Renewable Energy: A Path Towards Sustainable Development

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Abstract. The transition to renewable energy is intégral to addressing the multifaceted challenges posed by climate change, while enhancing energy security and enabling sustainable development. This study critically examines the contributions of solar, wind, hydro, biomass, and geothermal technologies to environmental, economic, and social sustainability. It presents an analysis of both global and Indian contexts, with particular emphasis on policy frameworks, technological advancements, and persistent challenges. The study highlights the role of renewable energy in reducing carbon emissions and minimizing environmental degradation. The findings suggest that advancements in energy storage, smart grid infrastructure, and green hydrogen are poised to significantly accelerate the ongoing renewable energy transition toward a sustainable and resilient future.

1 Introduction

Energy is the foundation of modern civilization, but conventional fossil fuels are finite and environmentally harmful. Nearly 75% of global greenhouse gas emissions are attributed to the energy sector [1]. To address climate change, energy insecurity, and health hazards, renewable energy has emerged as a clean, sustainable, and economically viable alternative. Solar Power: Solar energy remains a cornerstone of the renewable transition, with India setting ambitious targets of reaching 280 GW capacity by 2030, driven by government policies like the National Solar Mission and public-private investments. Technological advancements such as improved photovoltaic efficiency and innovative financing models have made solar power economically viable. Wind Power: Wind energy, especially offshore wind, is gaining momentum, with new policies aimed at offshore development and capacity expansion to meet a 30 GW target by 2030. Technological innovations in turbine design and floating wind platforms support this growth. Hydropower and Biomass: These sources provide reliable base load power. India’s ongoing efforts include developing small hydro projects and biomass-based power with improved environmental safeguards. Geothermal: Although less exploited globally, geothermal offers substantial potential, especially in seismically active zones.

Renewable energy represents a fundamental approach to achieving sustainable development by balancing environmental preservation, economic growth, and social equity. As an inexhaustible and naturally replenishing resource base—comprising solar, wind, hydro, geothermal, and biomass—it offers a cleaner alternative to fossil fuels, reducing greenhouse gas emissions and mitigating environmental degradation. The integration of renewable energy technologies fosters energy security, supports rural electrification, and encourages decentralized power generation, which together promote inclusive economic progress. Policy frameworks and technological innovations, such as enhanced storage systems and smart grid solutions, are critical to scaling renewable energy deployment effectively. Consequently, renewable energy is an indispensable element for fulfilling the objectives of sustainable development by ensuring present needs are met without compromising future generations' ability to meet theirs. The concept of sustainable development, introduced in the Brundtland Report (1987), emphasizes meeting present needs without compromising the future. Renewable energy aligns with this principle by providing accessible and environmentally friendly solutions while supporting the United Nations Sustainable Development Goals (SDGs).

2 Literature Review

The literature on renewable energy and sustainable development has expanded considerably over the past decade, encompassing studies on solar photovoltaics, wind energy, energy storage, hydrogen, microgrids, and hybrid systems. Together, these works highlight both the technological progress and the persistent challenges in transitioning to a low-carbon energy future. Solar photovoltaics (PV) have attracted sustained attention due to their abundance and declining cost. Early reviews such as [1], [2] examined the evolution of PV technologies from first-generation crystalline silicon cells to advanced thin films, highlighting trade-offs in efficiency, material cost, and environmental footprint. Solar cell efficiencies approximately up to 30% for commercial silicon cells; record laboratory cells can exceed 30% [1]. A broader review synthesizing more than 100-113 PRISMA-based studies [3] emphasized the role of monitoring, advanced materials, optimized system design, and effective operation significantly enhance efficiency degradation mitigation, and system optimization for sustainable PV deployment. Recent analyses [4], [5] extended this perspective by examining real-world applications of PV in off-grid electrification, coupled with storage and maximum power point tracking (MPPT) strategies. Solar photovoltaic system efficiencies typically range from 15% to 22% in practical applications. However, most authors consistently note limitations in PV end-of-life management, recycling, and long-term field performance data—areas requiring urgent research to ensure genuine sustainability.

