



Progress in Solar, Wind, and Hydropower Energy in the 21st Century: A Review of Technological Advancement

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Abstract

Technology for renewable energy has grown considerably in the 21st century, mostly due to the urgent need to fight climate change and decrease dependence on fossil fuels. This review provides a comprehensive overview of the progress made in solar, wind, and hydropower energy systems, highlighting key technological breakthroughs and emerging trends. In the solar energy sector, innovations in photovoltaic materials, efficiency enhancements, and integration with smart grid technologies have played a crucial role in accelerating adoption. Wind energy has seen notable developments in turbine design, offshore deployment, and energy storage solutions aimed at addressing variability and grid compatibility. Hydropower, while a mature technology, continues to evolve through innovations in small-scale systems, pumped-storage techniques, and environmentally sustainable practices. The review also examines how various technologies function together, highlighting the growing significance of integrated renewable energy frameworks and hybrid systems. Future prospects for sustainable and resilient energy systems are examined, along with issues including intermittency, environmental effect, and governmental impediments. Overall, the paper emphasizes how important technology development is in influencing the world's shift to a cleaner and safer energy future.

Subject Areas

Applied Physics

Keywords

Renewable Energy, Solar Energy, Wind Energy, Hydropower Energy, Technological Advancements, Technological Innovations

1. Introduction

The 21st century has increased awareness of the environmental and socioeconomic problems caused by reliance on fossil fuels. Global warming and environmental degradation have been greatly exacerbated by the burning of coal, oil, and natural gas, which continues to be the main source of greenhouse gas emissions [1]. In response, the international community has accelerated efforts to transition toward a low-carbon energy future, driven by commitments such as the Paris Agreement and the United Nations Sustainable Development Goals (SDGs)—particularly Goal 7, which calls for access to affordable, reliable, sustainable, and modern energy for all [2].

Solar, wind, and hydropower technologies are the most developed and extensively used renewable energy sources. Together, they account for more than 85% of the world's renewable electricity generation [3]. A major factor in their quick development and incorporation into the world's energy mix has been consistent technological innovation. For instance, the levelized cost of electricity (LCOE) for solar photovoltaic and wind power has decreased by more than 80% over the past 20 years, making them more competitive with fossil fuels [4]. Meanwhile, Digital controls, variable-speed turbines, and enhanced ecological flow systems are now being added to updated hydropower systems in an effort to reduce their negative effects on the environment and increase the lifespan of infrastructure [5].

Technological advancements in these fields include data-driven system optimization, energy storage, smart grid integration, material science, and energy conversion efficiency. For example, research on solar energy has produced multi-junction and perovskite-based solar cells with unprecedented efficiency levels [6], and advances in structural engineering and aerodynamic modeling have produced significant increases in the size and power output of offshore wind turbines [7]. Issues, including inconsistent regulatory support, aging infrastructure, land use disputes, and intermittency still exist in spite of these advancements. Evaluating these renewable sources' technological advancements is essential to inform future investment and policy choices as the world's energy needs continue to grow [4].

The aim of this review is to provide a comprehensive analysis of the technological advancements in solar, wind, and hydropower energy systems in the 21st century. It explores key innovations, current trends in global deployment, and the challenges that must be addressed to enhance the performance and sustainability of these energy systems. By synthesizing recent research and international developments, this paper seeks to contribute to the understanding of how technology is driving the renewable energy transition.

1.1. Significance of the Study

This study is significant as it provides a focused and up-to-date evaluation of technological advancements in the three most dominant forms of renewable energy—solar, wind, and hydropower—in the context of the 21st century. By synthesizing recent innovations, performance improvements, and deployment trends, the

review offers valuable insights for researchers, policymakers, and energy sector stakeholders who are working to accelerate the global energy transition. Understanding the technological progress in these areas is crucial for identifying best practices, guiding investment strategies, and shaping supportive policies aimed at decarbonizing the global energy system. Additionally, the study highlights remaining technical and operational challenges, which can inform future research directions and innovation priorities as the world moves toward more sustainable and resilient energy systems.

