

Breakthroughs in Solar and Wind Energy Technologies

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Abstract

The increasing urgency to combat climate change and transition toward sustainable energy systems has positioned solar and wind energy as cornerstone technologies in the global energy landscape. This study, titled “Breakthroughs in Solar and Wind Energy Technologies”, explores recent innovations and trends that have significantly enhanced the efficiency, reliability, and affordability of these renewable energy sources. Key advancements discussed include breakthroughs in photovoltaic technologies, such as perovskite solar cells and bifacial modules, as well as innovations in wind turbine design, including taller towers and advanced blade engineering. The study also examines the role of energy storage solutions, smart grid integration, and hybrid energy systems in addressing intermittency and improving energy reliability. Furthermore, it highlights the socio-economic and environmental benefits of solar and wind energy adoption, including job creation, energy access in remote areas, and contributions to achieving net-zero emissions. By analysing current challenges such as resource intermittency, land use, and environmental impacts, this study provides insights into overcoming barriers to large-scale deployment. The findings emphasize the need for collaborative efforts in research, policymaking, and infrastructure development to maximize the potential of solar and wind energy technologies in fostering a sustainable energy future.

Keywords: Photovoltaic (PV) technologies, Building-integrated photovoltaics (BIPV), solar and wind energy, Concentrated solar power (CSP) systems, levelized cost of energy (LCOE)

INTRODUCTION

The global energy landscape is undergoing a transformative shift, driven by the urgent need to mitigate climate change, reduce dependency on fossil fuels, and meet the growing energy demands of a rapidly expanding population. Among the myriad renewable energy sources available, solar and wind energy have emerged as leading solutions, owing to their abundant availability, technological scalability, and decreasing cost curves. The integration of these clean energy sources into global energy systems is not only pivotal for achieving net-zero emissions but also for fostering sustainable economic growth, enhancing energy security, and reducing environmental degradation. Solar and wind energy technologies have witnessed unprecedented advancements over the past few decades, fuelled by intensive research and development, public and private sector investments, and supportive policy frameworks [1]. These advancements have significantly improved the efficiency, reliability, and affordability of solar panels, wind turbines, and associated energy storage and grid

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integration systems. Innovations in materials science, artificial intelligence (AI), machine learning (ML), and digital twin technologies have further revolutionized the way solar and wind energy systems are designed, operated, and maintained. For instance, the development of bifacial solar panels and perovskite-based photovoltaic cells has dramatically increased the energy conversion efficiency of solar modules, while innovations such as taller turbine towers and advanced blade designs have enhanced the capacity factors of wind turbines [2].

Despite these advancements, the large-scale deployment of solar and wind energy technologies is accompanied by several challenges. Intermittency, land-use conflicts, energy storage limitations, and the environmental impact of manufacturing and decommissioning are critical issues that require comprehensive solutions. To address intermittency, researchers are exploring hybrid energy systems, where solar and wind energy are combined with energy storage solutions such as lithium-ion batteries and pumped hydro storage. Furthermore, advances in grid infrastructure, including smart grids and decentralized microgrids, are enabling more efficient integration of renewable energy into existing power systems, ensuring a stable and reliable energy supply. In the context of global energy policies, the role of solar and wind energy is increasingly being recognized. International agreements such as the Paris Climate Accord and national renewable energy targets are accelerating the adoption of these technologies [3]. For example, countries like Germany, China, and India have set ambitious goals for solar and wind energy capacity expansion, providing incentives for innovation and deployment. Additionally, the private sector's commitment to renewable energy adoption is exemplified by corporations pledging to achieve 100% renewable energy use through initiatives like RE100.

The socio-economic impact of solar and wind energy technologies is also noteworthy. These technologies are creating millions of jobs worldwide, from manufacturing and installation to maintenance and research. Moreover, their adoption is enabling energy access in remote and underserved regions, contributing to the United Nations Sustainable Development Goals (SDGs), particularly SDG 7: Affordable and Clean Energy. By fostering energy independence and reducing energy poverty, solar and wind energy technologies are empowering communities and driving inclusive development [4]. This study, titled "*Breakthroughs in Solar and Wind Energy Technologies*", aims to provide a comprehensive overview of the latest innovations, trends, and challenges in this dynamic field. It delves into the cutting-edge developments in photovoltaic and wind turbine technologies, explores breakthroughs in energy storage and grid integration, and examines the environmental, economic, and policy implications of scaling up solar and wind energy systems. By highlighting successful case studies and identifying gaps in current research and implementation, this study seeks to contribute to the ongoing discourse on achieving a sustainable and renewable energy future.