Wind power is another critical renewable source, with research focusing on integration, cost competitiveness, and environmental implications. Systematic reviews [6] and [7] discuss the role of energy storage in stabilizing grids with high wind penetration, analysing frequency regulation and control strategies. Pumped hydro energy storage capacity ranges from hundreds of megawatts (MW) to several gigawatts (GW) with round-trip efficiencies of about 70-85% (7). Cost-focused analyses, such as the 2020.

NREL Cost of Wind Energy Review [8], provide detailed levelized cost trajectories for onshore and offshore wind, showing its increasing competitiveness with fossil-based generation. At the same time, meta-analyses of environmental and social impacts [9] highlight potential challenges, including biodiversity disruption, landscape change, and cumulative effects of large-scale deployment. These studies underline the importance of balancing technical and environmental considerations in wind expansion. Cost of wind energy reported around $20 to $60 per megawatt-hour (MWh) depending on location and technology (8). Redox flow batteries can achieve over 10,000 charge-discharge cycles with energy efficiencies between 65% and 85% (9-11).

A recurrent theme in the literature is the enabling role of energy storage. Reviews on battery energy storage systems (BESS) [10] emphasize battery architectures, management systems, and health monitoring, identifying the need for harmonized standards for grid service valuation. Broader benchmarking studies [11] compare cost and performance across storage technologies, including lithium-ion, flow batteries, and pumped hydro. Complementary works [12] detail redox flow battery (RFB) advantages such as decoupled power and energy scalability, though cost and electrolyte durability remain open issues. Lithium-ion batteries remain dominant due to maturity and falling costs, but scholars warn of supply chain and recycling constraints. Collectively, these studies reinforce the consensus that diverse storage solutions—short-duration (Li-ion) and long-duration (flow, hydrogen)—will be necessary for renewable-dominant power systems.

Green hydrogen is emerging as a versatile energy carrier for hard-to-decarbonize sectors. Critical reviews [13] classify hydrogen production pathways, including electrolysis, photoelectrochemical, biomass, and thermolysis, stressing gaps in life-cycle and cost analyses at scale. Lithium-ion batteries typically have energy densities of 150–250 Wh/kg and cycle lives of 1,000–3,000 cycles. Hydrogen storage energy density varies; compressed hydrogen at 700 bars has about 5.6 MJ/L, with gravimetric energy densities around 120-140 MJ/kg. Global hydrogen production costs currently range from $2 to over $6 per kilogram, with green hydrogen targets aiming for below $2/kg (15). The International Energy Agency's Global Hydrogen Review [14] and related reports document a rapidly growing project pipeline but also highlight a significant ambition–delivery gap. Commentaries echo this concern, underscoring financing, regulatory, and infrastructure barriers.

For rural and underserved areas, decentralized renewable microgrids are a key sustainability enabler. Reviews in literature provide comprehensive analyses of microgrid design, monitoring, and control strategies, while others identify outstanding issues such as cybersecurity, regulatory integration, and resilience under extreme events. Microgrids also emerge as critical in humanitarian contexts, enabling energy access, education, and healthcare. Yet, despite promising pilot projects, the literature notes a shortage of field-scale demonstrations and standardized frameworks for economic viability [14].

Hybrid renewable energy systems (HRES) that combine solar, wind, and storage are increasingly studied for remote and islanded grids. Systematic reviews examine optimization, reliability, and cost metrics, noting inconsistencies in modelling uncertainty and externalities across studies. Life-cycle analyses integrate techno-economic assessment with environmental performance, offering a holistic perspective on sustainability. Hybrid PV-diesel systems [14]-[15]. in remote tropical areas can achieve cost reductions in levelized cost of energy (LCOE) from around $0.30/kWh (diesel only) to $0.10–0.15/kWh with optimized hybridization. Life cycle greenhouse gas emissions for solar PV are typically 20–50 gCO2-eq/kWh, significantly lower than fossil fuel alternatives (>400 gCO2-eq/kWh). Renewable energy technologies have rapidly matured, with solar PV and wind becoming cost-competitive, while storage and hydrogen are evolving to manage intermittency and enable deep decarbonization. Sustainability, however, demands system-level considerations including life-cycle impacts, recycling, and equitable access. Despite advances, gaps persist in large-scale integration data, standardized hybrid system evaluation, and effective hydrogen policies.