1.2. Scope of Study

In this review article, the three main renewable energy sources—solar, wind, and hydropower—as well as their technological developments, capacity trends, economic aspects, policy implications, and environmental issues are examined in the context of the twenty-first century. Recent worldwide advancements, inventions, and comparisons of various technologies until 2024 are all included in the study. Although geothermal, biomass, and tidal energy are other renewable sources with significant roles, they are not covered in this article to provide a thorough and targeted analysis. Insights from the article are intended to be helpful to scholars, decision-makers, and industry participants involved in the shift to sustainable energy systems.

2. Methods

This review was conducted by systematically searching the literature from January 2000 to June 2025 to cover technological advancements in solar, wind, and hydropower energy in the 21st century. Databases including Scopus, Web of Science, IEEE Xplore, ScienceDirect, and Google Scholar were used. Keywords such as “solar energy technology,” “wind power advancements,” “hydropower development,” “renewable energy trends,” and “sustainable energy innovation” guided the search. Articles were selected based on relevance to technological progress, peer-reviewed status, and publication in English. Both primary research and authoritative review articles were included, while outdated or non-technical sources were excluded.

2.1. Technological Advancements in Solar Energy

Solar energy has become one of the fastest-growing and most transformative sources of renewable power in the 21st century. Solar technologies, especially photovoltaic (PV) systems, have shown an exponential increase in efficiency and use globally, made possible by ongoing innovation and falling costs [8].

Growth and Deployment Trends

After hydropower, solar PV has become the greatest renewable electricity source in the world, with installed capacity growing from less than 5 GW in 2000 to over 1200 GW by 2023. With the help of advantageous laws, subsidies, and advancements in technology, nations like China, the US, India, and Germany have taken

the lead [9].

Technological Innovations

1) Photovoltaic Efficiency and Materials

Commercial silicon-based solar cells are now much more efficient, with laboratory-scale PV cells already achieving above 26% efficiency [10]. Although stability and scalability are still major obstacles, new materials like perovskite solar cells offer interesting alternatives because of their low cost, high efficiency potential, and adaptability.

2) Bifacial and Multi-Junction Cells

Increasingly popular, bifacial photovoltaic modules can produce up to 10% - 20% more energy than conventional panels because they absorb sunlight from both sides of the panel [7]. Multi-junction cells, which are mostly utilized in space and concentrated solar power (CSP) applications, are breaking efficiency records. In testing environments, they can achieve above 47% efficiency.

3) System Integration and Smart Technologies

Modern solar systems are now integrated with battery storage, smart inverters, and IoT-based monitoring systems, allowing for better grid stability, real-time energy management, and performance diagnostics [4]. Artificial intelligence and machine learning are also being applied to forecast solar output and optimize operation and maintenance.

4) Floating Solar and Building-Integrated PV (BIPV)

Floating solar farms have been set up on lakes and reservoirs in nations like China, India, and Japan to overcome land-use limitations. In urban settings, building-integrated photovoltaics (BIPV), which incorporate solar panels into windows, façades, and roofs, are also becoming more and more common [11].

Table 1. Capacity & generation trends.

Year	Installed Capacity (GW) ¹	Annual Additions (GW) ²	Annual Generation (TWh) ³	Suggested citation(s)
2010	40	15	50	[8]
2020	710	115	1200	[9]
2023	1419	347	2500	[9]

According to the data shown in **Table 1**, solar PV has grown rapidly, with capacity more than 35 times increasing between 2010 and 2023. In 2023, annual additions hit a record 347 GW, driven by global supporting policies and ongoing cost reductions.