The following sections of the study will systematically address key aspects of solar and wind energy advancements, starting with a detailed analysis of technological innovations. Subsequent sections will focus on the integration of these technologies into existing energy systems, their role in addressing global energy challenges, and future directions for research and policy-making. Ultimately, the study emphasizes the importance of collaborative efforts across governments, industries, academia, and communities in realizing the full potential of solar and wind energy technologies in driving the global energy transition.

LITERATURE SURVEY

The evolution of solar and wind energy technologies has garnered significant academic and industrial attention over the past decades, driven by the need for clean and sustainable energy solutions. This literature survey delves into the extensive body of work on advancements in solar and wind energy, highlighting key findings, technological innovations, challenges, and future directions in this domain.

Solar Energy Technologies

The development of photovoltaic (PV) technologies forms the cornerstone of solar energy advancements. Early research focused on silicon-based PV cells, with monocrystalline and polycrystalline silicon cells dominating the market due to their high efficiency and reliability. Recent studies, however, have shifted toward next-generation materials like perovskites, which promise higher efficiencies and lower manufacturing costs. Perovskite solar cells, as reviewed by National Renewable Energy Laboratory (NREL), have achieved efficiency levels exceeding 25%, rivalling traditional silicon cells, while being lightweight and flexible. Bifacial solar panels, capable of harvesting sunlight from both sides, have also emerged as a critical innovation, increasing energy output without significant additional cost [5].

Concentrated solar power (CSP) systems, which use mirrors or lenses to focus sunlight onto a receiver, have also been explored extensively. These systems, as reported by the International Renewable Energy Agency (IRENA), are particularly valuable for their ability to store thermal energy for power generation during non-sunny hours. Recent advancements in thermal storage materials, such as molten salts and phase change materials, have further enhanced the efficiency and reliability of CSP systems [6].

Solar energy research has also examined the integration of PV systems into urban infrastructure. Building-integrated photovoltaics (BIPV) and agrivoltaics are gaining traction for their dual functionality. BIPV systems, for example, serve as building materials while generating electricity, while agrivoltaics combine solar power generation with agricultural activities, optimizing land use.

Wind Energy Technologies

Wind energy technologies have advanced significantly since the early designs of horizontal-axis wind turbines (HAWTs). Recent research focuses on increasing turbine efficiency, capacity factors, and adaptability to diverse environmental conditions. Taller turbine towers and longer blades, enabled by advancements in composite materials, have been instrumental in capturing higher wind speeds at greater altitudes. Studies by the Global Wind Energy Council (GWEC) report that offshore wind farms have benefited from floating turbine designs, which allow installations in deeper waters where wind speeds are consistently higher [7].

Innovations in blade design, such as segmented and modular blades, have also been explored to improve transportation logistics and reduce costs. Additionally, artificial intelligence (AI) and machine learning (ML) are being employed to optimize wind farm operations, predict maintenance requirements, and maximize energy output. The concept of vertical-axis wind turbines (VAWTs), though less common, has seen renewed interest for urban and small-scale applications due to their ability to operate efficiently in turbulent wind conditions.

Energy Storage and Grid Integration

One of the critical challenges of solar and wind energy technologies is their intermittency. Energy storage systems are pivotal in mitigating this issue, and literature in this area focuses on improving the performance, cost-effectiveness, and scalability of storage solutions. Lithium-ion batteries dominate the market, but advancements in flow batteries, solid-state batteries, and hydrogen storage systems are expanding the range of options for large-scale energy storage. A 2023 study by the European Energy Research Alliance (EERA) highlights the potential of hybrid energy storage systems that combine multiple technologies to optimize performance across different timescales [5].

Smart grid technologies and decentralized microgrids are also extensively discussed in the literature. These systems enable efficient integration of renewable energy into existing power systems, balancing supply and demand through real-time monitoring and control. Research on vehicle-to-grid (V2G) technology, where electric vehicles act as mobile storage units, is another promising area for enhancing grid stability [8].

Environmental and Socio-Economic Considerations

The environmental and socio-economic dimensions of solar and wind energy adoption have been widely studied. Research underscores the need to address the environmental impact of manufacturing PV panels and wind turbines, including the use of rare earth metals and challenges in recycling. Studies, such as those by the International Energy Agency (IEA), advocate for a circular economy approach, focusing on material recovery and waste reduction.

From a socio-economic perspective, literature highlights the job creation potential of the renewable energy sector. The International Labour Organization (ILO) estimates that by 2030, solar and wind

energy projects could generate millions of new jobs globally. Moreover, renewable energy deployment is instrumental in reducing energy poverty and providing electricity access in remote areas, as evidenced by successful projects in sub-Saharan Africa and South Asia [9].