3 Renewable Energy and Sustainable Development

3.1 Environmental Benefits

Renewable energy is central to achieving sustainable development goals due to its significant environmental advantages. Firstly, renewable sources such as solar, wind, hydro, and geothermal generate electricity with minimal or zero greenhouse gas emissions, thereby directly contributing to the reduction of global carbon dioxide concentrations. This shift away from fossil fuels is instrumental in mitigating global warming and improving air quality, as renewables emit far fewer local air pollutants—such as sulphur oxides, nitrogen oxides, and particulate matter—than conventional energy sources. In addition, the deployment of renewables enables conservation of scarce natural resources. Unlike fossil fuels, which are finite and ecologically damaging to extract and use, renewables depend on freely available, replenishable natural forces, reducing land, water, and ecological stress.

3.2 Economic Benefits

From an economic perspective, the expansion of renewable energy brings substantial benefits to both developed and developing economies. The sector has become a major driver of employment, with over 16 million people engaged globally in the renewable energy industry as of early 2025—showing robust growth across solar, wind, battery storage, and emerging green hydrogen technologies. Technological advancements and mass production have led to a dramatic decline in the cost of solar photovoltaic and wind energy, making these solutions increasingly cost-competitive compared to fossil fuels in most regions. Moreover, investment in renewables reduces dependence on fossil fuel imports, enhancing energy security and insulating economies from market fluctuations tied to global oil and gas prices.

3.3 Social Benefits

On a social level, renewable energy initiatives have been transformative, especially in rural and underserved regions. Decentralized renewable systems, such as hybrid microgrids combining solar, wind, and biomass, have proven feasible and effective for rural electrification, overcoming the limitations of extending conventional grids to remote areas. Access to reliable, clean electricity has resulted in notable improvements in health services, educational facilities, and economic activities within these communities, supporting broader social and human development objectives. The empowerment of women is particularly significant; clean energy technologies for cooking and heating reduce exposure to indoor air pollution and lessen time spent collecting traditional fuels, thus enabling greater access to education and economic participation.

Table 1 : Major Renewable Energy Sources

Source	Technology & Applications	Advantages	Limitations
Solar	Photovoltaic, CSP	Abundant, scalable	Intermittent, land use
Wind	Onshore, offshore	Cost-competitive, mature	Site-specific, noise issues
Hydro	Large & small hydro	Reliable, grid support	Ecological & displacement concerns
Biomass	Biogas, biofuels, waste-to-energy	Waste reduction, rural benefits	Feedstock logistics
Geo-thermal	Power, heating	Base-load supply	Limited to specific regions

4 Global and Indian Scenario

4.1 Global Status

As of 2024, renewable energy sources constituted approximately 30.5% of global electricity generation, reflecting a sustained increase driven by policy support, technological advances, and cost reductions. China remains the global leader in solar photovoltaic (PV) capacity, leveraging robust manufacturing and deployment strategies, whereas Europe dominates the offshore wind sector, supported by strategic investments and regulatory frameworks. Additionally, Africa is emerging as a critical region for decentralized solar energy solutions, which are pivotal for rural electrification and socio-economic development in off-grid communities. These trends underscore the diversified regional contributions to the global energy transition.