Between 2022 and 2024, solar photovoltaic technologies saw notable improvements in both efficiency and cost (see **Table 2**). Crystalline silicon (c-Si), the dominant commercial technology, improved from 14.5% - 21.5% efficiency in 2022 to 16% - 23% in 2024. Simultaneously, its levelized cost of electricity (LCOE) dropped from \$0.048/kWh in 2022 to just \$0.039/kWh in 2024, driven by innovations in cell architecture and manufacturing scale [4]. Thin-film technologies, including

CdTe and CIGS, also gained ground, with efficiency increasing to 13% - 19% by 2024 and LCOE declining to approximately \$0.050/kWh [12]. Perovskite solar cells, while not yet commercially viable at scale, demonstrated the fastest laboratory efficiency improvements, rising from around 24% in 2022 to over 26% in pilot lines by 2024 [13]. Although no commercial LCOE is available for Perovskites yet, the technology is regarded as a potential game changer due to its low-cost materials and tandem application potential. Overall, the consistent downward trend in solar costs and upward movement in efficiency signals a maturing market with strong innovation momentum.

Table 2. Efficiency improvements & cost trends in solar PV (2022-2024).

Technology Type	Module Efficiency (%) ¹	LCOE (\$/kWh) ²	Year	Suggested citation(s)
Crystalline Silicon (c-Si)	14.5 - 21.5 (2022)	0.048	2022	[4] [8]
	15 - 22 (2023)	0.044	2023	[8] [10]
	16 - 23 (2024)	0.039	2024	[4] [10]
Thin-Film (CdTe, CIGS)	11 - 17.5 (2022)	0.058	2022	[4] [8]
	12 - 18 (2023)	0.055	2023	[4]
	13 - 19 (2024)	0.050	2024	[4]
Perovskite (Emerging)	~24 (lab scale, 2022)	N/A	2022	[10]
	25+ (lab scale, 2023)	N/A	2023	[8]
	26+ (lab scale, pilot, 2024)	N/A (pilot stage)	2024	[10]

Table 3. Technological innovations & applications.

Innovation	Description	Impact on Solar Energy	Suggested citation(s)
Bifacial Solar Panels	Capture sunlight from front and rear surfaces	5% - 15% more energy yield	[12]
Floating Solar Farms	PV installations on water bodies	Saves land space, reduces panel temperature	[14]
Solar + Storage Integration	Coupling PV with batteries or pumped hydro	Enables grid stability and 24/7 power supply	[12]
Perovskite Tandem Cells	Combining perovskite with silicon cells	Higher efficiency potential	[13] [15]
Building-Integrated PV (BIPV)	Solar materials integrated into building elements	Expands solar use to urban environments	[12]

Innovations that reduce land-use issues and increase productivity include floating solar farms and bifacial panels. Addressing intermittency issues requires the quick expansion of battery storage in conjunction with solar PV [14]. If perovskite tandem cells are effectively scaled, efficiency could be revolutionized [15] (see **Table 3**).

2.2. Technological Advancements in Wind Energy

Being the second-largest renewable electricity source after hydropower and expanding more quickly than the majority of conventional energy systems, wind energy has emerged as a key component of the worldwide clean energy transition. In the 21st century, technological advancements in offshore infrastructure, digitization, and turbine design have greatly increased wind power's capacity, efficiency, and dependability [16].

Growth and Global Positioning

Global wind energy capacity grew from around 17 GW in 2000 to more than 1000 GW by 2023, with rapid expansion in both onshore and offshore sectors [4]. China, the United States, Germany, and Denmark are global leaders in positioning and innovation. Notably, offshore wind has become a feasible large-scale alternative, especially in Europe and Asia, despite initially being economically and technically difficult [17].

Wind power typically offers greater capacity factors (30% - 50% vs. 15% - 25% for solar), which makes it more appropriate for base-load power generation in some places, even if solar PV has expanded more quickly in terms of new yearly installations [18].

Technological Innovations

1) Turbine Size and Design Improvements

Contemporary wind turbines are now taller and more potent. Around 1.5 MW of turbine capacity was the norm in the early 2000s; today, commercial turbines are operating at capacities of over 10 MW, with some offshore models reaching up to 18 MW [19]. Higher hub heights and rotor diameters have improved energy capture and performance in low-wind regions.

