

Solar Photovoltaic Technologies and Materials Science for High-Efficiency Energy Conversion



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Abstract

The rapid advancement of solar photovoltaic (PV) technologies has led to a paradigm shift in sustainable energy generation, yet challenges remain in ensuring reliability, efficiency, and seamless grid integration. Hybrid PV-diesel systems have emerged as a viable solution to address solar intermittency while reducing dependency on fossil fuels. These systems optimize energy generation through intelligent energy management strategies, incorporating advanced power electronics, energy storage, and predictive control mechanisms. The integration of blockchain technology enhances secure energy trading within PV microgrids, fostering decentralized and transparent energy markets. Artificial intelligence (AI) and the Internet of Things (IoT) play a pivotal role in real-time monitoring, demand forecasting, and grid stability, enabling smart solar energy management. Innovations in hydrogen storage and fuel cell technologies are driving new pathways for high-efficiency solar energy utilization, promoting a sustainable and resilient energy ecosystem. This book chapter provides a comprehensive analysis of hybrid solar energy systems, multi-source integration strategies, and emerging advancements in PV technology, emphasizing their role in achieving a decentralized, efficient, and intelligent energy future.

Keywords: Hybrid PV-diesel systems, Energy management, Blockchain, Smart grids, Hydrogen storage, Artificial intelligence in solar energy.

Introduction

The growing global demand for clean and sustainable energy has accelerated advancements in solar photovoltaic (PV) technologies, making them one of the most widely adopted renewable energy sources [1]. Solar PV systems offer numerous advantages, including zero greenhouse gas emissions, minimal operational costs, and abundant availability of solar radiation [2]. The intermittent nature of solar power due to weather variability and the absence of sunlight during nighttime hours remains a critical challenge for ensuring a stable energy supply [3]. To address these limitations, hybrid solar energy systems that integrate PV with other energy sources, such as diesel generators, energy storage systems, and emerging hydrogen-based solutions, have been developed [4]. These hybrid configurations enhance energy reliability, improve efficiency, and optimize power distribution, making them an ideal solution for both grid-connected and off-grid applications [5].

Hybrid PV-diesel systems have gained significant attention as a practical approach to overcoming the intermittency of solar power while reducing reliance on conventional fossil fuels [6]. These systems intelligently combine solar energy generation with diesel backup to provide uninterrupted electricity, particularly in remote and islanded locations where grid connectivity is limited [7]. During peak solar hours, PV panels generate electricity to meet the demand, while excess energy is stored or used to reduce generator operation [8]. When solar generation declines, diesel generators supplement the power supply, ensuring a seamless transition [9]. The integration of battery energy storage further enhances system efficiency by storing surplus solar power for later use, reducing fuel consumption and operational costs [10]. Advanced energy management strategies, including artificial intelligence (AI) and real-time optimization techniques, play a crucial role in maximizing the benefits of hybrid PV-diesel systems [11].

Beyond PV-diesel hybridization, blockchain technology is transforming energy trading within PV microgrids by enabling decentralized and secure peer-to-peer (P2P) transactions [11]. Traditional energy markets rely on centralized utilities and intermediaries, often leading to inefficiencies and increased costs [12]. Blockchain-based platforms eliminate these intermediaries by facilitating direct energy exchanges between prosumers and consumers. The integration of smart contracts automates transaction execution based on predefined agreements, ensuring transparency, security, and real-time settlements [13]. This decentralized approach not only enhances energy accessibility but also promotes the adoption of localized renewable energy generation, reducing grid dependency [14]. The convergence of blockchain with AI and IoT further strengthens smart energy management by enabling predictive analytics, real-time monitoring, and automated load balancing, paving the way for the development of intelligent PV microgrids [15].