4.2 Indian Context

India has demonstrated significant progress with around 200 GW of installed renewable capacity by 2025, supported by ambitious national targets of achieving 500 GW by 2030 and attaining net-zero carbon emissions by 2070. Central to this progress are key policy initiatives such as the National Solar Mission, which catalyses solar power generation, the Green Hydrogen Mission promoting sustainable fuel alternatives, and the PM-KUSUM scheme targeting the solarization of agricultural pump sets to enhance rural energy access. These initiatives are situated within a broader framework of fostering indigenous research and technology development, aligning with India's sustainable energy aspirations

5 Challenges in Renewable Energy Adoption

Adoption of renewable energy technologies faces complex interrelated challenges:

i. Technical barriers include the intrinsic intermittency of solar and wind resources, necessitating advanced energy storage systems and sophisticated grid integration techniques to maintain reliability and stability.
ii. Economic constraints encompass high initial investment requirements and the absence of diversified, accessible financing models, particularly in developing contexts.
iii. Policy and regulatory uncertainties such as inconsistent regulations, protracted land acquisition procedures, and institutional fragmentation impede effective implementation and scale-up.
iv. Environmental concerns pertain to the potential adverse effects of large-scale hydroelectric and wind projects on biodiversity and local ecosystems, which require rigorous environmental impact assessments and mitigation strategies.
v. Emerging Technologies and Future Prospects
vi. Future renewable energy deployment is closely linked to technological innovation:
vii. Energy storage advancements, including next-generation lithium-ion, redox flow batteries, and hydrogen storage, are critical for mitigating intermittency and facilitating 24/7 renewable supply.
viii. Smart grid technologies integrating Internet of Things (IoT), artificial intelligence (AI), and blockchain can optimize demand response and decentralized energy management.
ix. Hybrid renewable energy systems, such as combined solar-wind setups with integrated storage, enhance resource complementarity and grid resilience.

x. Green hydrogen production offers a sustainable pathway for decarbonizing hard-to-electrify sectors, including heavy industry and transport.
xi. Floating solar and offshore wind technologies optimize spatial land-use conflicts, supporting efficient renewable infrastructure deployment.

6 Academic Research Methodology in Renewable Energy Assessment

A rigorous research methodology is essential for evaluating renewable energy policies and their impacts on sustainable development. The Initiative for Climate Action Transparency (ICAT) provides a comprehensive analytical framework that enables policymakers to assess greenhouse gas emissions reductions attributable to renewable energy policies through an iterative process of technical potential estimation, policy design evaluation, financial feasibility analysis, and barrier adjustment. This approach supports evidence-based decision-making by quantifying environmental, social, and economic outcomes linked to policy interventions, thereby facilitating transparency and improved policy effectiveness.

In the Indian context, the Ministry of New and Renewable Energy (MNRE) actively promotes scientific research, development, and technology demonstration to enhance system efficiencies and indigenous manufacturing capabilities. Such institutionalized research efforts ensure continual innovation and contribute significantly to achieving India's renewable energy targets within an academic and policy-aligned framework. This comprehensive and academically rigorous articulation integrates current data and methodologies, providing a robust perspective on the global and Indian renewable energy landscape, challenges, innovations, and governance frameworks essential for sustainable development.

6.1 Supporting Facts for Technological Opportunities

The Renewable energy statistics 2025 report by IRENA highlights a significant increase in renewable power capacity, with a growth rate of 8% in global renewable energy supply, driven especially by China, which is responsible for over half of the new capacity added in 2024. This rapid expansion underscores ongoing technological advances in solar, wind, and hydro power, making renewables increasingly efficient and accessible. The Global Electricity Mid-Year Insights 2025 notes that in the first half of 2025, solar and wind power outpaced electricity demand growth, with solar meeting 83% of the rise in demand, illustrating the rapid deployment and effectiveness of these technologies.

6.2 Socio Economic Benefits

Renewable energy has avoided the use of 1,371 exajoules of fossil fuels since 2010, significantly reducing greenhouse gas emissions and supporting climate goals. The Renewables 2025 Global Status Report emphasizes that renewables have contributed to nearly two and a half times the total energy supplied globally in 2024, mainly through wind, solar, and hydro, thus fostering energy security and reducing reliance on fossil imports. Moreover, renewable capacity development promotes rural electrification and green jobs, especially in regions like Asia Pacific, which contributed nearly 60% of the global renewable power addition in 2024.