2) Offshore Wind Technology

Stable wind speeds and fewer problems with land usage are advantages of offshore wind farms. Significant technological developments consist of:

- Wind turbines that float, allowing for deployment in deeper waters.
- Better foundation designs, such as jackets and monopoles.
- To minimize energy losses across long distances, HVDC transmission is used

In the long term, offshore wind is competitive due to its capacity factors, which are frequently above 50%, even if it still requires more capital than onshore wind or solar PV.

3) Digitalization and Predictive Maintenance

Digital twins, AI-based diagnostics, and condition monitoring systems (CMS) are being used more and more in wind farms in an effort to anticipate problems, minimize downtime, and save operating and maintenance (O&M) expenses [20]. In terms of system intelligence and grid responsiveness, these digital tools are assisting wind energy in catching up to solar energy.

4) Hybrid and Co-Located Systems

In hybrid systems, wind energy is integrated with solar and battery storage to maximize energy output and minimize intermittency. For example, co-located

solar-wind farms in the United States and India can offer a more balanced power profile by sharing the same transmission infrastructure [21].

Comparative Impact and Cost Trends

Similar to cost reductions in solar PV, wind energy has seen a significant decline in LCOE, from \$0.14/kWh in 2010 to approximately \$0.03 - 0.06/kWh in 2022. However, especially offshore, wind projects usually need more complicated permitting and longer development periods.

In contrast to solar energy, which is very modular and adjustable even at the home level, Wind energy is still more appropriate for utility-scale applications because of land, noise, and visual impact issues. However, its greater energy output and compatibility with solar (wind peaks at night or in different seasons, for example) make it an essential component of a diverse renewable energy mix [22] (see Table 4 and Table 5).

Table 4. Installed capacity, additions, and share (2023).

Technology	Installed Capacity (GW)	Net Addition in 2023 (GW)	Share of Renewable Capacity (%)	Suggested citation(s)
Solar PV	1419 GW	347 GW	37% scribd.comreuters.com + 7query.no + 7reuters.com + 7	[9]
Wind	1017 GW	115 GW	26%	[17]
Hydropower	1265 GW	7 GW	33%	[9]

Table 5. LCOE and capacity factor comparison (2023).

Tech.	LCOE (Weighted Avg, \$/kWh)	YoY Change	Capacity Factor (%)	Suggested citation(s)
Solar PV (utility)	0.044	↓ 12% en.wikipedia.org + 1pnas.org + 1	16.2%	[4]
Onshore Wind	0.033	↓ 3%	~35% - 45% (Global avg ~23% earlier; range 25% - 45%)	[7] [16]
Offshore Wind	0.075	↓ 7%	~41%	[17] [19]
Hydropower	~0.027*	↓ 7%	~41% (world avg) but ↓ 35.6% in H1-2023 due to droughts; long-term avg ~41%	[4] [5]

According to recent data, solar PV has emerged as the renewable energy source with the greatest rate of growth. In 2023, its installed capacity worldwide reached 1419 GW, exceeding both wind and hydropower for the first time [23]. The scalability of PV systems across a range of geographic and economic contexts, encouraging government policies, and quick cost reductions are the main drivers of this expansion. At 1017 GW, wind energy, in contrast, continued to increase steadily, especially in nations like China, the United States, and Germany. With only 7 GW of new capacity installed globally in 2023 due to site saturation and environmental constraints, hydropower—long regarded as the foundation of renewable electricity

generation—has plateaued [9].

Despite its slower growth, hydropower still makes a substantial contribution to the world's electricity supply because of its high capacity factors and storage capacities, which make it crucial for applications involving base load and peak shaving [5]. The main sources of new renewable energy deployment, on the other hand, are solar and wind energy, despite their greater variability, especially in energy-hungry regions like Asia and Africa.

