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Current and Future Sustainable Energy Systems Worldwide: Technologies, System Integration, and Transition Pathways – A Review

I. C. Onuguh[1], D.C. McSatty[1], and F.E. Omofuma[2]
[1]Department of Chemistry, Igbinedion University Okada, Edo State Nigeria
[2]Department of Chemical & Petroleum Engineering, Igbinedion University Okada, Edo State Nigeria

Corresponding Author:
I.C. Onuguh
onuguh.chibueze@iuokada.edu.ng
08062943787

ABSTRACT
The global transition toward sustainable energy systems is central to achieving climate mitigation, energy security, and long-term socioeconomic development goals. While renewable energy technologies such as solar, wind, hydropower, and energy storage have experienced rapid deployment worldwide, their large-scale integration has revealed significant system-level challenges related to variability, storage limitations, infrastructure constraints, and sectoral decarbonization gaps. These challenges indicate that achieving net-zero energy systems requires more than the substitution of fossil fuels with renewable technologies. This review provides a comprehensive, system-level assessment of current and future sustainable energy systems, focusing on technologies, system integration, and transition pathways. Current sustainable energy technologies are reviewed and critically assessed based on their present applications and limitations. Emerging and future technologies—including advanced renewable systems, long-duration energy storage, hydrogen and Power-to-X pathways, firm low-carbon energy options, carbon removal technologies, and smart digital energy systems—are examined as complementary solutions designed to address the structural limitations of existing systems. The study synthesizes recent peer-reviewed literature and authoritative global energy reports to highlight the importance of system integration, including sector coupling, multi-timescale energy storage, digitalization, and coordinated infrastructure planning. The review further emphasizes that energy transition pathways are adaptive, portfolio-based, and region-specific, shaped by resource availability, infrastructure, policy frameworks, and socioeconomic conditions. Overall, the findings demonstrate that sustainable energy transitions are fundamentally system transformations rather than technology substitutions. The review contributes a structured framework for understanding how current and future technologies can be integrated into resilient, reliable, and equitable net-zero energy systems, while identifying key research gaps and priorities for future energy system development.

Keywords: Sustainable energy systems; Renewable energy technologies; Energy system integration; Energy transition pathways; Emerging energy technologies; Long-duration energy storage; Hydrogen energy systems; Power-to-X; Net-zero energy systems; Decarbonization

1. INTRODUCTION

The global energy system is undergoing a profound transformation driven by the urgent need to address climate change, improve energy security, and support sustainable socioeconomic development. The energy sector is responsible for nearly three-quarters of global greenhouse gas emissions, placing it at the center of efforts to meet international climate goals, including limiting global warming to 1.5 °C above pre-industrial levels (IPCC, 2023). As a result, accelerating the transition from fossil fuel–based systems to sustainable energy systems has become a key priority for governments, industries, and research communities worldwide.

In response to this challenge, renewable energy technologies such as solar, wind, hydropower, and bioenergy have expanded rapidly over the past decade, supported by declining costs and policy incentives (IEA, 2024). Energy storage technologies and hydrogen systems are also gaining attention as enablers of flexibility and sector coupling. Despite this progress, the large-scale deployment of these technologies has revealed significant system-level challenges, including variability of renewable generation, limited long-duration energy storage, grid and infrastructure constraints, and persistent difficulties in decarbonizing transport, industry, and heating sectors (IEA, 2023a; IRENA, 2023).

These challenges highlight a critical limitation of many existing studies, which tend to focus on individual technologies in isolation rather than on how technologies interact within complex energy systems. In practice, energy systems consist of interconnected components involving electricity generation, storage, transmission and distribution networks, end-use sectors, and governance frameworks. Without effective system integration, high shares of renewable energy can lead to inefficiencies, increased curtailment, and reliability concerns, even when sufficient generation capacity is available (Lund *et al.,* 2021).

At the same time, a new generation of emerging and future sustainable energy technologies is being developed to address the structural limitations of current systems. These include advanced renewable technologies, long-duration energy storage, hydrogen and Power-to-X pathways, firm low-carbon energy options, carbon removal technologies, and smart digital energy systems (IEA, 2024; IPCC, 2023). While these technologies hold significant promise, they vary widely in maturity, cost, and system role, and their contributions are best understood as complementary rather than substitutive.

Against this background, there is a growing need for integrated, system-level reviews that connect current technologies, emerging solutions, and transition pathways within a unified analytical framework. Such an approach is essential for understanding how sustainable energy systems can evolve over time toward reliable, resilient, and net-zero configurations, while accounting for regional differences in resources, infrastructure, and socioeconomic conditions (IRENA, 2023).

This review addresses this need by providing a comprehensive assessment of current and future sustainable energy systems worldwide, with a focus on technologies, system integration, and transition pathways. The study reviews key current technologies and their limitations, examines emerging and future solutions designed to overcome these challenges, and synthesizes insights on system integration and adaptive transition pathways. By adopting a system-oriented perspective, this review aims to support researchers, policymakers, and practitioners in designing effective and equitable pathways toward long-term sustainable energy futures.

