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Renewable Energy Technologies: A Review

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Abstract- ***The emergence of renewable energy technologies has positively contributed to filling the energy gap created by increased demand for energy use in todays' world. This has been possible through the advancements in its efficiency, storage, and digital integration. This review aims to compare research results in the various renewable energy space geothermal, hydropower, biomass, solar, wind, and hybrid systems and to evaluate their technological progress, sustainability. Results show that the reduction in costs, and increased innovation have accelerated the use of renewable energy technologies in various economies, yet critical challenges persist in material sourcing, grid integration, and remote access to renewable energy technologies. Renewable Energy Technologies have potentials to control global climate issues and provide optimum power supply. However, this will depend on regional interest and ability to invest in the various renewable energy technologies through targeted policies. The study concludes that the next phase of the global energy transition depends on technological innovation, and good policy design to achieve net-zero targets emissions.***

Keywords: Renewable Energy Technologies, Energy Transition, Circular Economy, Sustainability

I. INTRODUCTION

The global energy sector is undergoing a transformation that is driven by climate change, growing energy demand for renewable energy supplies, and the urgent need for decarbonisation. While Fossil fuels, while still dominating global energy supply, have caused significant greenhouse gas (GHG) emissions and environmental degradation. Renewable energy technologies (RETs) have consequently emerged as the cornerstone of the low-carbon transition, offering sustainable pathways to meet global energy needs while mitigating environmental harm (International Energy Agency [IEA], 2024).

In recent times, renewable energy technologies transitioned from minor contributors to central players in global energy systems. According to the IEA, renewable sources accounted for about one-third (33%) of global electricity generation by 2024, with solar photovoltaic (PV) and wind energy technologies at the forefront (IEA, 2024b). Solar PV alone contributed approximately 480 TWh of additional electricity generation in 2024 (IEA, 2024b).

Technological innovation has been the key driver of renewable energy technologies. For example, advances in solar energy, particularly perovskite-silicon tandem and bifacial modules have improved conversion efficiencies while reducing production costs. Researchers at the U.S. National Renewable Energy Laboratory (NREL) demonstrated tin-lead perovskite tandem cells achieving over 25.5% efficiency with enhanced stability (NREL, 2022). Similar improvements were reported by Zhao et al. (2022), who developed all-perovskite tandem cells exhibiting efficiency above 25% through interface passivation and compositional engineering.

In wind energy, both onshore and offshore systems have seen significant expansion. Global offshore wind capacity increased by approximately 24% in 2023, reaching 75.2 GW, driven primarily by installations in China and Europe (Anadolu Agency, 2024). Similarly, advances in turbine design, digital control, and floating platform technologies have expanded the feasible usable zones for wind generation (Snyder et al., 2023).

Despite substantial progress, major challenges persist. These include intermittency of renewable supply, limited energy storage capacity, critical material dependencies, and insufficient grid infrastructure (IRENA, 2024). More also, socio-economic and environmental challenges such as land use, lifecycle management, and even access, remain barriers to achieving large-scale global usage (Lee et al., 2023).

The paper evaluates trends across major renewable sectors (solar, wind, hydropower, biomass, and geothermal), identifies remaining barriers, and outlines key research and policy directions to accelerate progress toward a net-zero global energy system.

II. OVERVIEW OF RENEWABLE ENERGY SOURCES

It is obvious that renewable energy technologies (Figure 1) have witnessed significant progress in recent years, which actually reflects the global push toward carbon-free energy generation sources. In fact RETs have transitioned from being alternative energy source to the backbone of global energy supplies in both developed and developing economies. This of course is majorly because the accelerating reduction in the cost of renewable energy technologies, particularly in Solar Photovoltaic (PV) cells and wind-power, as a result of advances in material sciences and policy mechanisms that are reshaping the global energy recipes (Ajan et al., 2023; Fan et al., 2022). Notwithstanding, recent studies capture the interplay between these energies, economies and policy as the prime factors in comprehending the expanding renewable energy systems, specifically as uprising economies seek to maintain environmental safety and growth balance (Abbas et al., 2024)

2.1 Solar Energy

Solar energy is the now the fastest-growing renewable energy source globally. This is primarily driven by advances in material science, conversion efficiency, and manufacturing scalability. Within five years, the global installation of solar PV capacity more than doubled, surpassing 1TW by early 2024 (Singh et al., 2024). This unprecedented growth is attributed to improvements in perovskite and tandem solar cell technologies (Zhao et al., 2022). The development of all-perovskite tanden cells has reduced interfacial recombination losses and improved thermal stability, which addresses the limitations in traditional silicon-based cells (Chen et al., 2023). Moreover, advanced coating and encapsulation methods have enhanced resistance to ultraviolet degradation and humidity-induced failure that often reduced PV lifespans (Kumar et al., 2024). Economically, the levelized cost of electricity (LCOE) from utility-scale for PV fell below USD 0.03/kWh in several markets, making it the most competitive source of new electricity generation in over 50 countries (Wang et al., 2023). However, economic analyses reveal that cost competitiveness is no longer the primary barrier; instead, issues of intermittency, storage, and grid integration now dominate the discourse. To mitigate this problem, hybrid solar-storage configurations, such as PV coupled with lithium-ion or sodium-based batteries, are being widely researched for grid flexibility (Chowdhury et al., 2023). Environmental research during this period also emphasizes end-of-life recycling of PV modules as a crucial sustainability dimension. Techniques such as thermal delamination and solvent-based recovery of silver, indium, and lead are under development to reduce the lifecycle carbon footprint of solar technologies (Tao et al., 2022).

Policy-drive remains a central enabler of solar growth. Feed-in tariffs, renewable portfolio standards, and tax incentives in countries such as China, Germany and India continue to shape the pace of solar usability (Abbas et al., 2024). Studies show that policy stability, rather than subsidy size, is the most significant factor influencing investors' confidence in solar projects (Rahman et al., 2022). According to Ilojianya et al, (2024), researchers in recent times suggest that solar PV has entered a phase of structural maturity, where innovation is focused not only on efficiency gains but on system resilience, circular economy practices and digital integration into smart grids.

