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Concentrated Solar Power (CSP) Systems for Large-Scale Electricity Generation

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Abstract

The hybridization of Concentrated Solar Power (CSP) systems with complementary renewable energy technologies has emerged as a transformative approach for enhancing efficiency, reliability, and large-scale electricity generation. CSP, with its inherent ability to integrate thermal energy storage (TES), provides a dispatchable and stable energy supply, overcoming the intermittency challenges associated with other renewable sources. By integrating Photovoltaic (PV) systems, wind energy, Battery Energy Storage Systems (BESS), and hydrogen production technologies, hybrid CSP configurations optimize energy utilization, improve grid stability, and enable 24/7 renewable power generation. The CSP-PV hybrid model enhances solar resource utilization by leveraging direct electricity generation from PV during daylight hours while using CSP for thermal storage and extended power dispatch. The CSP-wind hybrid system addresses seasonal variations, ensuring a more continuous and resilient power supply. The incorporation of BESS in CSP plants enables fast-response grid balancing, while the integration of CSP with hydrogen production technologies facilitates large-scale, carbon-free hydrogen generation. This book chapter provides a comprehensive analysis of the latest advancements, case studies, and future prospects of hybrid CSP systems, highlighting their role in achieving sustainable energy transitions and large-scale decarbonization. The discussion includes technological evolution, design principles, economic feasibility, and policy frameworks that influence the large-scale deployment of CSP-based hybrid renewable energy solutions.

Keywords: Concentrated Solar Power (CSP), Hybrid Renewable Systems, Thermal Energy Storage, Large-Scale Electricity Generation, CSP-PV Hybridization, CSP-Hydrogen Production.

Introduction

The increasing global demand for sustainable and dispatchable power generation has led to significant advancements in renewable energy technologies [1]. Among these, Concentrated Solar Power (CSP) systems have gained attention due to their ability to store thermal energy and provide continuous electricity generation, overcoming the intermittency challenges faced by other renewable sources [2]. Unlike photovoltaic (PV) systems that convert sunlight directly into electricity, CSP systems utilize mirrors or lenses to concentrate solar radiation, generating high-temperature heat, which is then used to drive a steam turbine or heat engine for power production [3]. The integration of Thermal Energy Storage (TES) allows CSP plants to store excess solar energy and dispatch it when needed, making it a reliable alternative to conventional fossil fuelbased power plants [4]. Despite these advantages, standalone CSP systems face challenges such as high capital costs, efficiency limitations, and geographic dependency, necessitating hybridization with other renewable and storage technologies to enhance overall system performance [5].

Hybridizing CSP with Photovoltaic (PV) technology optimizes solar energy utilization by combining direct electricity generation from PV with CSP's ability to store and dispatch thermal energy [6]. PV systems operate efficiently under direct sunlight but lack storage capabilities, making them unsuitable for providing continuous power supply [7]. By integrating CSP with PV, a more stable and efficient solar power generation model is achieved, where PV contributes to immediate power generation during the day, while CSP with TES ensures uninterrupted energy availability during cloudy periods and nighttime hours [8]. This hybrid approach reduces energy curtailment, maximizes land use efficiency, and enhances economic viability, making it an attractive solution for large-scale solar power deployment [9]. Advancements in power electronics, smart grid integration, and predictive energy management systems further improve the operational efficiency and flexibility of CSP-PV hybrid systems, facilitating their large-scale commercial adoption [10].

In addition to PV integration, CSP-wind hybridization presents another promising approach for enhancing renewable power generation stability [11]. Wind energy, characterized by seasonal and nocturnal availability, complements CSP's daytime energy generation pattern, creating a synergistic energy mix that balances fluctuations in solar radiation and wind speeds [12]. By co-locating CSP and wind farms, hybrid plants can ensure a continuous and reliable power supply, reducing dependence on grid-based backup systems [13]. Hybrid CSP-wind systems can optimize grid utilization, reduce transmission losses, and enhance energy security, particularly in regions with variable solar and wind resources [14]. The integration of advanced forecasting algorithms and energy storage solutions further strengthens the dispatchability and efficiency of CSP-wind hybrid power plants, making them a viable option for large-scale renewable energy infrastructure [15].