2. Review Methodology

This review adopts a structured semi-systematic literature review approach to investigate current knowledge on sustainable energy systems and emerging future energy technologies at the global scale. A semi-systematic methodology is particularly suitable for interdisciplinary research domains such as sustainable energy, where studies span engineering, energy systems analysis, environmental science, and policy research, and where both conceptual integration and thematic synthesis are required (Snyder, 2019). This approach enables comprehensive coverage of recent developments while allowing flexibility to incorporate diverse perspectives on technology evolution, system integration, and transition pathways.

2.1 Literature Search Strategy

The literature search was conducted primarily using the Scopus database, which was selected due to its extensive coverage of peer-reviewed journals in energy, engineering, and sustainability research. To ensure completeness, Web of Science and IEEE Xplore were used as complementary databases, particularly for system-level studies and emerging technology research. Similar multi-database strategies are widely recommended for reviews addressing complex energy systems to reduce database bias and improve coverage (Tranfield *et al*., 2003; Xiao & Watson, 2019).

Search queries were developed using combinations of keywords related to sustainable energy systems, emerging and future energy technologies, system integration, and energy transition pathways. Representative search terms included *"sustainable energy systems," "future energy technologies," "energy system integration," "net-zero energy systems,"* and *"energy transition pathways."* Boolean operators, truncation, and field restrictions (title, abstract, and keywords) were applied to refine search results and ensure relevance.

2.2 Inclusion and Exclusion Criteria

To ensure the timeliness and relevance of the reviewed literature, this study focused primarily on peer-reviewed journal articles published between 2019 and 2024, reflecting the rapid evolution of sustainable energy technologies and transition research. Earlier publications were included selectively when they provided foundational system-level frameworks or highly cited conceptual models that remain relevant to current research. Studies were included if they addressed sustainable or low-carbon energy systems, emerging or future energy technologies, system integration, or transition pathways at regional or global scales.

Articles were excluded if they focused exclusively on single technologies without broader system implications, lacked relevance to sustainability or decarbonization objectives, or were non-peer-reviewed. In addition, conference papers and grey literature were generally excluded, except for selected reports from internationally recognized organizations where they provided authoritative insights into global energy trends and transition scenarios (IEA, 2023; IRENA, 2023).

2.3 Screening and Selection Process

The initial database search produced a large pool of publications, which were screened through a multi-stage process. First, titles and abstracts were reviewed to eliminate clearly irrelevant studies. Second, full-text screening was conducted to assess alignment with the objectives of this review, particularly the emphasis on current and future sustainable energy systems, system integration, and global transition pathways. The final set of selected articles was analyzed thematically, allowing the identification of dominant research trends, emerging technologies, and key system-level challenges, consistent with established practices for semi-systematic reviews (Snyder, 2019, Xiao & Watson, 2019).

2.4 Scope and Limitations

While this review aims to provide a comprehensive and forward-looking synthesis of sustainable energy systems, several limitations are acknowledged. The rapid pace of technological development means that cost estimates, performance metrics, and technology readiness levels for emerging energy technologies may evolve beyond the time frame considered. Furthermore, although the review adopts a global perspective, it does not attempt to provide exhaustive country-specific policy or market analyses. Instead, the focus is placed on system-level trends, comparative insights, and widely recognized transition frameworks, which are more robust to regional and temporal variability.

Figure 1 provides a conceptual framework summarizing the evolution from current sustainable energy technologies to emerging and future solutions, and their integration into resilient, net-zero energy systems.

