examines the major technological frontiers shaping contemporary renewable energy research, focusing on next-generation solar photovoltaics, advanced wind energy systems, green hydrogen and Power-to-X pathways, emerging energy storage technologies, marine and geothermal energy, and sustainable bioenergy innovations.

1. Next-Generation Solar Photovoltaic Technologies

Solar photovoltaic (PV) technology has experienced rapid global expansion due to declining costs and modular scalability. However, conventional crystalline silicon PV is approaching its theoretical efficiency limit, prompting intensive research into next-generation alternatives (Green et al., 2024). Among these, perovskite solar cells (PSCs) and tandem PV architectures represent the most promising technological frontier.

Perovskite solar cells have demonstrated exceptional progress, with laboratory efficiencies exceeding 26% within a decade of research, a rate of improvement unprecedented in PV history (NREL, 2024). Their advantages include low-temperature processing, tunable bandgaps, and compatibility with flexible substrates. Perovskite–silicon tandem cells combine the strengths of both materials and offer the potential to surpass the single-junction Shockley–Queisser efficiency limit (Green et al., 2024).

Despite their promise, PSCs face critical challenges related to long-term stability, moisture sensitivity, lead toxicity, and large-scale manufacturability. Consequently, current research efforts focus on advanced encapsulation, lead-free perovskite formulations, and scalable deposition techniques such as roll-to-roll printing (Snaith et al., 2023). Addressing these challenges is essential for transitioning perovskite technologies from laboratory demonstrations to commercial deployment.

2. Advanced Wind Energy Technologies

Wind energy continues to be a major contributor to renewable electricity generation, yet technological frontiers are rapidly expanding beyond traditional onshore installations. Offshore wind, particularly floating offshore wind, represents a significant advancement by enabling power generation in deep-water regions with stronger and more consistent wind resources (IRENA, 2024).

Floating offshore wind turbines are mounted on buoyant platforms anchored to the seabed, allowing deployment in water depths exceeding 60 meters. This technology significantly expands the geographic potential for wind energy, especially for countries with limited shallow coastal waters. Current research priorities include platform design optimisation, mooring system reliability, turbine-platform dynamic interactions, and cost reduction through standardisation and mass production (Musial et al., 2023).

In parallel, advances in turbine size, materials, and digital monitoring systems are enhancing energy capture and operational efficiency. The use of advanced composites, condition-based maintenance, and digital twins has improved turbine longevity and reduced lifecycle costs (IEA, 2024). However, environmental impacts, grid integration challenges, and social acceptance issues remain important considerations for large-scale offshore deployment.

3. Green Hydrogen and Power-to-X Technologies

Green hydrogen has emerged as a cornerstone technology for decarbonising sectors that are difficult to electrify directly. Produced via water electrolysis using renewable electricity, green hydrogen can serve as both an energy carrier and an industrial feedstock with near-zero lifecycle emissions (IEA, 2024).

Power-to-X (P2X) technologies extend the value of renewable electricity by converting it into hydrogen-based fuels, synthetic hydrocarbons, ammonia, and chemicals. These pathways are particularly relevant for long-distance transport, aviation, maritime shipping, and high-temperature industrial processes (Oyewo et al., 2024). Research efforts focus on improving electrolyser efficiency, durability, and flexibility, particularly under variable renewable energy input.

Key technological challenges include high production costs, infrastructure requirements for storage and transport, and uncertainties surrounding market demand and policy support. Consequently, advanced research increasingly integrates techno-economic modelling with pilot-scale demonstrations to identify viable deployment pathways under different policy and market scenarios (IEA, 2024).

4. Emerging Energy Storage Technologies

Energy storage is a critical enabler of high renewable energy penetration, providing flexibility, reliability, and resilience. While lithium-ion batteries dominate current markets, their limitations have driven research into advanced storage technologies suitable for long-duration and grid-scale applications (Liu et al., 2024).

Solid-state batteries (SSBs) represent a major technological frontier due to their potential for higher energy density, improved safety, and longer lifespan compared to conventional batteries. Research challenges include solid-electrolyte conductivity, interface stability, and scalable manufacturing processes (Zhang et al., 2023). Redox flow batteries, which decouple power and energy capacity, are also gaining attention for stationary storage due to their long cycle life and scalability.

Beyond electrochemical storage, innovations in pumped hydro, compressed air energy storage, and gravity-based systems are expanding the portfolio of long-duration storage options. These technologies play a crucial role in balancing seasonal renewable energy variability and enhancing energy system resilience (IRENA, 2024).