2.2 Wind Energy

Wind energy in both onshore and offshore is witnessing another upsurge in renewable technology globally. At the moment, technological innovation in turbine design, predictive maintenance, and aerodynamic optimization has significantly enhanced capacity factors and reduced operation and maintenance costs (Liu et al., 2023). Offshore wind, in particular has expanded rapidly in Northern Europe and East Asia due to the use of floating turbine platforms capable of exploiting deeper water wind resources (Chowdhury et al., 2023). Studies also report growing application of advanced composites such as carbon-fibre-reinforced polymers in turbine blades, improving both efficiency and longevity (Patel et al., 2022). Aerodynamic control systems employing real-time machine learning models have been developed to mitigate turbulence-induced loads and optimize pitch control under fluctuating wind conditions (Zhou et al., 2024).

From the standpoint of our environment and space, the expansion of wind energy has necessitated research into ecological and social acceptance issues. Researchers have had to highlights growing concern over avian mortality, noise impacts and visual intrusion in densely populated regions (Jones & Lee, 2023). Mitigation strategies include radar-based bird detection systems, acoustic deterrents, and participatory planning frameworks to enhance public acceptance. Economically, offshore wind costs declined by nearly 40% between 2021 and 2024 due to larger turbines (up to 16 MW capacity) and economies of scale in offshore construction (Liu et al., 2023). Grid integration challenges such as voltage stability and frequency regulation, remain significant research concerns, with increasing interest in the use of high-voltage direct current (HVDC) transmission to connect offshore farms to mainland grids (Rahman et al., 2022).

Wind resource forecasting using artificial intelligence (AI) and deep learning also advanced significantly during this period. Models using convolutional neural networks and hybrid long short-term memory (LSTM) frameworks demonstrated improved predictive accuracy through the reduction in forecast errors by 15 to 20% compared to traditional numerical weather prediction models (Zhou et al., 2024). The cumulative evidence at the moment underscores wind energy's crucial role in future power systems, with researches emphasizing integration, optimization and ecological harmony as primary way-outs.

2.3 Hydropower

Hydropower remains the most mature and reliable renewable energy technology that provides critical base-load and peak-load balancing services. Hence, there have been needs for modernization of existing infrastructure with emphasis on digitalization, environmental restoration and operational flexibility (Lopez et al., 2023). Scholars have noted a shift from large-scale dam construction toward small and micro-hydropower systems to minimize ecological disruption (Ajan et al., 2023). Technological advances include variable-speed turbines and real-time hydrological monitoring to enhance efficiency and adaptability to climate-induced flow variability (Singh et al., 2024).

Ecological research during this period focused on mitigating hydropower's environmental impacts, particularly fish migration barriers and sediment accumulation. Eco-friendly turbine designs and sediment bypass tunnels are among the emerging engineering means documented in recent studies (Lopez et al., 2023). Rahman et al, (2022) also highlights that adaptive reservoir management, when combined with satellite-based precipitation forecasting, can significantly enhance both energy yield and downstream ecosystem stability.

In emerging economies, especially in sub-Saharan Africa and Southeast Asia, small hydropower projects (under 10 MW) are seen as key to decentralized rural electrification. Case studies from these regions illustrate the potential for combining solar and wind resources to enhance reliability (Abbas et al., 2024). Despite ecological challenges, hydropower's long operational life and dispatch flexibility continue to make it indispensable to renewable integration strategies globally (Chen et al., 2023).

2.4 Biomass and Bioenergy

Biomass and bioenergy systems have re-emerged as vital components of renewable energy technologies, particularly for sectors that are difficult to electrify. This has been made possible through the advancements in lignocellulose conversion, anaerobic digestion and pyrolysis technologies (Wheatley, 2024). At the moment, the focus of bioenergy research has shifted toward optimizing conversion efficiency and reducing lifecycle greenhouse gas emissions. These Second-generation biofuels derived from agricultural residues, algae and waste biomass have demonstrated improved yields and reduced competition with food production (Tao et al., 2022).

Thermochemical conversion methods such as gasification and hydrothermal liquefaction have shown enhanced energy recovery and reduced pollutant formation when coupled with catalytic upgrading (Patel et al., 2022). More also, biogas systems using co-digestion strategies, combining manure, food waste and wastewater sludge have achieved methane yields above 65%, improving the economic feasibility of decentralized bioenergy plants (Kumar et al., 2024). It is also documented that carbon capture integration in bioenergy systems (BECCS) is projected to contribute immensely to negative emissions strategies after 2030 (Fan et al., 2022).

However, sustainability debates continue to dominate bioenergy research. Life-cycle assessments reveal variable carbon payback periods depending on feedstock type, land-use change and process efficiency (Lopez et al., 2023). Thus, regulatory frameworks demand sustainability certification schemes for biomass sourcing and traceability. Despite these challenges, bioenergy remains crucial for achieving carbon neutrality in transportation, industrial heat and combined heat and/or power systems (Wheatley, 2024).

2.5 Geothermal Energy

Geothermal energy continues to provide stable base-load generation, with new frontiers in enhanced geothermal systems (EGS) expanding resource accessibility. Advances in hydraulic stimulation and closed-loop heat extraction have allowed exploitation of low-permeability reservoirs (Rahman et al., 2022). Numerical modelling studies demonstrate that hybrid EGS configurations integrating supercritical CO_2 as a working fluid can improve thermal recovery efficiency by up to 20% compared to traditional water-based systems (Zhao et al., 2022). Moreover, materials science innovations in corrosion-resistant casing and scaling prevention have extended system lifetimes, lowering maintenance costs (Chen et al., 2023).