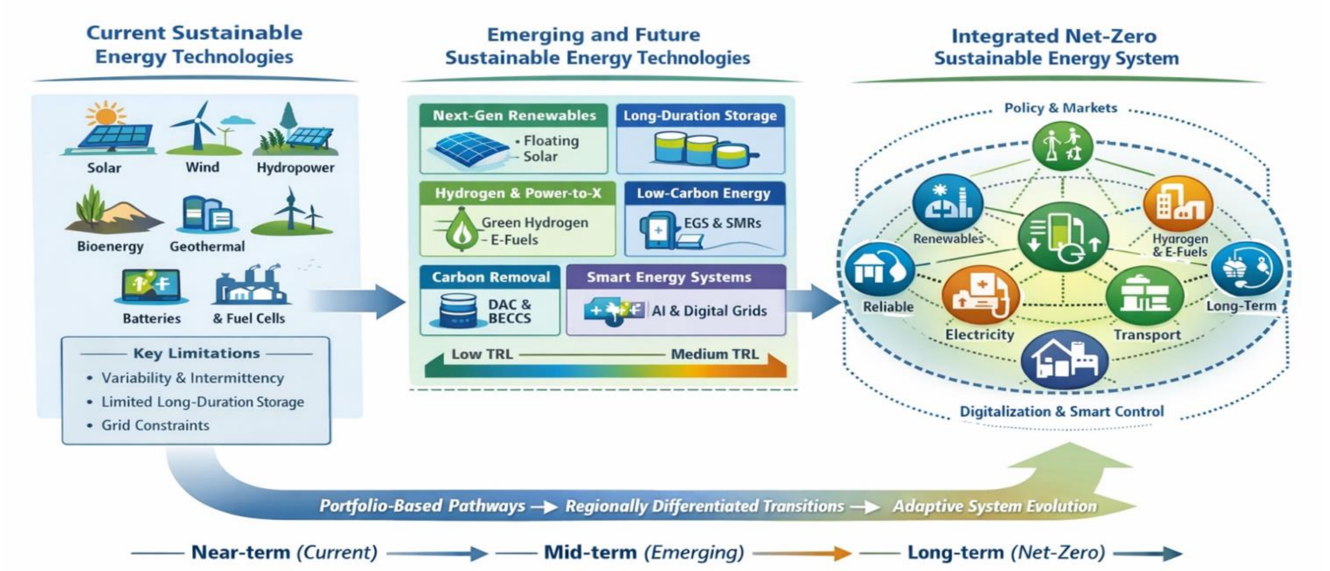

Figure 1: Conceptual framework of current and future sustainable energy systems and transition pathways

3. Current Sustainable Energy Technologies and Their System-Level Challenges

Current sustainable energy technologies constitute the foundation of ongoing global efforts to decarbonize energy systems. As summarized in Table 1, these technologies are already deployed at various scales and play important roles in electricity generation, energy storage, and sector coupling. However, their large-scale integration into energy systems reveals several technical, economic, and structural challenges that limit their ability to fully replace fossil fuel–based systems on their own.

3.1 Solar Energy Systems

Solar energy systems primarily include photovoltaic (PV) and solar thermal technologies that convert sunlight into electricity or heat. Solar PV is widely deployed at both distributed and utility scales due to its rapidly declining costs and modular nature (IEA, 2024). It currently plays a major role in electricity generation in many regions worldwide.

Despite its widespread adoption, solar energy is inherently variable and dependent on daylight and weather conditions. This intermittency creates challenges for grid stability and requires complementary storage or flexible demand solutions. In addition, large-scale deployment raises concerns related to land use, material supply chains, and end-of-life recycling of PV modules (IRENA, 2023).

3.2 Wind Energy Systems

Wind energy systems, including onshore and offshore wind turbines, convert kinetic energy from wind into electricity. Wind power is one of the fastest-growing renewable energy sources and contributes significantly to low-carbon electricity generation in many countries (GWEC, 2023).

However, wind energy output varies with wind availability, leading to temporal and spatial mismatches between supply and demand. Offshore wind faces additional challenges related to high capital costs, complex installation, and grid connection requirements. Public acceptance and environmental concerns also influence deployment in certain regions (IEA, 2024).

3.3 Hydropower Systems

Hydropower systems generate electricity by harnessing the potential energy of flowing or stored water. Unlike solar and wind, hydropower can provide dispatchable and flexible power, making it a valuable balancing resource in renewable-dominated systems (IEA, 2023a).

Nevertheless, large hydropower projects can have significant ecological and social impacts, including habitat disruption and community displacement. Climate change–induced variability in water availability also affects hydropower reliability, while opportunities for new large-scale projects are increasingly limited in many regions (IRENA, 2023).

3.4 Bioenergy Systems

Bioenergy systems produce electricity, heat, or fuels from biomass resources such as agricultural residues, forest products, and organic waste. Bioenergy offers dispatchable energy and can support energy storage in the form of biofuels (IPCC, 2023).

The sustainability of bioenergy remains a key concern. Competing land use, lifecycle greenhouse gas emissions, and impacts on food security limit the scale at which bioenergy can be responsibly deployed. As a result, bioenergy is increasingly viewed as a targeted solution rather than a universal replacement for fossil fuels (Searchinger *et al*., 2020).

3.5 Geothermal Energy Systems

Geothermal energy systems utilize heat from the Earth's interior to produce electricity and provide direct heating. Where resources are available, geothermal energy offers reliable, low-carbon baseload power (IEA, 2024).

However, conventional geothermal deployment is geographically constrained and often associated with high upfront exploration costs and geological risks. These limitations restrict its contribution to global energy supply despite its technical advantages (IRENA, 2023).

3.6 Battery Energy Storage Systems

Battery energy storage systems, particularly lithium-ion batteries, are widely used for short-duration storage, grid balancing, and integration of variable renewable energy. Batteries play an essential role in stabilizing power systems with high shares of solar and wind generation (IEA, 2023a).