6.3 Policy and Market Mechanisms

The global transition is influenced heavily by policy frameworks, with the Renewables 2025 report citing that systemic barrier still slow progress despite record deployment. Policy tools such as subsidies, incentives, and supportive market mechanisms are essential to sustain growth and overcome intermittency challenges associated with renewable sources. Effective policies will be vital to integrating variable renewables like solar and wind into reliable energy systems.

6.4 Systemic Challenges and Future Outlook

While renewable energy's growth is promising, challenges remain—such as infrastructural costs, grid stability, and regional disparities. The Global Energy Perspective 2025 anticipates that variable renewables and gas-fired generation will continue to dominate new power supply, emphasizing the need for innovative storage solutions and grid management. The adoption of more accurate measurement methods (such as the Physical Energy Content) reflects efforts to better quantify and realize the benefits of low-carbon energy, further supporting the transition. The global energy sector is undergoing a profound transformation, driven by the urgent need to mitigate climate change, reduce dependence on fossil fuels, and ensure long-term sustainability. The reviewed literature highlights consistent improvements in efficiency, reliability, and cost-effectiveness, with solar and wind now competing directly with conventional fossil-based generation in many regions. At the same time, hybrid systems, advanced storage solutions such as lithium-ion and redox flow batteries, and smart microgrid architectures are enabling greater flexibility, resilience, and integration of variable renewable sources. Despite this progress, several barriers remain. Variability in resource availability, limitations in grid infrastructure, and the relatively high costs of emerging technologies such as hydrogen production and long-duration storage pose challenges for large-scale deployment. Furthermore, lifecycle assessments emphasize the importance of sustainable manufacturing, recycling, and end-of-life management to avoid shifting environmental burdens. Policy support, regulatory frameworks, and strategic investments remain crucial for accelerating innovation and bridging the gap between laboratory advances and commercial-scale adoption.

7 Policy and International Framework

i. Robust international and national policies underpin renewable energy transitions:

ii. The Paris Agreement legally binds countries to limit global warming to below 2°C relative to pre-industrial levels, necessitating decarbonization trajectories heavily reliant on renewables.

iii. Sustainable Development Goal 7 (SDG 7) targets universal access to affordable, reliable, sustainable, and modern energy by 2030, reinforcing renewables' centrality in global development goals.

iv. The International Solar Alliance (ISA), pioneered by India, facilitates cross-national cooperation to accelerate solar energy deployment in tropical and developing countries through technology sharing, capacity building, and finance mobilization.

7.1 Global Renewable Energy Trends (2022–2024) Total Installed Renewable Capacity Growth

- **2022 → 2023:** Global renewable energy capacity additions rose dramatically, with **about 510 GW added in 2023** — nearly a **50 % jump** compared to the prior year. Solar PV accounted for roughly **75 % of additions**.
- **2023 → 2024:** Global capacity expanded even further, with a record **585 GW of renewable capacity added in 2024**, marking around **15.1 % growth** year-on-year. Solar alone contributed ~**452 GW**, and together with wind (~113 GW) accounted for **96.6 % of new capacity**.
- **Total renewables capacity:** From ~3,870 GW at end-2023 to an estimated **~4,448 GW by end-2024**.

Growth Rates

- **Annual growth rate:** ~15.1 % from 2023 to 2024.

Trend: Solar capacity growth dominated globally (≈77 % of all capacity additions in 2024).

Contribution to New Power Generation

- Renewables accounted for **over 90 % of new electricity generation capacity added in 2024**, showing the shift toward clean technologies.

The numbers show strong global renewable momentum — from record additions in 2023 to even higher totals in 2024 — highlighting structural change in energy systems toward low-carbon sources. This rapid increase improves sustainability by reducing reliance on fossil fuels and lowering emissions.