Policy and Future Directions

Policy frameworks and international agreements play a critical role in driving solar and wind energy adoption. The Paris Agreement and national renewable energy targets have incentivized investments and innovation in these technologies. Literature emphasizes the importance of carbon pricing, feed-in tariffs, and subsidies in accelerating the transition to renewable energy.

Looking ahead, future research must address remaining challenges, such as resource intermittency, land-use conflicts, and end-of-life management of renewable energy systems. The integration of AI and digital twin technologies for predictive maintenance, improved forecasting, and dynamic system optimization is a growing area of interest. Additionally, advancing energy storage solutions and enhancing grid flexibility will be essential for scaling up solar and wind energy deployment.

This literature survey demonstrates that while significant progress has been made in solar and wind energy technologies, continued innovation, interdisciplinary collaboration, and supportive policy frameworks are vital for realizing their full potential in transforming the global energy landscape.

INTRODUCTION TO RENEWABLE ENERGY LANDSCAPE

The transition from fossil fuels to renewable energy is central to combating climate change, ensuring energy security, and achieving sustainable development. Solar and wind energy have emerged as two of the most promising renewable energy sources due to their abundance, scalability, and technological advancements. Their adoption has been catalysed by decreasing costs, increased efficiency, and supportive policies worldwide. However, scaling up their deployment requires addressing technical, economic, and environmental challenges. This section explores the latest advancements in solar and wind energy technologies, their integration into energy systems, and their role in shaping a sustainable future [10].

Advancements in Solar Energy Technologies

Recent innovations in solar energy technologies have significantly improved efficiency, versatility, and scalability across photovoltaic systems, thermal storage, and infrastructure-integrated applications.

Photovoltaic (PV) Systems

The heart of solar energy technology lies in photovoltaic systems, which convert sunlight directly into electricity. The efficiency of these systems has steadily increased due to advancements in materials and design. Monocrystalline and polycrystalline silicon cells have been the industry standard for decades. However, the emergence of perovskite solar cells has revolutionized the field. These cells, made from a hybrid organic-inorganic material, offer higher efficiency, flexibility, and lower production costs. Researchers have reported efficiency levels exceeding 25%, making them competitive with traditional silicon-based systems [8].

Bifacial PV modules, which capture sunlight on both sides, have also gained prominence, allowing for higher energy yields without significant additional costs. Floating solar installations, particularly in water-scarce regions, have further expanded the scope of solar energy by utilizing water bodies to reduce land-use conflicts and improve panel cooling efficiency.

Concentrated Solar Power (CSP) Systems

Concentrated solar power systems use mirrors or lenses to concentrate sunlight onto a receiver, converting it into heat energy. This heat can be stored in materials like molten salts, enabling power generation during non-sunny periods. Recent advancements in thermal storage materials and system

designs have significantly enhanced CSP efficiency and reliability. Hybrid systems combining PV and CSP technologies are being explored to maximize energy output and storage capabilities [5].

Solar Integration in Infrastructure

Building-integrated photovoltaics (BIPV) represent a growing trend in sustainable architecture. By embedding solar panels into building materials, such as roofs, windows, and facades, BIPVs provide dual functionality, reducing the need for separate installation space. Agrivoltaics, which involve installing solar panels above agricultural fields, optimize land use by enabling simultaneous farming and energy generation.

Advancements in Wind Energy Technologies

Advancements in wind energy technologies have revolutionized turbine design, efficiency, and deployment, with innovations spanning offshore systems, AI integration, and urban renewable energy solutions.

Wind Turbine Design and Efficiency

Wind energy technologies have seen dramatic improvements, particularly in turbine design. Taller towers and longer blades allow turbines to capture higher-altitude winds, which are stronger and more consistent. Advanced blade designs, incorporating lightweight composite materials, have reduced material costs while improving aerodynamic performance [3].

Offshore wind energy has experienced a significant boom, driven by floating turbine technology. Traditional fixed-bottom turbines are limited to shallow waters, but floating designs enable installations in deeper oceans, where wind speeds are higher. Research indicates that offshore wind capacity could meet a substantial portion of global energy demand if deployed at scale.

Artificial Intelligence and Automation

AI and machine learning are being employed to optimize wind farm operations. Predictive maintenance, powered by AI, reduces downtime by identifying potential failures before they occur. Furthermore, AI-driven algorithms help in site selection, layout optimization, and energy forecasting, maximizing energy output.

Urban Wind Energy Solutions

Vertical-axis wind turbines (VAWTs) are being explored for urban applications, as they perform well in turbulent wind conditions common in cities. These compact and quieter turbines can be installed on rooftops and other urban structures, providing localized energy solutions for densely populated areas.