Since 2010, utility-scale solar PV's levelized cost of electricity (LCOE) has decreased by almost 90%, reaching \$0.044/kWh in 2023. As a result, in many areas, solar energy is the most economical way to generate fresh electricity. With an LCOE of roughly \$0.033/kWh, onshore wind comes in second, whereas offshore wind offers far larger capacity factors and large-scale potential despite being more costly at \$0.075/kWh. Despite project and geographic variations, hydropower continues to be one of the most affordable electricity sources, with an expected LCOE of \$0.027/kWh. But older, deteriorated infrastructure is frequently reflected in these expenses. Depending on the area, onshore wind usually ranges from 30 to 45%, while solar PV trails behind with 15% to 25%. In contrast, hydropower and offshore wind have significantly higher capacity factors, averaging between 40% and 50% [9].

Growth and cost differences between solar, wind, and hydropower demonstrate the effects of specific policy changes. For example, feed-in tariffs, net metering, and tax incentives have sped up the implementation of solar photovoltaic systems, especially in the commercial and residential sectors. Complicated regulatory procedures are necessary since wind projects, particularly those that are offshore, sometimes call for lengthy construction schedules, complicated permitting, and environmental evaluations [24]. Despite its technical maturity, the development of hydropower is coming under more scrutiny because of the possible negative effects it may have on the environment and society, including the disturbance of riverine ecosystems and the displacement of communities [5]. Therefore, policy-makers need to make sure sustainability principles are maintained while striking a balance between new construction and the upgrading of aging infrastructure.

To support all three technologies, cross-sector policies that invest in grid modernization, energy storage, and research and development are essential. Aligning investment with climate goals and energy access targets, as laid out in the UN Sustainable Development Goals, will also ensure an equitable transition [25].

Every renewable energy source has its own advantages and disadvantages, which emphasizes how crucial technology integration is. Despite being widely available and adaptable, solar photovoltaics suffer from intermittent power outages and poor capacity factors. While hydropower supplies dispatchable power and serves as a natural buffer against the unpredictability of solar and wind, wind generation, especially offshore, offers a more consistent production [26].

Hybrid renewable energy systems—such as solar-wind farms situated alongside battery storage or pumped hydro—are increasingly bringing this interdependence

to life. In addition to improving dependability and energy security, these technologies optimize transmission and land infrastructure. It is anticipated that future systems will use sector coupling (e.g., with heating or transportation), digitization, and AI-driven grid management to build an intelligent, adaptable, and resilient energy infrastructure [27].

2.3. Technological Advancements in Hydropower Energy

The largest and oldest renewable electricity source is still hydropower. Despite the rise of solar and wind, hydropower remains a key component of decarbonization initiatives due to its dispatchable, flexible, and affordable electricity.

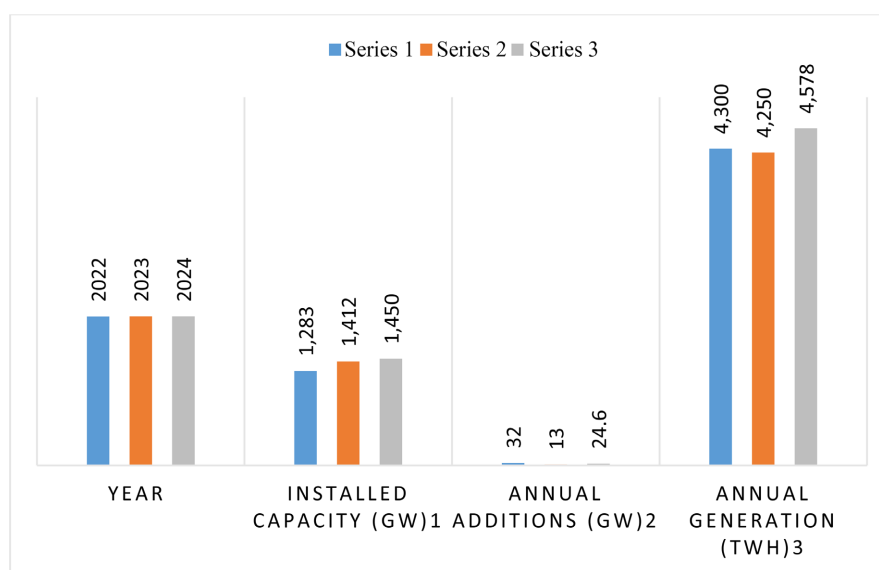


Figure 1. Hydropower capacity and trends (2022-2024).