Techno-economic analyses show that geothermal high initial capital cost remains its main barrier, but long operational lifetimes and capacity factors exceeding 90% ensure competitive lifecycle costs in favourable geological zones (Liu et al., 2023). Integration with district heating and industrial applications is expanding rapidly, particularly in Iceland, Japan and East Africa (Ajan et al., 2023). Research in recent times also highlights growing attention to induced seismicity and subsurface monitoring using fibre-optic sensing for safety optimization (Patel et al., 2022).

Overall, geothermal energy represents an underutilized but technically mature component of the renewable technologies which offers continuous, low-emission power with minimal environmental impacts. Its future development depends on improved exploration techniques, enhanced drilling efficiency and continued investment in EGS research.

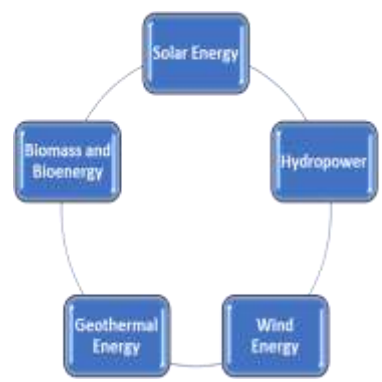

Figure 1: Current Renewable Energy Technologies

2.6 Electricity Generation Processes in Renewable Energy Technologies

Solar PV systems generate electricity by converting sunlight directly into electrical current through the photovoltaic effect (Figure 2). When photons from sunlight strike a semiconductor (e.g., silicon), they excite electrons, freeing them from their atomic bonds and creating electron-hole pairs; the internal electric field of the cell drives these electrons to flow, producing a direct current (DC) that is typically converted into alternating current (AC) via an inverter for grid use (Shaik et al., 2023; Kenu et al., 2020). The design and arrangement of semiconductor layers, doping, and contacts all influence how efficiently light is captured and turned into electricity (Ziar et al., 2021).

Wind turbines generate electricity by harnessing the kinetic energy of moving air (Figure 2). As wind flows over turbine blades, it exerts lift (and drag), causing them to spin around a hub; that rotating shaft turns a generator, where a rotor (often a magnet) spins inside or around coils of wire, inducing an electric current via electromagnetic induction (Zhang et al., 2025). The efficiency of conversion depends on blade design, wind speed, and the electromechanical design of the generator; advances in vibration-based "flow-induced vibration" harvesters are exploring non-traditional configurations that exploit wind more flexibly (Zhang et al., 2025).

Hydroelectric power plants convert the potential and kinetic energy of moving water into electricity (Figure 2). Water stored at a height (in a reservoir) flows down through penstocks (large pipes), and the pressure head of the water turns turbines (e.g., Francis, Kaplan, or Pelton turbines) as it flows. The turbine's shaft then drives a generator, converting mechanical energy into electrical energy (Karre et al., 2022; Niladri et al., 2022). Because the electricity output is proportional to both the flow rate and the head (height drop), plant design carefully matches turbine type to site topography (Shahgholian et al., 2020).

Biomass-based electricity generation relies on converting organic matter (such as wood chips, agricultural residues, or biogas) into heat or gas, which then drives turbines or internal combustion engines (Figure 2). In direct combustion systems, biomass is burned to produce heat, which generates steam that drives a steam turbine connected to a generator; in gasification, biomass is converted into a synthesis gas (syngas) in a low-oxygen environment, and that syngas is then combusted in gas turbines or engines to generate electricity (Balopi et al., 2025). Alternative pathways include anaerobic digestion, which produces biogas used in engines, and emerging fuel-cell technologies using hydrogen-rich syngas (Balopi et al., 2025). In the context of Nigeria, biomass from agricultural residues has considerable promise for decentralized electricity generation (Okafor, 2022).

Geothermal power plants exploit the Earth's internal heat by tapping into deep reservoirs of hot water or steam (Figure 2). In dry-steam plants, naturally occurring steam emerges from the ground and drives turbines directly. In flash-steam plants, high-pressure hot water is brought to the surface; as pressure drops, part of the water "flashes" into steam, which then drives the turbine. Binary-cycle plants use moderate-temperature geothermal fluid to heat a secondary working fluid (with a lower boiling point) in a closed loop, and the vapour from this secondary fluid then powers the turbine (IRENA, 2017; Sharmin, 2023). These systems can efficiently generate electricity even from lower-temperature reservoirs while minimizing environmental emissions (Sharmin, 2023; IRENA,

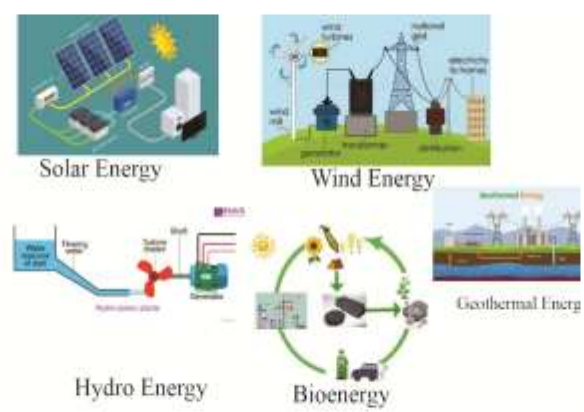

Figure 2: Electricity Generation Processes in Renewable Energy Technologies

2.7 Global Renewable Energy Technologies Development Process

Globally, the clearest front liners in renewable-energy technologies today are the large industrialized and manufacturing nations, most notably China, the United States, and several European countries (for example Germany and Denmark). These countries combine massive deployment (wind, solar, and grid-scale storage), deep manufacturing supply chains (especially for solar PV and batteries), and substantial Research and Development spending that pushes down technology costs and accelerates deployment (IEA, 2024; IRENA, 2024). China in particular has dominated recent capacity growth and module manufacturing, enabling rapid global reductions in solar and wind costs and supplying much of the world's hardware.

An important cluster of leaders includes countries that have institutionalized systems for innovation and grid integration, which include Germany, Denmark, and parts of the European Union, where policy design, market rules, and industry clusters allow cutting-edge technologies (offshore wind, smart grids, and demand-side management) to scale while retaining high reliability and local industrial benefit (REN21, 2024; IEA, 2024).. These nations often act as technology demonstrators: their ambitious targets, auction designs, and feed-in/contracting mechanisms create stable markets that attract investment in next-generation turbines, electrolysers (for green hydrogen), and grid software.

