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Recent Developments and Challenges in Renewable Energy Engineering: Solar, Wind, and Hybrid Systems

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Abstract: Renewable energy engineering has advanced rapidly over the last two decades due to technological innovation, climate policy imperatives, and economic competitiveness. Solar and wind energy systems now represent the fastest-growing sources of electricity worldwide, while hybrid renewable configurations are increasingly adopted to overcome intermittency and grid integration challenges. This review critically examines recent engineering developments in solar photovoltaic technologies, wind energy systems, and integrated hybrid renewable energy architectures. Emphasis is placed on system design evolution, performance enhancement strategies, power electronics, and control mechanisms. Persistent challenges related to variability, storage integration, grid stability, material sustainability, and large-scale deployment are discussed in detail. The review synthesizes current literature to identify research gaps and outlines future engineering directions aimed at improving efficiency, reliability, and scalability of renewable energy systems.

Keywords: Renewable Energy, Solar Engineering, Wind Energy Systems, Hybrid Power Systems, Grid Integration

1. Introduction

The accelerating demand for energy, combined with growing environmental concerns, has positioned renewable energy engineering at the center of global energy system transformation. Conventional fossil-fuel-based power generation faces increasing scrutiny due to carbon emissions, resource depletion, and geopolitical vulnerabilities. In contrast, renewable energy sources such as solar and wind offer sustainable alternatives with minimal operational emissions and long-term availability [1]. Over the past decade, remarkable progress has been achieved in reducing the cost of renewable technologies through economies of scale, improved manufacturing processes, and optimized system designs. Solar photovoltaic module prices have declined dramatically, while wind turbines have increased in size and efficiency, enabling higher energy yields per installed unit [2]. These advancements have facilitated large-scale deployment across diverse geographical regions. Despite these successes, renewable energy systems introduce new engineering complexities. Variability in resource availability, integration with existing power grids, and the need for advanced energy storage solutions pose significant challenges. This review examines how recent engineering innovations address these issues while highlighting unresolved problems that require continued research and development.

2. Engineering Progress in Solar Energy Systems

2.1 Photovoltaic Technology Evolution

Solar photovoltaic engineering has undergone substantial transformation, driven by continuous improvements in semiconductor materials and device architectures. Crystalline silicon technology remains dominant due to its

reliability and well-established supply chain. Engineering enhancements such as selective emitters, rear surface passivation, and advanced anti-reflective coatings have incrementally increased module efficiencies [3]. In parallel, emerging photovoltaic materials have attracted significant research interest. Thin-film technologies, including cadmium telluride and copper indium gallium selenide, offer advantages in material usage and flexibility. More recently, perovskite-based solar cells have demonstrated exceptional efficiency gains within a short development period, positioning them as potential candidates for next-generation photovoltaics [4]. Tandem configurations combining perovskite and silicon layers aim to maximize solar spectrum utilization and surpass conventional efficiency limits.

2.2 System-Level Design and Performance Enhancement

Beyond cell efficiency, overall solar plant performance depends heavily on system engineering. The adoption of bifacial modules allows energy capture from both direct and reflected sunlight, improving annual yield without proportional increases in land usage [5]. Solar tracking mechanisms dynamically adjust module orientation, increasing energy output particularly in high-irradiance regions. Power electronics play a critical role in system efficiency and reliability. Advanced inverter technologies enable higher conversion efficiencies while supporting grid services such as voltage regulation and frequency response. These features are increasingly essential as solar penetration levels rise within electrical networks [6].

3. Wind Energy Engineering Developments

3.1 Turbine Design and Aerodynamic Innovations

Wind energy engineering has progressed through significant increases in turbine scale and aerodynamic sophistication. Modern wind turbines feature larger rotor diameters, optimized blade profiles, and lightweight composite materials that enhance energy capture while reducing structural loads [7]. Computational fluid dynamics and aeroelastic modeling have become integral tools in turbine design, enabling improved performance under variable wind conditions. Offshore wind energy has emerged as a major growth sector due to higher and more consistent wind speeds. Engineering innovations such as monopile foundations, jacket structures, and floating platforms have expanded feasible deployment zones into deeper waters [8].

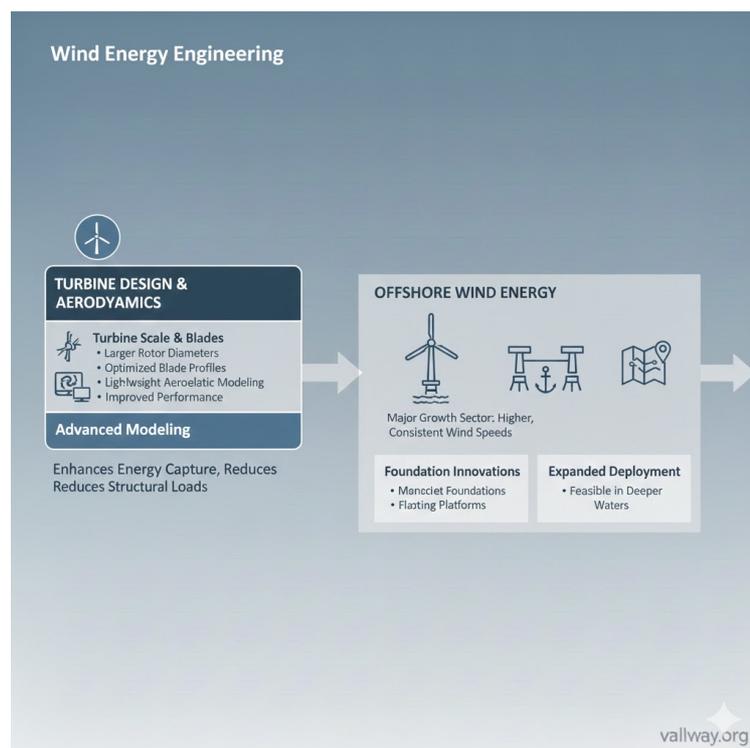


Fig. 1

3.2 Control Systems and Reliability Engineering

Advanced control strategies have improved turbine efficiency and operational lifespan. Individual pitch control and adaptive yaw systems mitigate fatigue loads and optimize power output. Condition monitoring systems utilizing vibration analysis and machine learning algorithms enable early fault detection, reducing maintenance costs and downtime [9]. Despite these advances, wind turbines remain exposed to harsh environmental conditions, necessitating ongoing research into materials durability, lightning protection, and offshore maintenance strategies.