Key challenges include limited storage duration, material supply risks, degradation over time, and recycling constraints. These factors limit the ability of batteries to address long-term or seasonal energy balancing on their own (IRENA, 2023).

3.7 Pumped Hydropower Storage

Pumped hydropower storage stores energy by pumping water to a higher elevation during periods of excess electricity and releasing it to generate power when needed. It currently represents the largest form of grid-scale energy storage globally (IEA, 2023a).

Despite its maturity and long lifetime, pumped hydropower is constrained by geographical suitability, environmental impacts, and lengthy permitting processes. These challenges restrict its expansion in many regions (IEA, 2024).

3.8 Hydrogen Energy Systems

Hydrogen energy systems use hydrogen as an energy carrier for storage, transport, and end-use applications. Currently, hydrogen is mainly produced from fossil fuels and used in industrial processes, with growing interest in low-carbon and renewable hydrogen pathways (IEA, 2023b).

While hydrogen enables sector coupling and long-term energy storage, present systems face low overall efficiency, high costs, and limited infrastructure. These constraints limit hydrogen's near-term role in energy systems dominated by direct electrification (IRENA, 2023).

3.9 Fuel Cell Technologies

Fuel cell technologies convert hydrogen or other fuels directly into electricity and heat through electrochemical processes. Fuel cells are used in niche applications such as backup power, material handling, and demonstration-scale transport systems (IEA, 2023b).

Challenges include high capital costs, durability issues, and reliance on hydrogen supply infrastructure. As a result, fuel cells are currently complementary technologies rather than mainstream power generation solutions (IPCC, 2023).

3.10 Synthesis of Current Technology Limitations

In summary, the technologies presented in Table 1 play vital roles in current sustainable energy systems but exhibit structural limitations when deployed at scale. Variability, storage duration constraints, infrastructure requirements, and sustainability concerns collectively limit their ability to fully decarbonize energy systems. These challenges provide the motivation for the emerging and future technologies discussed in the next section.

Table 1: Comparison of Current Sustainable Energy Technologies: Limitations and Proposed Solutions

Technology	Primary Role in Current Energy Systems	Key Limitations	Proposed / Ongoing Solutions
Solar energy (PV & CSP)	Electricity generation	Intermittency and diurnal variability; land use for large-scale PV; reliance on critical materials; end-of-life recycling challenges	Grid-scale and distributed storage; demand-side management; advanced grid integration; material-efficient PV designs; recycling and circular-economy approaches (IEA, 2024; Fraunhofer ISE, 2024)
Wind energy (onshore & offshore)	Large-scale low-carbon electricity generation	Variability and site dependence; transmission bottlenecks; environmental and social acceptance issues	Expanded transmission infrastructure; hybrid systems with storage; offshore wind deployment; improved siting and environmental mitigation strategies (GWEC, 2023; REN21, 2023)
Hydropower	Dispatchable renewable electricity and grid flexibility	Ecosystem disruption; social displacement; climate sensitivity to droughts; limited new sites	Modernization of existing plants; pumped hydropower optimization; improved environmental flow management; climate-resilient planning (IEA, 2023a; IPCC, 2023)
Bioenergy / biomass systems	Dispatchable electricity, heat, and transport fuels	Land-use competition; feedstock sustainability concerns; lifecycle emissions uncertainty	Use of residues and wastes; sustainability certification; integration with carbon capture (BECCS); limited, targeted

Technology	Primary Role in Current Energy Systems	Key Limitations	Proposed / Ongoing Solutions
			deployment (Searchinger et al., 2020; IEA, 2023b)
Geothermal energy	Baseload electricity and direct heat	Geographical constraints; high upfront costs; exploration risks; induced seismicity	Enhanced geothermal systems (EGS); risk-sharing mechanisms; improved drilling technologies; hybrid geothermal systems (IRENA, 2023; IEA, 2024)
Battery energy storage (mainly Li-ion)	Short-duration storage and grid balancing	Limited duration; material supply risks; degradation and recycling challenges	Alternative chemistries; recycling infrastructure; integration with long-duration storage; improved system design (IEA, 2023a; Sepulveda et al., 2021)
Pumped hydropower storage	Large-scale, long-duration electricity storage	Geographic constraints; environmental impacts; long permitting timelines	Repurposing existing reservoirs; closed-loop systems; hybrid storage portfolios (IEA, 2023a; IRENA, 2023)
Hydrogen energy systems	Energy carrier for storage, industry, transport, and power	Low system efficiency; high costs; limited infrastructure; reliance on renewable electricity availability	Cost reductions in electrolysis; hydrogen carriers (ammonia, LOHCs); infrastructure development; sector coupling (IEA, 2023c; IRENA, 2023)
Fuel-cell technologies	Conversion of hydrogen to electricity and heat	High capital costs; durability and material constraints; infrastructure dependence	Materials innovation; scale-up manufacturing; integration with green hydrogen systems (IEA, 2023c; IRENA, 2023)

4. Emerging and Future Sustainable Energy Technologies

Building on the limitations of current sustainable energy systems discussed in Section 3, this section examines emerging and future sustainable energy technologies that form the basis of Table 2. These technologies are designed to overcome structural challenges such as variability, insufficient long-duration storage, sectoral decarbonization gaps, and system inflexibility. Rather than replacing existing solutions, they are increasingly viewed as complementary components of integrated, low-carbon energy systems.