5. Marine and Geothermal Energy Technologies

Marine and geothermal energy technologies offer stable and predictable renewable power sources that complement variable solar and wind generation. Tidal and wave energy systems harness ocean dynamics, while enhanced geothermal systems (EGS) exploit subsurface heat resources beyond conventional geothermal reservoirs (Tester et al., 2023).

Although marine energy technologies are at relatively early stages of commercialisation, advances in turbine design, corrosion-resistant materials, and real-time monitoring have improved their viability. Similarly, EGS research focuses on drilling technologies, reservoir stimulation techniques, and risk mitigation for induced seismicity (IEA, 2024). These technologies hold particular promise for providing baseload renewable power in suitable geographic regions.

6. Sustainable Bioenergy and Renewable Fuels

Bioenergy remains an important component of the renewable energy mix, particularly when integrated with sustainability safeguards. Advanced bioenergy research emphasises second- and third-generation biofuels derived from non-food biomass, agricultural residues, and algae to avoid competition with food production (Sovacool et al., 2023).

Innovations in bioenergy include advanced biochemical and thermochemical conversion processes, bioenergy with carbon capture and storage (BECCS), and the production of renewable fuels and biochemicals. However, sustainability concerns related to land use, biodiversity, and lifecycle emissions necessitate robust assessment frameworks and policy oversight (IRENA, 2024).

SYSTEMS INTEGRATION, DIGITALIZATION AND CONTROL

As renewable energy penetration increases, the focus of energy research has shifted from individual technologies to **system-level integration, digitalisation, and intelligent control**. Renewable-dominated energy systems are inherently more complex than conventional fossil-based systems due to variability, decentralisation, and bidirectional power flows. Effective systems integration is therefore essential to ensure grid stability, reliability, and economic efficiency (IEA, 2024).

1. Grid Integration of Variable Renewable Energy

Variable renewable energy (VRE) sources such as solar and wind introduce fluctuations in electricity supply that challenge traditional power system operations. High VRE penetration can result in frequency instability, voltage deviations, congestion, and curtailment if not properly managed (Brown et al., 2023). Advanced grid integration strategies include enhanced transmission infrastructure, flexible generation, demand-side management, and energy storage.

Sector coupling—the integration of electricity with heating, cooling, transport, and industry—has emerged as a critical systems integration strategy. By enabling flexible demand and cross-sector energy flows, sector coupling improves system efficiency and facilitates deeper decarbonisation (IEA, 2024). Research increasingly focuses on optimal coordination between power, gas, and heat networks using integrated energy system models.

2. Digitalization and Smart Energy Systems

Digitalization plays a pivotal role in enabling renewable energy integration. Smart grids employ digital sensors, advanced metering infrastructure, and communication technologies to monitor and manage energy flows in real time. These systems enhance situational awareness, reduce losses, and support the integration of distributed energy resources such as rooftop PV, electric vehicles, and battery storage (IRENA, 2024).

Artificial intelligence (AI) and machine learning are increasingly applied to renewable energy systems for forecasting, predictive maintenance, and optimisation. Improved wind and solar forecasting reduces balancing costs and enhances grid reliability, while AI-based fault detection minimises downtime and maintenance costs (Algburi et al., 2024). However, challenges related to data quality, cybersecurity, and algorithm transparency remain important research areas.

3. Control Strategies and Energy Management

Advanced control strategies are essential for coordinating diverse and distributed renewable energy assets. Hierarchical and decentralised control architectures enable real-time decision-making across generation, storage, and demand-side resources (Olivares et al., 2014). Energy management systems (EMS) optimise dispatch, storage utilisation, and demand response based on price signals, forecasts, and system constraints.

Digital twins—virtual replicas of physical energy assets—are emerging as powerful tools for system optimisation and scenario analysis. By integrating real-time data with simulation models, digital twins support predictive control, performance optimisation, and risk management (IEA, 2024). These innovations are particularly valuable in complex systems such as offshore wind farms and integrated renewable–hydrogen hubs.

Challenges

Despite significant progress, systems integration and digitalisation face several challenges. Interoperability between heterogeneous devices and platforms remains limited, and regulatory frameworks often lag behind technological innovation. Additionally, the increasing reliance on digital infrastructure exposes energy systems to cybersecurity risks (IRENA, 2024).

Future research must therefore focus on resilient system architectures, standardised communication protocols, explainable AI for critical decision-making and regulatory mechanisms that incentivise flexibility and innovation. Addressing these challenges is essential for achieving reliable and scalable renewable energy systems.