According to the IEA report, (2024), Africa, accounts for just 2% of global clean energy investment despite representing 20% of the global population. Africa is characterised by strong regional imbalances. South Africa and North Africa account for less than 20% of the population but more than 45% of energy investment and over 65% of installed electrical capacity. By contrast, Sub-Saharan Africa, home to most of the region's population, receives less energy investment and has limited access to reliable electricity. New connection rates have steadily increased since 2000 but remain well below the universal access target set for 2030, with 600 million people still lacking electricity access and more than 1 billion people without clean cooking means.

Africa Renewable Energy Technology Landscape

Africa's renewable energy contribution today is two-fold: it supplies a substantial share of rural and off-grid energy needs through bioenergy and small solar systems, and it holds vast untapped potential for large-scale low-carbon power that could fuel industrialization and cooling needs as populations grow. Much of Africa's present energy consumption particularly in rural areas still relies on traditional biofuels. But modern renewables (solar PV, hydro, wind, and geothermal) are rapidly being scaled for electricity access and productive uses. (IRENA, 2021).

Investment flows into African renewables have increased but remain well below what is needed to meet both energy access and climate goals; recent tracking shows hundreds of billions invested globally while Africa captures only a small fraction, leaving a clear finance gap that development banks and multilateral initiatives are trying to close.

Leading countries in Africa differ by technology and enabling policy. South Africa has led utility-scale renewable procurement through its well-structured procurement program, becoming a regional market leader; Morocco has become a solar and wind investment hub because of ambitious national targets and large-scale projects (including green hydrogen and desalination linked to renewables); Kenya and Ethiopia lead in geothermal and large hydropower respectively due to rich resources and public investment; Egypt is rapidly expanding renewables and grid infrastructure as well. These leaders combine strong resource endowments with clear procurement frameworks and significant public or concessional financing.

Despite the potential and pockets of leadership, Africa's overall share of global renewable investment remains small, and large-scale industrial uptake is constrained by limited grid capacity, currency and off-take risks, and continuing dominance of traditional biomass for household energy. That said, off-grid solar and mini-grids have been transformative for household and small-business access in many countries, representing an important near-term pathway to close the energy access gap while utility systems modernize.

Renewable Energy Technologies in Nigeria

Nigeria has major renewable potentials and a national Energy Transition Plan that sets targets for grid and decentralized renewables. These include solar, wind, hydro, bioenergy and geothermal. Currently, a lot of researches have been carried out to unravel the vast potentials for renewable energy technologies in Nigeria, but unfortunately, the outcome of these researches have not been adequately translated into workable realities. For instance, Kenneth et al, (2024) did an extensive geographical information system based assessment of the various renewable energy technologies potentials across the country using the ARCGIS software, and found the wealth of power that could be utilized. However, their usage has been hampered by weak transmission infrastructure, policy and implementation challenges. The prominence of gas and oil systems have also undermined the diversification into the uprising renewable energy sectors (IEA, 2024; World Bank, 2024). Notwithstanding, Nigeria shows important progress in distributed renewable energy and large multilateral programs with deals signed in lately. These aim to accelerate such projects as mini grids and off-grids solar in rural electrification and distributed renewables. Nonetheless, ensuring those projects scale to meet national targets will require steady reforms, stronger grid investments and easier access to finance for private developers.

Additionally, Nigeria's focus on renewable energy is driven primarily by the need to address energy access issues and reduce dependence on fossil fuels. As noted by Oyedepo (2012), Nigeria's energy sector faces challenges related to energy scarcity, inefficiency, and environmental degradation. The Nigerian government has initiated various policies and programs to promote renewable energy, but implementation remains slow. Oyedepo's analysis indicates that solar energy, given Nigeria's geographical location, offers the most significant potential for meeting the country's energy needs. Small-scale solar installations is now growing progressively, even in rural areas where grid electricity is unavailable. Biomass energy, particularly in the form of biogas, is also gaining attention as a viable option for rural electrification and sustainable agricultural development. The Nigerian government's commitment to renewable energy is evident in its Vision 30:30:30, which aims to achieve 30% renewable energy in the national energy mix by 2030.

Again, Nigeria's annual renewable investment keeps rising steadily. Recent analyses report that Nigeria captures a meaningful share of West Africa's renewable project finance (notably in distributed solar, mini-grids and off-grid solar home systems). Research and policy reports point to repeated bottlenecks which include, limited local-currency financing, regulatory uncertainty, weak utilities and insufficient project-preparation facilities (Ukoima, 2025; Namahoro et al., 2025). It is observed that if Nigeria reduces policy and currency risk, scales up her project preparation and increased finance deployed strategically, the country could raise her renewable energy outputs significantly.

2.8 Global Investment in Renewable Energy Technologies

Global investment in renewable energy (Figure 3) accelerated strongly after 2021 as post-pandemic recovery. Energy-security concerns and falling technology costs pushed capital toward low-carbon power, storage and grids. The IEA's World Energy Investment series shows clean-energy and energy-transition investment rising to roughly USD 2.0 trillion in 2024 with further increases projected into 2025 that all reflect large investment into solar PV, wind and batteries. (IEA, 2024; IEA, 2025). Recent cross-country analyses likewise find that the research and investments for renewables expanded rapidly in recent years (Mohnot, 2025).

At the national level the investment picture is highly concentrated. China is the single largest national investor in clean energy, accounting for roughly a third of global clean-energy spending in 2024. Their achievements have been driven by large manufacturing, storage investments and increased domestic build-out (Ember, 2025; IEA, 2024). The United States remains the second biggest market by annual investment, which are all supported by private capital, state procurement and federal incentives. Larger shares of her finance go into battery storage, grid modernization and corporate off-take rather than the rapid manufacturing expansion seen in China (IEA, 2024; Xue, 2024). These differences reflect diverging policy approaches. Industrial policy and manufacturing incentives are operational in China, while tax credits and market incentives are more pronounced in the U.S. These in turn shape the size and character of annual investment flows (Xue, 2024; IEA, 2024).