4.1 Perovskite Solar Cells

Perovskite solar cells are next-generation photovoltaic technologies characterized by high power conversion efficiencies and low material requirements. Compared with conventional silicon photovoltaics, perovskite cells offer the potential for higher efficiency and lower manufacturing costs, particularly when deployed in tandem configurations (Green *et al.,* 2023). Their key contribution lies in improving land-use efficiency and energy yield. However, long-term stability, scalability, and concerns related to lead-based materials remain significant challenges (IEA, 2024).

4.2 Tandem Solar Cells

Tandem solar cells combine multiple absorber layers to capture a broader spectrum of sunlight, thereby exceeding the efficiency limits of single-junction solar cells. Silicon–perovskite tandems, in particular, can substantially increase electricity output without increasing land or infrastructure requirements (IRENA, 2023). Despite their promise, challenges persist in manufacturing complexity, durability, and cost-effective large-scale deployment.

4.3 Floating Solar Photovoltaics

Floating solar photovoltaic systems are installed on water bodies such as reservoirs and lakes, reducing competition for land and enabling synergies with existing hydropower infrastructure. These systems can improve overall system efficiency by reducing water evaporation and benefiting from natural cooling effects (IRENA, 2023). However, higher installation costs, environmental impacts on aquatic ecosystems, and long-term structural reliability require further investigation.

4.4 Floating Offshore Wind

Floating offshore wind technology enables wind energy deployment in deep-water regions where fixed-bottom turbines are not feasible. This significantly expands the global wind resource base and offers access to stronger and more consistent wind speeds (GWEC, 2023; IEA, 2024). Key challenges include high capital costs, complex installation processes, and the need for dedicated offshore transmission infrastructure.

4.5 Airborne Wind Energy Systems

Airborne wind energy systems use tethered kites or drones to harvest high-altitude wind resources, which are typically stronger and more consistent than surface winds. These systems could reduce material use and expand deployment flexibility compared to conventional turbines (REN21, 2023). However, airborne wind remains at an early development stage, facing regulatory, safety, and reliability challenges.

4.6 Long-Duration Energy Storage Technologies

Long-duration energy storage (LDES) technologies enable energy storage over periods ranging from several hours to multiple days or seasons, addressing one of the most critical limitations of renewable-dominated systems. Technologies such as thermal, mechanical, and chemical storage can support system reliability during prolonged periods of low renewable output (Sepulveda et al., 2021; IEA, 2023a). Key barriers include high costs, efficiency losses, and limited large-scale operational experience.

4.7 Advanced Battery Technologies

Advanced battery chemistries, including sodium-ion and solid-state batteries, aim to overcome the material, safety, and cost limitations of lithium-ion batteries. These technologies could reduce dependence on critical minerals and improve safety while supporting grid-scale storage applications (IRENA, 2023). However, most remain at pilot or early commercial stages, with manufacturing scalability and long-term performance still uncertain.

4.8 Green Hydrogen via Advanced Electrolysis

Green hydrogen is produced through water electrolysis powered by renewable electricity and serves as a versatile energy carrier for storage and sector coupling. Compared with direct electrification, hydrogen enables decarbonization of hard-to-electrify sectors such as steelmaking, chemicals, and long-distance transport (IEA, 2023b). Major challenges include high production costs, efficiency losses, and limited infrastructure availability.

4.9 Power-to-X Fuels

Power-to-X technologies convert renewable electricity into synthetic fuels such as ammonia, methanol, and e-fuels. These fuels facilitate long-distance energy transport and seasonal storage, supporting decarbonization of aviation, shipping, and industry (IPCC, 2023). Their main limitations are low overall efficiency and high system costs, restricting their use to sectors with limited alternatives.

4.10 Enhanced Geothermal Systems

Enhanced geothermal systems (EGS) expand geothermal energy deployment beyond naturally occurring reservoirs by engineering subsurface heat extraction. EGS can provide reliable, dispatchable, low-carbon electricity and heat, improving system stability (IEA, 2024). Challenges include high upfront investment costs, geological uncertainty, and risks related to induced seismicity.

4.11 Small Modular Nuclear Reactors

Small modular reactors (SMRs) are advanced nuclear technologies designed for flexible deployment and enhanced safety. They offer firm, low-carbon power that can complement variable renewable generation (Sepulveda et al., 2021). However, high capital costs, regulatory complexity, and public acceptance concerns limit their near-term impact.