Integration of Solar and Wind Energy

The integration of solar and wind energy requires innovative solutions, including storage systems, hybrid models, and smart grids to ensure consistent and reliable power supply.

Energy Storage Solutions

One of the major challenges in solar and wind energy adoption is intermittency. Energy storage systems are critical to ensuring a reliable supply. Lithium-ion batteries dominate the market due to their high energy density and decreasing costs. However, alternative storage technologies, such as flow batteries, solid-state batteries, and hydrogen storage systems, are being developed to address scalability and long-duration storage needs [9].

Hybrid Energy Systems

Hybrid systems combining solar and wind energy have shown significant promise in addressing intermittency. By leveraging the complementary nature of solar and wind resources, solar energy during the day and wind energy at night, these systems provide a more consistent energy output. When coupled with advanced energy storage, hybrid systems can ensure round-the-clock renewable energy supply.

Smart Grids and Decentralized Microgrids

Integrating renewable energy into existing power grids requires advanced grid infrastructure. Smart grids, equipped with sensors and real-time data analytics, enable efficient energy distribution and load balancing. Decentralized microgrids, powered by solar and wind systems, are increasingly being used in remote areas, providing reliable energy access while reducing dependency on centralized fossil fuel-based power plants [2].

Environmental and Socio-Economic Impacts

Renewable energy offers significant environmental, economic, and social benefits, though challenges in production, disposal, and equitable access must be thoughtfully addressed.

Environmental Considerations

While solar and wind energy are environmentally friendly during operation, their production and disposal have environmental implications. Manufacturing PV panels and wind turbine blades involves the use of rare earth metals and other non-renewable materials. Addressing these challenges requires a circular economy approach, focusing on recycling and reusing materials to minimize waste.

Economic Benefits

The renewable energy sector has become a major driver of economic growth. According to the International Renewable Energy Agency (IRENA), the sector has created millions of jobs globally, spanning manufacturing, installation, and maintenance. The decreasing costs of solar and wind technologies have made them competitive with fossil fuels, attracting investments and fostering local industries.

Energy Access and Social Equity

Renewable energy technologies are pivotal in bridging the energy access gap, particularly in underserved regions. Decentralized solar and wind systems provide affordable and sustainable energy solutions for off-grid communities, empowering them with electricity for education, healthcare, and economic activities.

Policy and Future Directions

Effective policies and future-focused research are vital to accelerate renewable energy adoption, enhance system efficiency, and support the global transition to sustainable power.

Supportive Policies

Policy frameworks play a crucial role in driving renewable energy adoption. Feed-in tariffs, tax incentives, and renewable energy targets have been instrumental in promoting solar and wind energy projects worldwide. The Paris Agreement and other international commitments underscore the need for accelerated action to achieve net-zero emissions.

Future Research Directions

Future research should focus on improving energy storage technologies, enhancing grid flexibility, and addressing environmental concerns associated with renewable energy systems. Innovations in AI, blockchain, and digital twin technologies offer exciting possibilities for optimizing renewable energy operations. Additionally, interdisciplinary collaboration among scientists, engineers, policymakers, and communities will be essential to address the complex challenges of large-scale renewable energy deployment [5]. The advancements in solar and wind energy technologies represent a critical step toward a sustainable energy future. By overcoming technical and economic barriers, integrating renewable energy into power systems, and addressing socio-environmental concerns, these technologies can play a transformative role in mitigating climate change and fostering global development. Continued innovation, coupled with strong policy support and international cooperation, will be key to unlocking their full potential.

DISCUSSION

The advancements in solar and wind energy technologies represent a transformative step toward achieving a sustainable energy future. However, while these technologies have made significant progress, challenges remain in their large-scale deployment and integration into global energy systems. This discussion explores the implications of recent advancements, the barriers to widespread adoption, and the potential pathways to overcome these challenges [4].

Technological Implications

Solar and wind energy technologies have achieved remarkable efficiency gains, cost reductions, and scalability. Innovations in solar technology, such as perovskite solar cells, bifacial modules, and floating solar installations, have expanded the applications of solar power, from urban infrastructure to water-based systems. Similarly, advancements in wind turbine design, including taller towers, longer blades, and offshore floating turbines, have significantly increased energy output and reduced the levelized cost of energy (LCOE) [8].

These advancements demonstrate that solar and wind energy technologies are no longer limited to experimental or niche applications. They are becoming economically viable alternatives to fossil fuels, even in regions with moderate solar and wind resources. However, their widespread adoption depends on addressing the intermittency issue and ensuring reliable energy supply across various geographic and temporal scales.