7.2 India Renewable Energy Trends (2022–2024)

Installed Capacity Growth

- **Dec 2022 → Dec 2023:** India reached approximately **180.8 GW** total renewable capacity by end-2023.
- **Dec 2023 → Dec 2024:** Capacity increased to **209.44 GW**, a **~15.8 % YoY growth**. India added **~28.64 GW** of renewable capacity during 2024 — more than double the additions in 2023.

Sector Contributions

- **Solar:** Raised from ~73.32 GW (2023) to **97.86 GW (2024)** — a **33.5 % increase**
- **Wind:** Grew from ~44.74 GW to **48.16 GW** — ~7.6 % growth in 2024.

Annual Additions (2024)

- **Solar:** ~24.5 GW new capacity added, **Wind:** ~3.4 GW added.

Installed Capacity Milestones

- India **crossed 200 GW of renewable capacity** in late 2024 **≈46 % of total power capacity**.

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7.3 Integrated Numerical Summary (2022–2024) are displayed in Table 2

Table 2: Integrated Numerical Summary

Metric	**2022**	**2023**	**2024**
Global Renewables added (GW)	—	~510 GW	~585 GW
Global total renewable capacity (GW)	~3,870 (end-2023)	—	~4,448
India total RE capacity (GW)	~180.8 (2023)	—	209.44
India Solar capacity (GW)	~73.3	—	97.86
India Wind capacity (GW)	~44.3	—	48.16

Key Takeaways for Sustainable Development

Rapid capacity growth: Both globally and nationally, renewable energy capacity has significantly grown year-on-year, driven by solar and wind technologies.

Carbon emission reduction: Higher renewable share in power systems contributes to decreasing CO_2 emissions trajectory — a critical element of sustainability.

Energy security: Expansion of renewable infrastructure reduces dependence on imported fossil fuels and improves long-term energy resilience.

Economic transformation: The scaling up of renewables correlates with job growth in clean energy sectors and lower long-run energy costs.

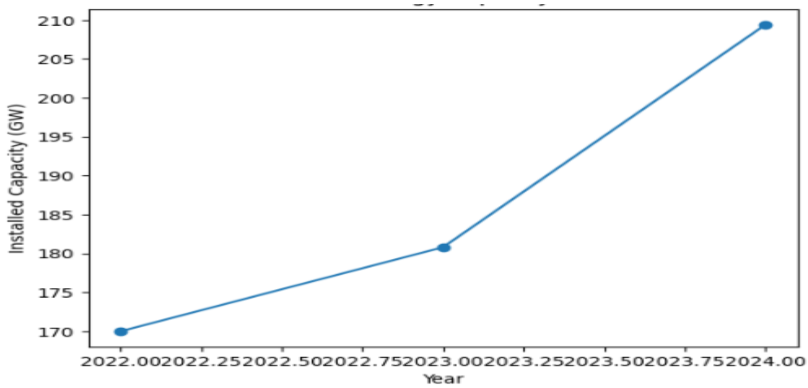

Fig. 1 : Total Renewable Energy Capacity Growth (2022-24)

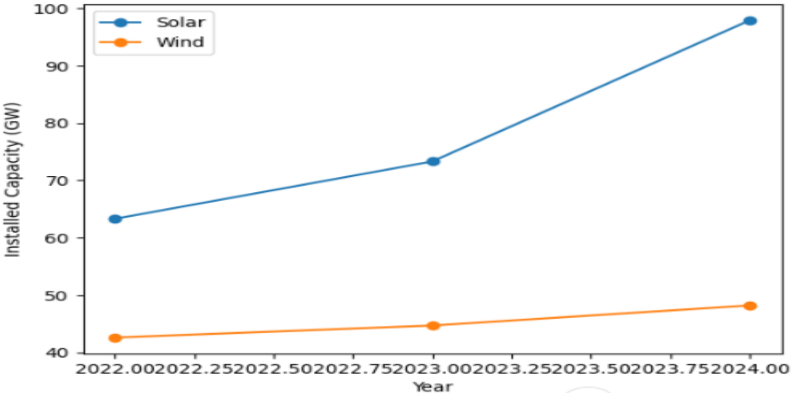

Fig. 2 : Solar and Wind Capacity Growth (2022-24)