Between 2022 and 2024, global hydropower experienced moderate but consistent growth. Installed capacity increased from 1283 GW in 2022 to 1412 GW in 2023, and further to approximately 1450 GW by the end of 2024 (see **Figure 1**). Notably, capacity additions dropped significantly in 2023 to just 13 GW, following a more robust 32 GW increase in 2022 (IRENA, 2024). Growth rebounded in 2024 with 24.6 GW of new capacity—16.2 GW from conventional projects and 8.4 GW from pumped storage—driven largely by new developments in China and Africa (International Hydropower Association [28]). Although hydropower lagged behind solar and wind in terms of growth rate, global generation rose from ~4250 TWh in 2023 to ~4578 TWh in 2024, attributed to improved rainfall after widespread droughts the previous year [29].

Solar energy experienced explosive growth over the past three years. In 2022, global installed solar capacity was around 1000 GW (see **Figure 2**). This figure jumped to 1420 GW by the end of 2023, then surged again to approximately 1900 GW by the end of 2024. Most of this growth was driven by China, which alone accounted for about 64% of the world's newly added capacity in 2024. This

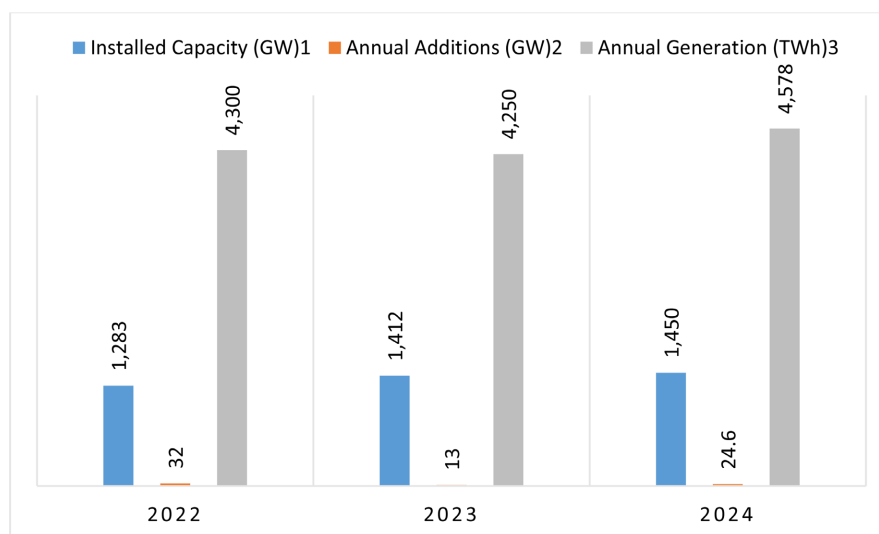


Figure 2. Global installed renewable energy capacity (GW).

massive expansion made solar the fastest-growing renewable energy source [30]. Wind power followed a steady but slower growth trajectory. From around 930 GW in 2022, global capacity rose to 1021 GW in 2023 and reached about 1140 GW in 2024. The Global Wind Energy Council (GWEC) reported a record 117 GW of new wind capacity installed in 2024, with China accounting for over 60% of the new installations. While wind growth is strong, it still trails solar in both absolute and percentage terms [31]. Hydropower remained relatively stable with moderate growth. Installed capacity increased from 1270 GW in 2022 to around 1412 GW in 2023 and further to about 1450 GW in 2024. In 2024, approximately 24.6 GW of new hydropower capacity was added globally, including pumped storage, with China and Africa leading the expansion. However, growth was modest compared to solar and wind. Notably, generation (in TWh) rebounded in 2024 due to improved rainfall after major droughts in 2023 [29].

After reviewing the indivisible progress of solar, wind, and hydropower energy sectors, it is important to consider their relative performance over the recent three-year period (2022-2024) to understand their complementary roles in the global renewable energy landscape.