Challenges and Barriers

Despite their benefits, solar and wind energy systems face significant challenges. Intermittency remains a primary concern, as solar and wind energy depend on weather conditions and time of day. This variability necessitates the development of advanced energy storage solutions and hybrid systems to ensure a consistent energy supply. While lithium-ion batteries dominate the market, their scalability and environmental impact are areas of concern. Emerging technologies like flow batteries, solid-state batteries, and hydrogen storage show promise but require further development and cost reductions [10].

Land use and environmental impact are other critical challenges. Large-scale solar farms and wind farms require substantial land or water area, potentially leading to conflicts with agriculture, biodiversity, and local communities. Offshore wind projects mitigate some of these issues but introduce new challenges, such as higher installation and maintenance costs and potential impacts on marine ecosystems.

Another barrier is the recycling and disposal of materials used in solar panels and wind turbine blades. The increasing deployment of these technologies will lead to a significant amount of end-of-life materials, necessitating effective recycling strategies and a circular economy approach to minimize waste [2].

Socio-Economic Implications

The socio-economic impact of solar and wind energy is profound, offering job creation, economic growth, and improved energy access. However, these benefits are not evenly distributed. Developing countries often face challenges in accessing the financial, technical, and policy resources needed to implement large-scale renewable energy projects. Ensuring equitable access to solar and wind technologies requires international cooperation, capacity-building, and financing mechanisms tailored to the needs of low-income regions.

Moreover, while renewable energy creates new employment opportunities, it also disrupts traditional energy sectors. The transition from fossil fuels to renewables must be managed to minimize social and economic dislocation for communities dependent on coal, oil, and gas industries. This calls for just transition policies that support reskilling, economic diversification, and social safety nets [4].

Integration into Energy Systems

The integration of solar and wind energy into existing power grids poses both technical and regulatory challenges. Smart grids and decentralized microgrids are essential for managing the variability of renewable energy and balancing supply and demand. These systems rely on real-time data analytics, AI-driven optimization, and advanced communication networks.

Additionally, hybrid systems combining solar, wind, and energy storage are emerging as viable solutions for ensuring a stable energy supply. These systems can optimize resource utilization and reduce dependence on fossil fuel-based backup power. However, their implementation requires significant investment in research, infrastructure, and policy alignment [7].

Pathways for Advancement

Addressing the challenges of solar and wind energy adoption requires a multi-faceted approach:

- *Technological innovation:* Continued research into advanced materials, energy storage, and grid integration technologies is essential. Innovations such as AI, machine learning, and digital twins can further optimize the performance and efficiency of renewable energy systems.
- *Policy support:* Governments must implement supportive policies, such as feed-in tariffs, tax incentives, and carbon pricing, to accelerate the adoption of solar and wind energy. International agreements like the Paris Accord can provide a framework for global cooperation.
- *Capacity building:* Developing countries need access to technical expertise, financing, and infrastructure to implement renewable energy projects. International partnerships and funding mechanisms can bridge these gaps.
- *Sustainability practices:* Recycling and waste management strategies must be developed to address the environmental impact of solar and wind energy systems at the end of their lifecycle.

While significant progress has been made in solar and wind energy technologies, challenges in storage, integration, environmental impact, and equity remain. Overcoming these barriers requires a collaborative effort involving governments, industries, researchers, and communities. By leveraging technological innovation, policy support, and international cooperation, solar and wind energy can become the backbone of a sustainable global energy system.

CONCLUSION

The rapid advancements in solar and wind energy technologies mark a pivotal shift in the global transition toward sustainable and renewable energy systems. Solar technologies, including innovations in perovskite solar cells, bifacial modules, and floating solar installations, have significantly improved efficiency, reduced costs, and broadened applications. Similarly, breakthroughs in wind turbine design, such as taller towers, advanced blade engineering, and offshore floating systems, have enhanced energy output and expanded deployment possibilities.

While these technologies demonstrate immense potential, challenges such as intermittency, environmental impact, and resource management remain. Energy storage solutions, hybrid systems, and smart grid integration are critical to overcoming these barriers and ensuring reliable energy supply. Addressing land use, material recycling, and socio-economic impacts is equally essential to foster equitable and sustainable development. Solar and wind energy are no longer merely alternatives but essential components of the global energy mix. Their continued progress relies on technological innovation, supportive policies, and international cooperation. By addressing current challenges and embracing a holistic approach, solar and wind energy can drive the transition to a low-carbon future, contributing significantly to climate change mitigation, energy security, and economic growth. This journey underscores the necessity of collective effort in building a sustainable energy landscape for future generations.

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