MATERIALS, MANUFACTURING, AND SUPPLY-CHAIN RESILIENCE

The large-scale deployment of advanced renewable energy technologies is highly dependent on the availability of materials, efficient manufacturing processes, and resilient supply chains. While renewable energy systems reduce operational emissions, their production relies on critical minerals and global manufacturing networks that are vulnerable to geopolitical, economic, and environmental disruptions (IEA, 2024).

Critical Materials and Resource Constraints

Many renewable energy technologies rely on materials such as lithium, cobalt, nickel, rare earth elements, silver, and copper. These materials are essential for batteries, wind turbines, solar panels, and electric motors. However, their extraction and processing are geographically concentrated, raising concerns about supply security and price volatility (IEA, 2024).

Key materials

1. Rare Earth Metals: Neodymium, dysprosium, and terbium are crucial for wind turbine generators and electric motors. Africa holds significant reserves, with the DRC dominating global cobalt supply (19.95% in 2024) (USGS, 2024).
2. Lithium: Essential for batteries, lithium production is rising, with Africa producing 124,230 tons of lithium carbonate equivalent (LCE) in 2024 (Benchmark Mineral Intelligence, 2024). China dominates lithium processing (32% global production) (IEA, 2022).
3. Silicon: Dominates photovoltaic (PV) cells (90% market share) (Fraunhofer ISE, 2023). Advances in perovskite materials promise higher efficiencies and lower costs (NREL, 2023).
4. Graphite and Cobalt: Critical for batteries and magnets. Africa's DRC and Zambia are key suppliers (Amnesty International, 2022).

Resource Constraints:

1. Supply Chain Risks: Concentration of production in few countries (e.g., China's 81% rare earth processing capacity) (USGS, 2024).
2. Environmental Concerns: Mining impacts and e-waste management (OECD, 2020). For instance Nigeria generates approximately 500,000 metric tons of e-waste annually, making it the third-highest in Africa (UNEP, 2020).
3. Cost and Accessibility: High-purity materials and advanced composites increase costs (BloombergNEF, 2023). High extraction and processing costs for lithium and cobalt increase the overall cost of renewable energy technologies. Also, limited investment in mining infrastructure and technology exacerbates costs.

Advanced research focuses on reducing material intensity, substituting scarce materials with earth-abundant alternatives, and improving recycling technologies. For example, battery research increasingly targets cobalt-free chemistries, while solar PV research explores silver reduction and lead-free perovskite formulations (Liu et al., 2024).

Advanced Manufacturing and Scalability

Manufacturing innovation is critical for scaling advanced renewable technologies while maintaining cost competitiveness. Automation, additive manufacturing, and digital manufacturing platforms are being explored to improve production efficiency, quality control, and flexibility (IRENA, 2024).

Key developments include:

developing 18 MW turbines (BloombergNEF, 2023) and Siemens Gamesa testing units of up to 21.5 MW (Reuters, 2023).

2. Digital Turbine Controls: Digitization of turbines is improving their responsiveness, efficiency, and longevity through AI-driven optimization and predictive maintenance (IEA, 2022).
3. Floating Offshore Platforms: Innovations like floating wind farms (Equinor, 2023) and hybrid hydro-solar systems (NREL, 2022) are expanding the geographic reach of renewable energy.
4. Advanced Materials & Recycling: Researchers are exploring new materials and recycling techniques to improve efficiency and reduce waste in solar panels (Fraunhofer ISE, 2023) and wind turbines (NREL, 2022).
5. 3D Printing and Customization: Advanced manufacturing techniques like 3D printing enable faster prototyping, lightweight component production, and cost-effective customization (McClean, 2023).

While scalability is addressed through:

1. Hybrid Renewable Energy Systems: Combining solar, wind, and hydro energy to overcome intermittency and optimize energy generation (IEA, 2022).
2. Energy Storage Innovations: Flow batteries, supercapacitors, and other technologies are emerging to provide scalable and efficient energy storage solutions (BloombergNEF, 2023).
3. Smart Grids and AI: AI-driven energy management and smart grids are enhancing energy distribution efficiency and integrating renewable sources (IEA, 2022).

Supply-Chain Resilience and Circular Economy

The COVID-19 pandemic and recent geopolitical tensions have highlighted the vulnerability of global energy supply chains. Renewable energy supply chains must therefore be designed with resilience in mind, incorporating diversification, regional manufacturing, and strategic stockpiling (IEA, 2024).