4.12 Bioenergy with Carbon Capture and Storage

Bioenergy with carbon capture and storage (BECCS) combines biomass energy generation with CO_2 capture, enabling net-negative emissions. BECCS can offset residual emissions from other sectors and support climate targets (IPCC, 2023). Sustainability concerns related to biomass sourcing, land use, and lifecycle emissions remain significant challenges.

4.13 Direct Air Capture

Direct air capture (DAC) technologies remove carbon dioxide directly from the atmosphere, offering flexibility in location and deployment. DAC plays a potential role in balancing unavoidable emissions and achieving net-negative emissions in the long term (IEA, 2024). However, current systems are energy-intensive and costly, limiting scalability.

4.14 Smart Grids and Digital Energy Systems

Smart grids integrate digital technologies, advanced sensors, and artificial intelligence to optimize energy system operation. These systems improve flexibility, reliability, and efficiency in renewable-dominated energy systems (Lund et al., 2021). Challenges include cybersecurity risks, data governance, and regulatory adaptation.

4.15 Fusion Energy

Fusion energy aims to replicate the processes powering the sun to generate large amounts of low-carbon electricity. If successfully commercialized, fusion could provide abundant, reliable energy with minimal fuel constraints (IEA, 2024). Despite recent progress, fusion remains a long-term option facing substantial technical, economic, and temporal challenges.

4.16 Synthesis and System-Level Implications

Collectively, the technologies summarized in Table 2 demonstrate that future sustainable energy systems will depend on diverse, complementary solutions rather than singular technological breakthroughs. Their successful deployment requires coordinated system integration, infrastructure development, and supportive policy frameworks. These insights form the foundation for the system integration and transition pathways discussed in the next section.

Table 2: Emerging and Future Sustainable Energy Technologies: Readiness, Challenges, and System Roles

Technology	Primary Purpose in Future Energy Systems	Indicative TRL	Key Challenges	Expected System-Level Role
Perovskite & tandem solar cells	High-efficiency, low-material solar electricity generation	5–7	Long-term operational stability, large-scale manufacturing, and environmental concerns related to lead-based materials (Green et al., 2023; IEA, 2024)	Increased solar efficiency and reduced land and material intensity in future solar deployment (IEA, 2024)
Floating solar PV	Expansion of solar deployment without land competition	6–8	Structural durability, impacts on aquatic ecosystems, and higher capital costs compared with ground-mounted PV (IRENA, 2023)	Complementary solar capacity near demand centers and hybridization with hydropower systems (IRENA, 2023; IEA, 2024)
Floating offshore wind	Access to deep-water, high-quality wind resources	6–7	High investment costs, complex marine engineering, and grid connection challenges (GWEC, 2023; IEA, 2024)	Large-scale renewable electricity generation in coastal and deep-water regions (IEA, 2024)
Airborne wind energy	High-altitude wind energy harvesting	3–5	System reliability, control complexity, safety, and regulatory uncertainty (IRENA, 2023; REN21, 2023)	Long-term niche generation with potentially high capacity factors (IRENA, 2023)
Long-duration energy storage (LDES)	Multi-day to seasonal energy balancing	4–7	High costs, efficiency losses, and lack of market mechanisms supporting long-duration storage (Sepulveda et al., 2021; IEA, 2023a)	Enabling high shares of variable renewables and reducing curtailment in deeply decarbonized systems (IEA, 2023a)

Technology	Primary Purpose in Future Energy Systems	Indicative TRL	Key Challenges	Expected System-Level Role
Advanced battery chemistries (e.g., sodium-ion, solid-state)	Safer and lower-cost electrical energy storage	5–7	Manufacturing scale-up, performance validation, and lifecycle sustainability (IEA, 2023a; IRENA, 2023)	Diversification of storage options and reduced dependence on critical minerals (IRENA, 2023)
Green hydrogen (advanced electrolysis)	Energy carrier for long-term storage and sector coupling	6–7	High electrolysis costs, large renewable electricity demand, and efficiency losses across the value chain (IEA, 2023b; IRENA, 2023)	Long-duration storage and decarbonization of industry, transport, and power systems (IEA, 2023b)
Power-to-X (ammonia, synthetic fuels)	Conversion of renewable electricity into transportable fuels	4–6	Low overall efficiency, infrastructure requirements, and high production costs (IEA, 2023b; IPCC, 2023)	Decarbonization of aviation, shipping, and chemical sectors where electrification is limited (IPCC, 2023)
Enhanced geothermal systems (EGS)	Firm, low-carbon baseload electricity	4–6	Geological uncertainty, induced seismicity risks, and high upfront investment costs (IEA, 2024; IRENA, 2023)	Dispatchable renewable baseload power supporting grid stability (IEA, 2024)
Bioenergy with carbon capture and storage (BECCS)	Net-negative emissions with energy generation	6–7	Biomass sustainability, land-use impacts, and CCS infrastructure availability (IPCC, 2023; IEA, 2023a)	Carbon dioxide removal to offset residual emissions in net-zero pathways (IPCC, 2023)
Direct air capture (DAC)	Removal of CO_2 directly from the atmosphere	4–6	Very high energy demand, high costs, and limited storage deployment (IPCC, 2023; IEA, 2024)	Long-term climate stabilization and carbon management (IPCC, 2023)
Advanced nuclear (SMRs)	Firm, low-carbon electricity generation	5–7	Capital costs, licensing complexity, and public acceptance (Sepulveda et al., 2021; IEA, 2024)	Firm low-carbon power supporting deep decarbonization scenarios (IEA, 2024)
Fusion energy	Long-term, high-density clean energy	2–4	Technical feasibility, cost, and long development timelines (IEA, 2024; IPCC, 2023)	Potential post-2050 baseload energy source (IEA, 2024)
AI-enabled smart energy systems	Optimization of complex, multi-vector energy systems	6–8	Cybersecurity, data governance, and regulatory adaptation challenges (Lund et al., 2021; IEA, 2023a)	System integration, flexibility, and reliability at high renewable penetration (Lund et al., 2021)