According to the IEA report, (2024), Africa accounts for just 2% of global clean energy investment despite representing 20% of the global population. Africa is characterized by strong regional imbalances. South Africa and North Africa account for less than 20% of the population but more than 45% of energy investment and over 65% of installed electrical capacity. By contrast, Sub-Saharan Africa, with more population, receives less energy investment and has limited access to reliable electricity. However, with private investment concentrated in a handful of countries; notably South Africa, Morocco, Egypt and Kenya, where enabling policy, project pipeline development and concessional finance made larger deals possible (Chiteka & Enweremadu, 2025; Obi, 2025).

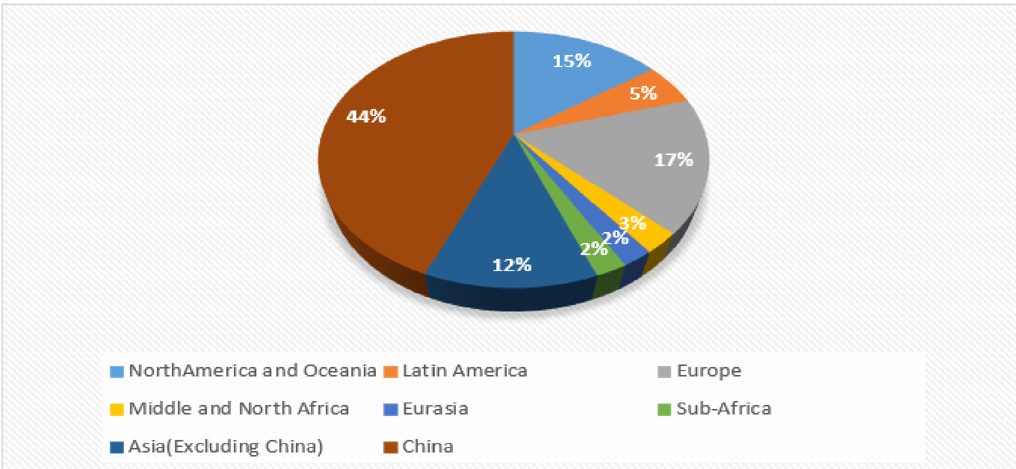

Figure 3:2024 Annual Regional Investment in RETs (IEA, 2024)

2.9 Global Shares of Renewable Energy Technologies

Global renewable electricity generation is increasing rapidly in recent times. This is primarily driven by solar and wind power, which are becoming more cost-competitive. In the first half of 2025, solar and wind growth surpassed global demand growth, with solar alone meeting 83% of the rise in demand (IEA, 2025).

At the end of 2024, renewable power capacity was dominated by solar (1,865 GW), followed by hydropower (1,283 GW) and wind (1,133 GW) (in table 1 and figure 4). For the first half of 2025, solar generation grew significantly, boosting its share in the global electricity mix from 6.9% to 8.8% (IEA, 2025)

In the first half of 2025, renewables overtook coal as a power source, with a share of 34.3% of global electricity compared to coal's 33.1%. The International Energy Agency (IEA) projects that renewables will become the largest global energy source, accounting for almost 45% of electricity generation by 2030 (IEA, 2025)

Table 1: 2024 Global Share of Renewable Energy Technologies (IEA, 2024)

RET	Share in Giga Watt (GW)	Percentage (%)
Solar	1865	42
Wind	1133	25.5
Bioenergy	151	3.4
Hydro	1283	28.9
Geothermal	15	0.34

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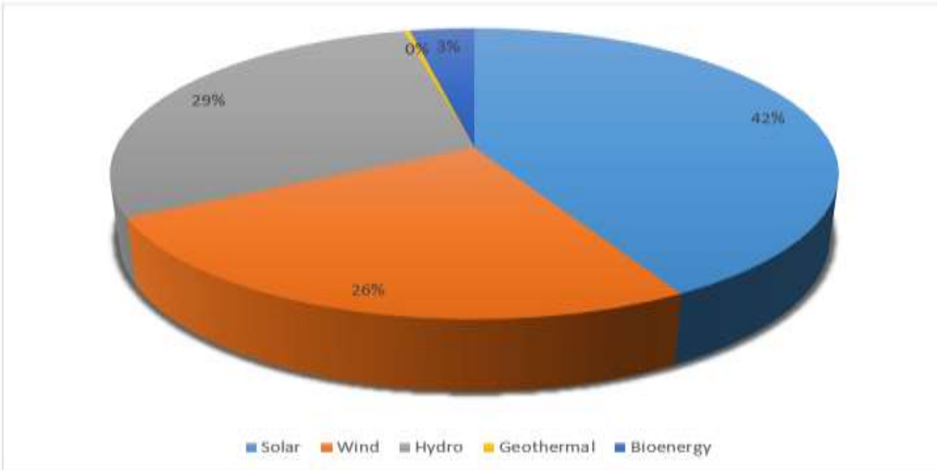

Figure 4: Global Shares of Renewable Energy Technologies (IEA, 2024)

2.10 Renewable Energy Technologies Share Projections

For these Renewable Energy Technologies Share Projections, data were condense from Statistical Agencies such as EIA, IRENA and REN21. And since it is a projection, the comments are the reviewers' predicated on the earlier factors of previous years. These Agencies and market outlooks show solar as the single largest contributor to capacity additions through the late 2020s (IRENA: solar 42% of renewable capacity in 2024). The IEA projects solar to be the dominant source of new renewable generation growth to 2030 and expects solar to overtake hydropower as the largest renewable by generation in the late 2020s. Researches in energy attributes solar energy acceleration to following factors; steep LCOE declines, factory scale (especially in China), faster project permitting for utility and rooftop PV, falling balance-of-system costs, plus growing development in battery storage.