Solar energy demonstrated the most rapid growth in installed capacity, nearly doubling within three years, and was driven largely by substantial additions in China. However, its relatively low capacity factor highlights ongoing challenges related to intermittency and efficiency. Wind power showed steady capacity growth with a higher utilization rate than solar, resulting in significant electricity generation increases. Hydropower, although expanding more modestly, maintained its position as the most efficient and highest electricity-producing renewable source, despite some variability caused by climatic factors.

This comparison reveals that while hydropower currently provides the largest share of renewable electricity generation and the highest efficiency, solar and wind energies are rapidly scaling up to meet growing global energy demands. Together,

these technologies form a diversified and resilient renewable energy mix crucial for advancing the transition towards sustainable power systems worldwide.

Table 6. Growth of solar, wind and hydropower energies between 2022 and 2024.

Year	Tech	Installed Capacity (GW)	Annual Additions (GW)	Generation (TWh)	Capacity Factor (%)	Suggested citation(s)
2022	Solar	1000	~260	~1300	~15	[30] [32]
	Wind	930	~77	~1870	~23	[27] [30]
	Hydro	1283	32	~4300	~38	[29]
2023	Solar	1420	~407 - 446	~1700	~16	[30]
	Wind	1021	~91 - 117	~2000	~22 - 23	[32]
	Hydro	1412	13	~4250	~34 (drought)	[29]
2024	Solar	~1866 - 1900	597	~2200	~17	[30]
	Wind	1136 - 1140	117	~2300	~23	[27]
	Hydro	1450	24.6	4578	~36	[31]

Between 2022 and 2024, solar, wind, and hydropower energies exhibited distinct growth and usage patterns (see **Table 6**). Solar energy showed the fastest expansion in installed capacity, increasing from 1000 GW in 2022 to nearly 1900 GW by 2024, primarily driven by significant deployments in China (Solar Power Europe, 2025; Reuters, 2024). Despite this rapid growth, solar's capacity factor remained relatively low, around 15% - 17%, due to its intermittent nature and dependence on daylight [32].

Wind power followed a steadier trajectory, with global capacity growing from 930 GW in 2022 to approximately 1140 GW in 2024. Wind's capacity factor, roughly 22% - 23%, was higher than solar's, resulting in greater electricity generation, which reached about 2300 TWh in 2024. The wind sector also saw record annual installations, adding 117 GW in 2024 alone, signifying strong but more moderate growth compared to solar [33].

Hydropower remained the largest contributor in terms of electricity generation, producing around 4300 TWh in 2022 and increasing to roughly 4578 TWh in 2024. It also maintained the highest capacity factor (approximately 34% - 38%), underscoring its role as the most efficient renewable energy source. However, hydropower's installed capacity grew more modestly from 1283 GW to 1450 GW, with generation fluctuations affected by climate variability such as droughts in 2023 and improved rainfall in 2024 [29].

In summary, hydropower leads in efficiency and total generation, wind power offers a balance of efficiency and growth, and solar power is the fastest-growing source by installed capacity but with lower utilization. Together, these renewable technologies complement one another in the global energy transition.

3. Limitations

This review is based primarily on secondary data obtained from institutional reports, academic publications, and market analyses. While efforts were made to ensure data credibility and recency, several limitations should be acknowledged. First, levelized cost of energy (LCOE) estimates vary widely depending on project scale, financing structures, and local policy environments, which introduces uncertainty in cost comparisons across technologies. Second, capacity factor data is subject to regional variation influenced by climate, geography, and infrastructure, potentially limiting the generalizability of global averages. Finally, the reliance on published sources means the review may not capture the most recent real-time developments or unpublished industrial innovations.

4. Conclusion

Hydropower is still a fundamental renewable energy source because it provides storage capacity, competitive pricing, and dependable base load power. As the building of new major dams slows down, upgrading and pumped storage will be necessary to accommodate the increasing use of wind and solar power. Environmental preservation, hybrid renewable system integration, and sustainable upgrading must be given top priority in regional policy.

Conflicts of Interest

The authors declare no conflicts of interest.

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