TRL = Technology Readiness Level

5. System Integration, Transition Pathways, and Key Research Priorities

The transition to sustainable energy systems extends beyond the deployment of individual low-carbon technologies and requires effective system integration and coordinated transition pathways. As highlighted in earlier sections, current and emerging sustainable energy technologies can only achieve their full potential when they are integrated across energy sectors, infrastructures, and governance frameworks.

5.1 System Integration in Sustainable Energy Systems

System integration refers to the coordinated operation of electricity generation, energy storage, transmission networks, and end-use sectors such as heating, transport, and industry. High shares of variable renewable energy increase the need for flexibility through a combination of energy storage, demand-side management, sector coupling, and grid expansion (Lund *et al*., 2021; IEA, 2023a). Without such integration, renewable-dominated systems risk increased curtailment, reliability challenges, and higher system costs.

Sector coupling plays a particularly important role by linking electricity with other energy uses through electrification and energy carriers such as hydrogen and synthetic fuels. This approach enables surplus renewable electricity to be utilized more effectively and supports decarbonization of hard-to-electrify sectors (IRENA, 2023). Digitalization, including smart grids and data-driven control systems, further enhances system flexibility and operational efficiency by enabling real-time coordination of increasingly complex energy systems (IEA, 2023a).

5.2 Transition Pathways toward Sustainable Energy Futures

Energy transition pathways describe how energy systems evolve over time from fossil-fuel dependence toward low-carbon and net-zero configurations. Most recent global assessments emphasize a phased transition, with rapid deployment of mature renewable technologies and energy efficiency measures in the near term, followed by increasing roles for emerging technologies such as long-duration energy storage, hydrogen systems, firm low-carbon energy sources, and carbon removal technologies in the medium to long term (IPCC, 2023; IEA, 2024).

Importantly, transition pathways are region-specific and influenced by resource availability, infrastructure, economic conditions, and policy priorities. While developed regions often focus on retrofitting existing systems, developing regions face the dual challenge of expanding energy access while avoiding carbon-intensive development pathways (UN DESA, 2023). Consequently, no single transition pathway is universally applicable, reinforcing the need for adaptive and context-dependent strategies.

5.3 Key Research and Implementation Priorities

Despite substantial progress, several critical challenges remain that require continued research and policy attention. A major priority is improving understanding of system-level interactions among renewable generation, storage, grids, and sector coupling, particularly at high renewable penetration levels (Lund et al., 2021). In addition, long-duration and seasonal energy storage remains underdeveloped, yet essential for ensuring reliability in renewable-dominated systems (IEA, 2023a).

Other key priorities include addressing the sustainability of materials and supply chains, improving the scalability and cost competitiveness of emerging technologies, and ensuring that energy transitions are socially inclusive and equitable. Policy frameworks and market designs must also evolve to value flexibility, long-term system benefits, and negative-emission technologies, rather than focusing solely on short-term costs (IEA, 2024; IPCC, 2023).

6. Research Gaps and Future Directions

Despite significant progress in sustainable energy technologies and deployment, several critical research gaps remain that limit the effectiveness, scalability, and equity of global energy transitions. Addressing these gaps is essential for moving from incremental decarbonization toward fully integrated, resilient, and net-zero energy systems.

A major gap lies in system-level integration research. Much of the existing literature continues to evaluate individual technologies in isolation, while real-world energy systems involve complex interactions among generation, storage, networks, and end-use sectors. Limited attention has been given to how high shares of variable renewable energy affect system stability, flexibility requirements, and infrastructure planning when multiple technologies operate simultaneously (Lund *et al*., 2021; IEA, 2023a).

