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Solar Thermal Energy Storage Technologies for Sustainable Energy Supply

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Abstract

Thermochemical energy storage (TCES) systems have emerged as a highly efficient solution for large-scale and long-duration energy storage, particularly in high-temperature industrial applications and renewable energy integration. By leveraging reversible chemical reactions, TCES offers superior energy density, minimal thermal losses, and extended storage duration compared to conventional energy storage technologies. However, challenges such as slow reaction kinetics, material degradation, and suboptimal heat and mass transfer mechanisms limit the widespread adoption of TCES. This book chapter explores advanced strategies for enhancing the efficiency, stability, and economic feasibility of TCES systems, focusing on innovative reactor designs, nanomaterial-enhanced thermochemical materials, and hybrid energy storage configurations. Special attention is given to improving the thermal conductivity of TCES materials using nanostructures, optimizing reactor materials for high-temperature stability, and integrating TCES with renewable and waste heat recovery systems to maximize energy utilization. A techno-economic analysis is presented to assess the viability of hybrid TCES systems for industrial applications, highlighting cost-benefit trade-offs, operational scalability, and long-term sustainability. Addressing these critical aspects is essential for advancing TCES technologies, enabling their large-scale implementation in industrial processes, grid stabilization, and carbon-neutral energy solutions. Future research directions and emerging innovations in thermochemical storage materials, system optimization, and integration with smart energy networks are also discussed.

Keywords: Thermochemical Energy Storage, High-Temperature Stability, Nanomaterials, Heat Transfer Enhancement, Hybrid Energy Systems, Techno-Economic Analysis

Introduction

Thermochemical energy storage (TCES) has emerged as a highly promising solution for addressing the challenges associated with large-scale and long-duration energy storage [1]. Unlike conventional thermal storage methods, such as sensible and latent heat storage, TCES relies on reversible chemical reactions to store and release energy, allowing for significantly higher energy densities and reduced thermal losses over extended periods [2]. This unique characteristic makes

TCES particularly well-suited for applications requiring high-temperature heat storage, including concentrated solar power (CSP) plants, industrial process heating, and waste heat recovery systems. By utilizing endothermic and exothermic reactions, TCES enables efficient thermal management, enhances energy utilization, and facilitates load shifting in renewable energy systems [3]. Despite these advantages, the widespread implementation of TCES remains limited due to challenges related to material stability, reaction kinetics, and system integration, necessitating further research and technological advancements [4].

One of the critical limitations of TCES lies in the selection and optimization of thermochemical materials [5]. The efficiency of a TCES system is largely determined by the thermodynamic and kinetic properties of the storage materials, which influence reaction reversibility, heat transfer rates, and energy storage capacity [6]. Materials such as metal oxides, carbonates, and hydroxides have been extensively studied for their suitability in high-temperature TCES applications, yet issues such as degradation over multiple cycles, slow reaction kinetics, and material sintering remain significant concerns [7]. In addition, the efficiency of heat transfer within the storage medium plays a crucial role in determining the overall performance of the system [8]. Poor thermal conductivity in many TCES materials limits the rate of heat absorption and release, leading to inefficiencies and non-uniform temperature distributions [9]. To address these challenges, advanced material engineering approaches, including the incorporation of nanomaterials and composite structures, have been explored to enhance thermal conductivity, improve reaction stability, and extend the operational lifespan of TCES systems [10].