Wind as major contributor to annual additions, and its offshore is expanding in several markets. But compared to solar, wind's growth rate is slower because of higher capital intensity, longer permitting and construction lead times, and material/supply-chain bottlenecks seen intermittently in the mid-2020s. Agency scenarios show steady wind additions through 2030 (IEA/REN21), which justifies a modest rise in percentage share while solar dominates part hydropower's share. These analyses identify permit timelines, grid connection costs and the need for installation infrastructure as constraints that slow wind's relative acceleration compared with PV.

Hydropower remains the largest cumulative generator today but has limited scope for huge new builds in many regions because of siting limits, long lead times and financing challenges. Agency projections (IEA/IRENA) explicitly show hydropower's share falling as solar and wind provide most of the incremental additions through 2030. This work points to environmental permitting, social/environmental mitigation costs, and site scarcity as the principal reasons new hydro additions are modest relative to PV and wind expansion; climate-driven water variability may also reduce output volatility and effective shares year-to-year.

Bioenergy is important for heat, industry and some power, but global growth is constrained by sustainability, competition for land and stricter emissions/land-use scrutiny in many regions. Agency statistics and modelling show bioenergy's absolute output can grow modestly, but relative share would decline as other renewable energy technologies expand rapidly. These analyses flag feedstock sustainability rules and limited scalable residues as key limitations.

Geothermal global share remains small due high upfront exploration/drilling risk and location-specific resources. Agencies' projections expect record growth in specific markets and faster deployment where supportive policy reduces exploration risk. Nonetheless, geothermal energy supply is still projected to remain a small fraction of total renewable generation by 2030.

III. HYBRID AND EMERGING RENEWABLE SYSTEMS

Hybrid Renewable Systems (HRES) in Figure 7 below, combining solar, wind, and biomass and storage technologies have received significant research focus at the time. Studies consistently demonstrate that hybridization improves grid stability, reduces curtailment and enhances economic viability (Ferdaus et al., 2025). Rashid et al, (2024) noted that hybrid micro grids integrating solar and wind with battery or hydrogen storage can reduce LCOE by up to 35% compared to standalone systems. Optimization research employing meta-heuristic algorithms such as particle swarm optimization and genetic algorithms has achieved enhanced energy management efficiency (Chen et al., 2023).

Another vital trend involves digitalization and artificial intelligence applications in hybrid systems. Predictive energy management using reinforcement learning and model predictive control has improved real-time dispatch in hybrid grids (Zhou et al., 2024). Studies also emphasize hybrid renewable hydrogen production, using surplus solar and wind energy for water electrolysis to generate green hydrogen (Wang et al., 2023). This approach offers long-term storage potential and reduced carbonization of industrial processes.

Research in hybrid systems has further clarify the importance of system flexibility and resilience. Integrated techno-economic assessments suggest that hybrid systems can accelerate renewable penetration in weak or off-grid regions, particularly in sub-Saharan Africa and island nations (Abbas et al., 2024). The researches at the moment noted that hybrid renewable systems represent the next evolutionary step toward achieving carbon-neutral and stable energy designs.

3.1 Integration and Storage Technologies

The rapid global adoption of renewable energy in recent times has intensified research on grid integration and energy storage technologies as critical enablers of system reliability, flexibility, and decarbonisation. Renewables such as solar and wind are inherently intermittent, and their increasing penetration has required power systems to evolve from rigid, centralized designs to dynamic, distributed, and intelligent networks (Abbas et al., 2024; Zhou et al., 2024). Researches have consistently identify energy storage as the aider of this transition (Rahman et al., 2022). In parallel, digital integration through smart grids, artificial intelligence (AI), and Internet-of-Things (IoT) technologies has been widely recognized as essential to balancing supply stability that improves forecasting accuracy and ensuring optimal energy dispatch (Ferdaus et al., 2025).

Battery technologies have seen remarkable advancements recent years, particularly in lithium-ion, sodium-ion, and solid-state chemistries. Lithium-ion batteries continue to dominate large-scale energy storage markets due to their high energy density, fast response time and declining costs, averaging below USD 130 per kWh by 2023 (Wang et al., 2024). Research has focused on improving electrode materials, electrolyte stability and lifecycle sustainability. Solid-state batteries, in particular, have attracted significant attention for their enhanced safety and potential to double energy density compared with conventional lithium-ion cells (Chen et al., 2023). Recent findings demonstrate stable operation at room temperature using sulphide-based solid electrolytes and composite anodes, reducing dendritic formation and fire risks (Zhou et al., 2024).
Sodium-ion batteries have re-emerged as cost-effective alternatives due to the abundance of sodium and their environmental advantages. Studies report improved cycle stability through layered oxide cathodes and hard-carbon anodes, achieving 80 to 90 % capacity retention over 2,000 cycles (Patel et al., 2022). Meanwhile, battery recycling and second-life applications have become major research themes. Analyses reveal that end-of-life recovery of cobalt, nickel, and lithium using hydrometallurgical methods can reduce the lifecycle carbon footprint by over 35% (Kumar et al., 2024). Beyond chemistry, system-level

innovation, including modular BESS designs and AI-based state-of-charge (SoC) monitoring has enhanced grid responsiveness and reduced degradation rates.

3.2 Hydrogen and Power-to-X Technologies

We have witnessed a dramatic surge in hydrogen research and deployment as part of the global shift toward carbon-neutral energy systems. Electrolytic hydrogen production using renewable electricity commonly termed "green hydrogen" has emerged as a key solution for large-scale energy storage and sectorial coupling (Wang et al., 2023). Proton exchange membrane (PEM) and alkaline electrolysers dominate current markets, with solid oxide electrolysers gaining momentum due to higher efficiency and thermal integration potential (Ferdaus et al., 2025). Researches on techno-economic studies estimate that green hydrogen costs declined by nearly 50% between 2021 and 2025, reaching parity with blue hydrogen in favourable markets such as the EU and Japan (Abbas et al., 2024).