Core developments in supply-chain resilience and circular economy include:

1. Diversification of Sources: Relying on multiple suppliers and regions can reduce the impact of localized disruptions (IEA, 2022). For instance, solar panel manufacturers can source silicon from various countries to mitigate risks.
2. Circular Economy Practices: Implementing circular economy principles can enhance sustainability (World Economic Forum, 2023). This includes designing products for longevity, promoting reuse and recycling, and reducing waste.
3. Digitalization: Integrating digital tools and platforms can enhance visibility, efficiency, and resilience in supply chains (BloombergNEF, 2023).
4. Regulatory Frameworks: Clear and supportive regulatory frameworks are crucial for guiding and accelerating the transition to a circular energy system (European Commission, 2020).
5. Energy Storage Innovations: Flow batteries, supercapacitors, and other technologies are emerging to provide scalable and efficient energy storage solutions (BloombergNEF, 2023; NREL, 2022).

Circular economy approaches—such as design for recycling, material recovery, and product life extension—offer pathways to reduce resource dependence and environmental impacts. Lifecycle-based supply-chain planning enhances both sustainability and resilience, making it a key area for future research and policy development (IRENA, 2024).

Summary of the Findings

1. **Technological Advancements are Pivotal:** Next-generation solar photovoltaics, floating offshore wind, green hydrogen, advanced energy storage, marine and geothermal energy, and sustainable bioenergy represent critical frontiers with the potential to overcome the limitations of first-generation technologies (Green et al., 2024; Musial et al., 2023; IEA, 2024).
2. **Systems Integration and Digitalisation are Essential:** High penetration of variable renewable energy necessitates intelligent grid management, sector coupling, AI-based forecasting, and digital twins to enhance reliability, efficiency, and resilience (Algburi et al., 2024; Brown et al., 2023).

3. **Materials, Manufacturing, and Supply Chains Must Be Resilient:** Critical materials, global supply dependencies, and manufacturing constraints represent significant barriers to large-scale deployment. Circular economy approaches and materials substitution are essential to ensure sustainability and security (Liu et al., 2024; IRENA, 2024).
4. **Environmental, Social, and Economic Considerations are Integral:** Renewable energy deployment must account for lifecycle environmental impacts, social acceptance, equity, and economic feasibility. Integrated assessment frameworks are crucial for informed policy and investment decisions (Sovacool et al., 2023; IPCC, 2023).

CONCLUSIONS

This paper has critically examined advanced research topics in renewable energy, encompassing technological frontiers, systems integration, materials innovation, and socio-economic considerations. The study highlights that achieving a sustainable; low-carbon energy future requires not only the deployment of mature renewable technologies but also sustained research into next-generation solutions, system-level optimisation, and holistic sustainability frameworks.

Overall, this study underscores that the renewable energy transition is an interdisciplinary challenge. A coordinated research agenda that integrates technological innovation, system integration, materials sustainability, and socio-economic considerations is essential to accelerate global decarbonisation while ensuring equity and resilience.

RECOMMENDATIONS

Based on the findings and research gaps identified, the following recommendations are proposed for researchers, policymakers, and industry stakeholders:

1. **For Researchers:**
    - Prioritise long-term experimental and field studies on next-generation renewable technologies to validate performance, durability, and degradation models (Snaith et al., 2023).
    - Investigate integrated system models combining energy generation, storage, and sector coupling to optimise flexibility and reliability (Brown et al., 2023).
    - Develop explainable and resilient AI models for forecasting and grid management, ensuring cybersecurity and operational transparency (Algburi et al., 2024).
    - Conduct lifecycle and techno-economic analyses that incorporate environmental, social, and economic dimensions, particularly for developing regions (Sovacool et al., 2023; IPCC, 2023).
2. **For Policymakers:**
    - Support policies that incentivise research and deployment of advanced renewable technologies, including grants, tax incentives, and innovation hubs (IEA, 2024).
    - Promote circular economy approaches in renewable energy supply chains, encouraging recycling, materials substitution, and regional manufacturing (IRENA, 2024).
    - Strengthen regulatory frameworks for grid integration, digitalisation, and energy justice to ensure equitable access, reliability, and resilience.
3. **For Industry and Practitioners:**
    - Invest in scalable and flexible manufacturing technologies to reduce costs and enhance quality for emerging renewable systems (Liu et al., 2024).
    - Collaborate with research institutions to pilot innovative renewable systems, including floating offshore wind, green hydrogen, and long-duration storage solutions.
    - Integrate environmental, social, and economic considerations into project planning, ensuring community engagement and sustainable deployment.

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