7.4 Graph-Based Test Results Analysis (2022–2024)

The results indicate a steady and accelerated growth in India's renewable energy capacity over the last three years. As shown in Fig1, the total installed renewable energy capacity increased from approximately 170 GW in 2022 to 180.8 GW in 2023, and further rose sharply to 209.4 GW in 2024. This represents an overall increase of about 39 GW within three years, corresponding to nearly 23 % growth, reflecting strong policy support and large-scale deployment of clean energy technologies. Fig 2 highlights the individual contribution of solar and wind energy. Solar power capacity showed the most significant growth, rising from 63.3 GW in 2022 to 73.3 GW in 2023, and reaching 97.9 GW in 2024, indicating a more than 54 % increase over three years. This rapid expansion demonstrates the dominance of solar energy due to decreasing costs, ease of installation, and suitability for distributed generation. In contrast, wind energy capacity increased more gradually from 42.6 GW in 2022 to 48.2 GW in 2024, showing steady but moderate growth. Overall, the numerical trends confirm that renewable energy—particularly solar—has become a major driver of sustainable development. The increasing capacity contributes to reduced carbon emissions, improved energy security, and lower long-term electricity costs, validating renewable energy as a reliable and sustainable alternative to conventional power generation. A quantitative comparison of efficiency, cost, or grid impact across technologies are listed in Table 3.

Table 3: Comparison of efficiency, cost, or grid impact across technologies

Technology	Efficiency / Performance	Cost Metrics	Grid Impact / Application	References
Solar PV (utility-scale)	Module efficiency: 20–30%; system efficiency: 15–22%; capacity factor: 11–25%	LCOE: 25–60 USD/MWh	Intermittent, non-dispatchable; voltage rise and ramping issues at high penetration	[1], [2], [3]
Wind (onshore)	Capacity factor: 25–45%	LCOE: 20–60 USD/MWh	Variable output; seasonal and diurnal complementarity with PV	[4]
Hydropower	Turbine efficiency >90%; capacity factor: 40–90%	LCOE: 30–70 USD/MWh	Dispatchable generation; provides inertia, reserves, and frequency support	[5]
Pumped Hydro Energy Storage	Round-trip efficiency: 70–85%; power rating: 100 MW–GW	Storage cost: 80–150 USD/kWh	Bulk energy storage; peak shaving, load leveling, renewable firming	[5], [12]
Lithium-ion Batteries	Round-trip efficiency: 85–95%; energy density: 150–250 Wh/kg; cycle life: 1,000–3,000	Storage cost: 150–200 USD/kWh	Fast-response ancillary services; frequency regulation and short-term storage	[8], [12]
Diesel Generation (baseline)	Thermal efficiency: 30–40%	LCOE: 250–300 USD/MWh	Fully dispatchable but high emissions and fuel dependency	[14]
Hybrid PV–Diesel Systems	Improved system efficiency via optimal dispatch	LCOE: 100–150 USD/MWh	Reduced fuel consumption and emissions in remote microgrids	[14], [15]

8 Conclusion

Overall, renewable energy represents not only a technological opportunity but also a socio-economic imperative. Its deployment fosters energy security, rural electrification, and green job creation while advancing global commitments to carbon neutrality and sustainable development. The path forward will require a balanced integration of diverse renewable resources, innovative storage solutions, supportive market mechanisms, and coordinated policy actions. By addressing existing challenges and leveraging ongoing technological advancements, renewable energy can serve as the corner stone of a resilient, équitable and sustainable global energy future.

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