4. Hybrid Renewable Energy Systems

4.1 Concept and Engineering Rationale

Hybrid renewable energy systems combine multiple energy sources, such as solar and wind, often integrated with energy storage. The complementary nature of solar and wind resources enhances overall system reliability by reducing variability in power generation [10]. Engineering design of hybrid systems focuses on optimal sizing, control coordination, and cost-effectiveness.

4.2 Energy Storage Integration

Energy storage technologies are critical to hybrid system performance. Battery storage systems, particularly lithium-ion technologies, provide fast response and high efficiency for short-term balancing. Long-duration storage solutions, including pumped hydro and hydrogen-based systems, support seasonal energy shifting [11].

Power management algorithms coordinate generation and storage to ensure stable operation under fluctuating conditions. Advances in optimization techniques and predictive control have significantly improved hybrid system dispatch strategies.

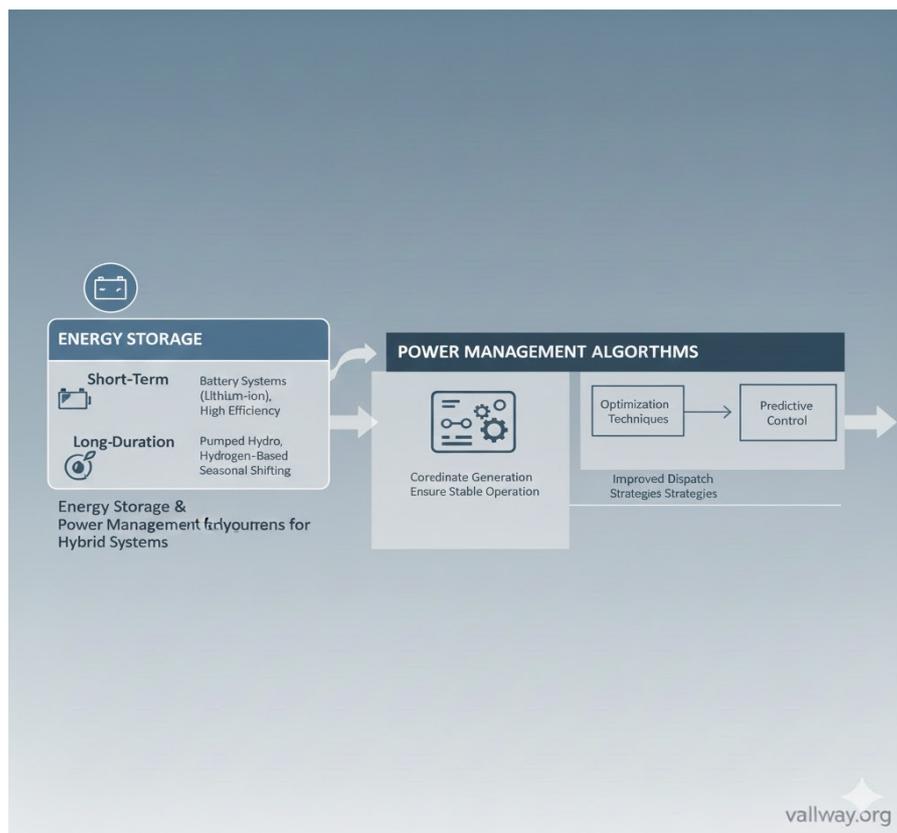


Fig. 2 Energy Storage

5. Grid Integration and Power Electronics Challenges

High penetration of renewable energy sources introduces challenges related to grid stability, frequency regulation, and fault management. Power electronic interfaces decouple generation from grid inertia, necessitating synthetic inertia and advanced control mechanisms [12]. Grid codes increasingly require renewable plants to support voltage and frequency regulation, driving innovation in inverter design. Transmission infrastructure expansion and smart grid technologies are essential to accommodate geographically dispersed renewable resources. Digital monitoring and communication systems enhance grid resilience and operational flexibility.

6. Environmental and Material Sustainability Considerations

While renewable energy systems offer environmental benefits, their lifecycle impacts require careful assessment. Material extraction, manufacturing emissions, and end-of-life disposal pose sustainability challenges. Research into recyclable photovoltaic modules, biodegradable composites, and circular economy approaches aims to reduce environmental footprints [13].

7. Future Research Directions

Future renewable energy engineering will emphasize system integration, digitalization, and resilience. Artificial intelligence, digital twins, and predictive analytics are expected to enhance operational efficiency and maintenance planning. Hybrid systems combining renewable generation with advanced storage and sector coupling will play a critical role in achieving carbon neutrality targets.

8. Conclusion

Renewable energy engineering has achieved remarkable progress in solar, wind, and hybrid systems. Continued innovation in materials, system design, and grid integration is essential to overcome remaining challenges and enable large-scale, reliable deployment. Interdisciplinary research and coordinated policy support will shape the next phase of renewable energy development.

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