In addition to energy storage, hydrogen's versatility underpins the emerging Power-to-X (P2X) paradigm, where renewable hydrogen is converted into fuels, chemicals, and heat. Research into Power-to-Methane and Power-to-Ammonia pathways demonstrates promising efficiencies of 60–70 % and substantial potential for industrial decarbonisation (Tao et al., 2022). Hydrogen storage in metal hydrides, liquid organic hydrogen carriers (LOHCs), and high-pressure tanks continues to be an active research field. Among these, LOHCs such as toluene–methyl cyclohexane systems have shown high reversibility and energy density suitable for seasonal storage (Patel et al., 2022). Integration studies indicate that coupling renewable hydrogen with ammonia synthesis and direct reduced iron (DRI) production could reduce industrial CO_2 emissions by 20% within a decade (Liu et al., 2023).

3.3 Smart Grids and Digital Integration

The modernization of electrical grids has grown rapidly through digital transformation, leveraging AI, machine learning (ML) and IoT technologies to manage decentralized renewable electricity generation. Smart grid research in recent times focuses on predictive analytics for dynamic system control (Rashid et al., 2024). Advanced sensors, phase measurement units (PMUs) and control algorithms enable real-time monitoring of grid parameters that reduces outage durations and improves stability in power supply. Studies employing reinforcement learning and model-predictive control have achieved notable improvements in energy dispatch efficiency and frequency regulation (Zhou et al., 2024).

Decentralized energy management using block-chain technology has also gained scholarly attention, particularly for peer-to-peer (P2P) energy trading and micro-grid coordination (Ferdaus et al., 2025). Block chain-enabled smart contracts provide secure, transparent transactions among prosumers, though scalability and regulatory alignment remain ongoing challenges. Furthermore, the integration of electric vehicles (EVs) into smart grids as mobile storage units known as vehicle-to-grid (V2G) systems has expanded substantially. Models show that aggregated EV fleets could contribute up to 15% of grid balancing needs during peak hours by 2025 (Wheatley, 2024). Collectively, digital integration represents a paradigm shift from static grid operations toward autonomous, data-driven networks that optimize renewable utilization.

IV. SYSTEM INTEGRATION CHALLENGES

Despite substantial progress, full integration of renewable energy into national and regional grids continues to face challenges related to intermittency, grid congestion and investment risk. Research assessments have noted the necessity of flexible market mechanisms, advanced forecasting, and supportive regulation to accelerate renewable energy technologies integration (Rahman et al., 2022; Abbas et al., 2024). Interconnection between nations and regional grids, enabled by high-voltage direct current (HVDC) systems, is a promising strategy to distribute surplus renewable energy and enhance system resilience (Liu et al., 2023). Similarly, hybrid micro-grids combining multiple energy sources with local storage are emerging as viable solutions for off-grid communities, particularly in sub-Saharan Africa and Southeast Asia (Ajan et al., 2023).

Looking ahead it can be expected that integrated energy systems combining electricity, heat, gas, and mobility sectors often termed "sector coupling" will define the next decade of renewable energy transition (Fan et al., 2022). Continued research into hybrid storage configurations, AI-enabled predictive maintenance, and grid-edge intelligence will be vital for achieving stability efficiency and sustainability in future energy systems. This period thus marks a crucial phase where integration and storage technologies have risen from auxiliary supports into core enablers of a renewable-dominated global energy mix.

4.1 Economic Policies on Renewable Energy Technologies

This era has witnessed a marked acceleration in renewable energy utilization due better policy frameworks, declining technology costs and international climate commitments under the Paris Agreement. Current analyses have observed that government-led industrial strategies, comprising fiscal incentives, carbon pricing and green industrial policies, have redefined energy markets and fostered a competitive renewable energy sector (Allan et al., 2022; Chen et al., 2023). Across China and emerging economies, policy instruments drive technology-push subsidies toward integrated frameworks that combine innovation, infrastructure investment and market reform (Lopez et al., 2023). The shift reflects a maturation of the renewable energy sector from early-stage support dependency toward market-oriented competitiveness (Ferdaus et al., 2025).

Global policy trends during this period highlight an increasing reliance on long-term planning through national energy transitions. The European Union's Green Deal, the U.S. Inflation Reduction Act (IRA) of 2022, and China's 14th Five-Year Plan all include renewables technologies within broader frameworks of economic resilience and industrial operations (Abbas et al., 2024). The IRA, for instance, allocates over USD 369 billion to clean energy and climate incentives, with production and investment tax credits directly tied to domestic manufacturing and labour standards. Empirical studies demonstrate that such integrated policy design has led to a 15 to 25% increase in domestic clean-energy manufacturing investments in less than two years (Kumar et al., 2024). In China, the combination of command-and-control mandates with competitive market modes has yielded record additions of solar and wind capacity exceeding 230 GW as at 2024 (Zhou et al., 2025).

Economic competitiveness remains central to renewable energy expansion. The levelized cost of energy (LCOE) for utility-scale solar photovoltaic has declined to USD 35 to 45/MWh, while onshore wind averages USD 40 to 50/MWh, representing cost reductions of 60 to 70% relative to 2015 benchmarks (Wang et al., 2023). Scholars attribute these trends to scale economies, innovation diffusion, and supply-chain localization, particularly in Asia (Patel et al., 2022). Hydrogen and battery technologies, though still cost-intensive, are following steep curves: the cost of green hydrogen production fell from USD 4 to 6/kg in 2020 to below USD 2/kg in pilot-scale operations by 2025 (Tao et al., 2022). The intersection of renewable energy generation, energy storage and flexible market design has also improved grid stability and reduced losses (Ferdaus et al., 2025).