Another key gap concerns long-duration and seasonal energy storage. While short-duration battery storage is increasingly deployed, technologies capable of balancing energy supply and demand over days, weeks, or seasons remain underdeveloped. Comparative assessments of long-duration storage options—such as hydrogen, thermal storage, and mechanical systems—are still limited, particularly in terms of system-level cost, efficiency, and environmental impacts (IEA, 2023a; IRENA, 2023).

There is also considerable uncertainty surrounding the scalability and maturity of emerging energy technologies. Many future solutions, including advanced storage systems, green hydrogen pathways, and carbon removal technologies, face challenges related to cost reduction, infrastructure requirements, and real-world performance. More large-scale demonstration projects and harmonized assessments of technology readiness are needed to reduce investment and planning risks (IEA, 2024).

Material supply chains and sustainability represent another important research gap. The rapid expansion of renewable energy and storage technologies increases demand for critical minerals and materials, raising concerns about supply security, environmental impacts, and geopolitical dependence. Greater emphasis is needed on lifecycle assessment, recycling technologies, and circular-economy approaches to ensure long-term sustainability of energy transitions (IEA, 2023b).

In addition, regional and social dimensions of energy transitions remain underexplored. Many global transition scenarios are based on assumptions derived from industrialized regions and may not adequately reflect the realities of developing economies. Research should place greater emphasis on region-specific pathways, decentralized systems, energy access, affordability, and social acceptance to support equitable transitions (UN DESA, 2023; IPCC, 2023).

Finally, gaps persist in policy, market design, and governance research. Existing market structures often undervalue flexibility, long-term system benefits, and negative-emission technologies. Future studies should explore adaptive policy frameworks and market mechanisms that better align technological innovation with system needs and societal goals (IEA, 2024).

In summary, future research on sustainable energy systems should prioritize system-level integration, long-duration storage, technology scalability, sustainable supply chains, regionally differentiated pathways, and adaptive governance. Addressing these interconnected challenges will be critical for translating technological potential into effective, inclusive, and durable global energy transitions.

6.1 Summary of Key Research Priorities

In summary, future research on sustainable energy systems should prioritize:

- System-level and cross-sector integration
- Long-duration and seasonal energy balancing
- Scalable deployment of emerging technologies
- Sustainable materials and circular supply chains
- Regionally differentiated and socially inclusive pathways
- Adaptive policy and governance frameworks

Addressing these research gaps will be essential for translating technological potential into effective, equitable, and enduring global energy transitions.

7. Conclusions and Recommendations

7.1 Conclusions

This review has examined current and future sustainable energy systems with a focus on technologies, system integration, and transition pathways. The analysis shows that while significant progress has been made in deploying renewable energy technologies such as solar, wind, hydropower, and energy storage, these technologies alone are insufficient to achieve reliable, resilient, and fully decarbonized energy systems.

A key conclusion is that sustainable energy transitions are fundamentally system-level transformations, rather than simple substitutions of fossil fuels with renewable technologies. The limitations of current systems—such as variability, insufficient long-duration storage, infrastructure constraints, and sectoral decarbonization gaps—highlight the need for complementary emerging and future technologies. These include advanced renewable technologies, long-duration energy storage, hydrogen and Power-to-X systems, firm low-carbon energy sources, carbon removal technologies, and smart digital energy systems.

The review further demonstrates that system integration—through sector coupling, multi-timescale energy storage, digitalization, and coordinated infrastructure planning—is central to the effective functioning of high-renewable energy systems. Transition pathways toward net-zero energy systems are therefore best understood as adaptive, portfolio-based processes that evolve over time and vary across regions depending on resources, infrastructure, and socioeconomic conditions.

Overall, achieving sustainable and net-zero energy systems requires not only technological innovation but also coordinated system design, supportive policy frameworks, and long-term planning that aligns energy, climate, and development objectives.

7.2 Recommendations

Based on the findings of this review, several key recommendations are proposed:

1. Adopt a system-oriented approach in energy planning and research, with greater emphasis on integration across electricity, heat, transport, and industrial sectors rather than isolated technology deployment.
2. Prioritize the development of long-duration and seasonal energy storage, which is essential for balancing high shares of variable renewable energy and ensuring system reliability.
3. Support the responsible scaling of emerging technologies, including hydrogen systems, Power-to-X fuels, firm low-carbon energy, and carbon removal technologies, through targeted research, demonstration projects, and infrastructure investment.
4. Strengthen energy infrastructure and digital systems, including smart grids and advanced control platforms, to enhance flexibility, efficiency, and resilience in future energy systems.
5. Design adaptive policy and market frameworks that value flexibility, long-term system benefits, sustainability, and equity, while accounting for regional differences and development needs.

By implementing these recommendations, policymakers, researchers, and industry stakeholders can better support the transition toward integrated, resilient, and sustainable energy systems capable of meeting global climate and development goals.

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