Investment patterns between in recent times demonstrate a historic reallocation of global capital toward renewable energy technologies. According to economic analyses, annual global investment in clean energy surpassed USD 1.3 trillion by 2024, outpacing fossil fuel investments for the first time in history (Chen et al., 2023). Institutional investors and sovereign wealth funds are increasingly directing capital toward green bonds, driven by environmental, social and governance (ESG) criteria. Renewable energy companies have benefited from lower weighted average cost of capital (WACC) relative to fossil-based counterparts, averaging 3.5% versus 6.5%, respectively, indicating investor confidence in the long-term stability of the renewable sector (Allan et al., 2022). However, developing nations continue to face higher financing costs due to perceived political and currency risks. Scholars argue for increased financial and multilateral guarantees to raise investments in low-income regions (Fan et al., 2022).

4.2 Environmental and Social Impacts of Renewable Energy Technologies

The use of renewable energy technologies over the last half-decade has been accompanied by a mix of environmental and social concerns. On the environmental front, numerous life-cycle assessment (LCA) studies confirm that renewable energies deliver substantial reductions in greenhouse-gas (GHG) emissions compared with fossil-fuel systems. For instance, recent meta-analyses show that life-cycle emissions for solar and wind power typically fall below 50 g CO_2-eq per kWh, which is roughly an order of magnitude lower than coal-based generation (Bruckner et al., 2023; Xu & Zhang, 2022). However, as renewable energy capacity expands, concerns over upstream material extraction and end-of-life management have grown. Studies highlight that the manufacture of photovoltaic (PV) modules and wind turbines relies on critical minerals such as lithium, cobalt and rare earth metals, whose mining can impose local ecological burdens if not properly managed (Akinlabi et al., 2022; Díaz et al., 2024). Consequently, research attention has turned toward circular-economy strategies including design for recyclability and secondary material recovery to reduce the embodied energy and ecological impacts of renewable energy systems.

Beyond emissions, land and water use remain major environmental considerations. Large-scale solar farms require substantial surface area, often leading to habitat fragmentation or land-use competition with agriculture. Recent spatial-planning studies recommend integrating solar installations with agrivoltaic systems to mitigate these conflicts (Hernandez et al., 2023). Wind projects, while less land-intensive, can influence avian and bat populations; however, technological improvements such as ultrasonic deterrents and adaptive turbine shutdown systems have demonstrated significant reductions in wildlife mortality (Reichenbach & Allan, 2021). Hydropower continues to raise concerns about riverine ecosystem disruption and methane emissions from reservoirs. This prompts a shift toward small-scale, run-of-river designs that balance power generation with ecological preservation (Kumar & Prakash, 2022). Meanwhile, the life-cycle water of bioenergy and geothermal technologies highlight the need for region-specific resource management to ensure sustainability in arid zones (Liu et al., 2024).

V. FUTURE PROSPECTS IN RENEWABLE ENERGY TECHNOLOGIES

As the global energy transition accelerates, the future of renewable energy technologies will depend on the combination of scientific innovation, system-level integration and good policy frameworks. There has been progress in energy conversion efficiency, digital optimization and material science. Yet the next decade will demand not only technological breakthroughs but also systemic changes in infrastructure, governance and market design to ensure sustainability. The coming years are likely to witness remarkable shifts toward smart, hybrid and circular energy systems that integrate variable renewable technologies with advanced storage and digital management tools (IEA, 2023; Sovacool et al., 2024). However, realizing this vision requires addressing persistent barriers such as material scarcity, grid constraints, socio-political inertia and uneven global investment flows.

On the technological frontier, several innovations are coming up to redefine renewable energy generation and storage. Advances in perovskite solar cells, for instance, have achieved conversion efficiencies exceeding 25%, approaching the performance of silicon photovoltaics while offering lower production costs and tunable properties (Green et al., 2023). Research efforts are now directed toward stabilizing perovskite materials against moisture and thermal degradation through compositional engineering and encapsulation techniques (Kojima et al., 2024). In parallel, next-generation wind systems, especially floating offshore turbines are expanding renewable potential into deep-sea regions that were not accessible to fixed platforms. Recent prototypes demonstrate significant reductions in levelized cost of energy (LCOE) through modular fabrication and predictive maintenance enabled by artificial intelligence (Fuglsang & Larsen, 2023). Similarly, the rise of green hydrogen has opened pathways for reducing carbon emissions in industrial sectors that are difficult to electrify, such as steelmaking, cement and maritime transport. Electrolyzer technologies, particularly proton exchange membrane (PEM) and solid oxide systems are expected to achieve major cost declines by 2030 due to learning curves and material substitution (Li et al., 2023; Sharma & Nanda, 2024)

The future of renewable energy technologies will increasingly rise with digitalization, circularity and resilience imperatives. Artificial intelligence, block-chain and advanced sensors are set to transform the monitoring, forecasting and optimization of renewable systems. Circular design principles are expected to govern the next generation of technologies, emphasizing recyclability, modularity and low-impact materials. Moreover, climate adaptation is emerging as a key frontier ensuring that renewable infrastructure remains resilient to extreme weather, resource variability, and cyber risks (Bohm et al., 2023). At the same time, global energy equity must remain at the core of future strategies. Without deliberate inclusion of marginalized regions and populations, the renewable energy transition could replicate the inequalities of the fossil era. Ultimately, the success of renewable energy technologies beyond 2025 will hinge not only on technical excellence but also on policy coherence, ethical supply chains and social legitimacy for a sustainable global energy future (Henderson et al., 2025).

VI. CONCLUSION

Renewable energy technologies have evolved from side alternatives into central pillars of global energy systems. The direction of progress across solar, wind, hydro, biomass, geothermal and hybrid platforms demonstrates that the energy transition is no longer a technological aspiration but a material reality. Substantial declines in the levelized cost of electricity (LCOE) for wind and solar power have contributed to the viability of renewable energy technologies (IRENA, 2023). Yet, while technological and financial investment have risen the global renewable energy technologies utilization, the transition remains incomplete and uneven, owing to structural, environmental and social barriers. It is necessary to probe the readiness of low investing regions in the likes of sub-Saharan Africa into RETs, and encourage the same through capita incentives in order to attain even global renewable energy technology distribution.

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