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Experimental Performance Evaluation of Thermal Energy Storage Systems for Integration with Solar Power Plants

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Abstract: The intermittent nature of solar energy poses significant challenges to its reliable integration into large-scale power generation systems. Thermal energy storage systems offer a promising solution by enabling the capture, storage, and controlled release of solar thermal energy, thereby enhancing dispatchability and grid stability. This study presents an experimental performance evaluation of thermal energy storage systems designed for integration with solar power plants. Both sensible and latent heat storage configurations were developed and tested using representative storage media, including molten salts and phase change materials. Thermal charging and discharging behavior, heat transfer efficiency, and energy retention characteristics were systematically analyzed under controlled and field-simulated conditions. The experimental results were complemented by thermodynamic modeling to assess system efficiency and scalability. Findings demonstrate that optimized thermal energy storage configurations significantly improve solar plant capacity utilization and reduce energy losses during off-sunshine periods. The study provides valuable insights into the practical deployment of thermal energy storage technologies for sustainable solar power generation.

Keywords: Thermal Energy Storage, Solar Power Integration, Phase Change Materials, Heat Transfer Analysis, Renewable Energy Systems

1. Introduction

Solar energy is widely recognized as a cornerstone of the global transition toward sustainable and low-carbon energy systems. Concentrated solar power and solar thermal plants, in particular, offer the advantage of high-temperature operation suitable for electricity generation and industrial applications. However, the inherent intermittency of solar radiation limits the continuous availability of power, necessitating effective energy storage solutions [1]. Thermal energy storage systems enable the decoupling of energy collection from energy utilization by storing excess thermal energy during peak solar availability and releasing it during periods of low or no solar input. By enhancing plant dispatchability, thermal energy storage improves grid reliability, reduces reliance on fossil fuel backup systems, and increases the economic viability of solar power plants [2]. Various thermal energy storage technologies have been explored, including sensible heat storage using molten salts, latent heat storage employing phase change materials, and thermochemical storage systems. Among these, sensible and latent heat storage systems have reached higher levels of technological maturity and are currently deployed in commercial solar power plants. Nevertheless, challenges related to heat transfer efficiency, thermal stability, material compatibility, and system integration persist. This research focuses on the experimental evaluation of thermal energy storage systems suitable for solar power plant integration. By combining laboratory-scale experiments with thermodynamic modeling and field-relevant testing conditions, the study aims to provide a comprehensive assessment of system performance and practical feasibility.

2. Design and Configuration of Thermal Energy Storage Systems

The design of thermal energy storage systems requires careful consideration of storage medium properties, operating temperature range, containment materials, and heat exchanger configuration. In this study, two storage

configurations were developed: a sensible heat storage system using molten salt and a latent heat storage system incorporating phase change materials. The molten salt storage system utilized a eutectic mixture selected for its high thermal stability, favorable heat capacity, and compatibility with solar thermal operating temperatures. The phase change material-based system employed encapsulated materials with melting temperatures aligned to the operating range of solar thermal collectors. Encapsulation improved thermal conductivity and prevented leakage during phase transition [3]. Heat exchanger design played a critical role in system performance. Enhanced surface area and optimized flow paths were implemented to improve heat transfer between the heat transfer fluid and storage media. Thermal insulation was carefully designed to minimize heat losses during storage.

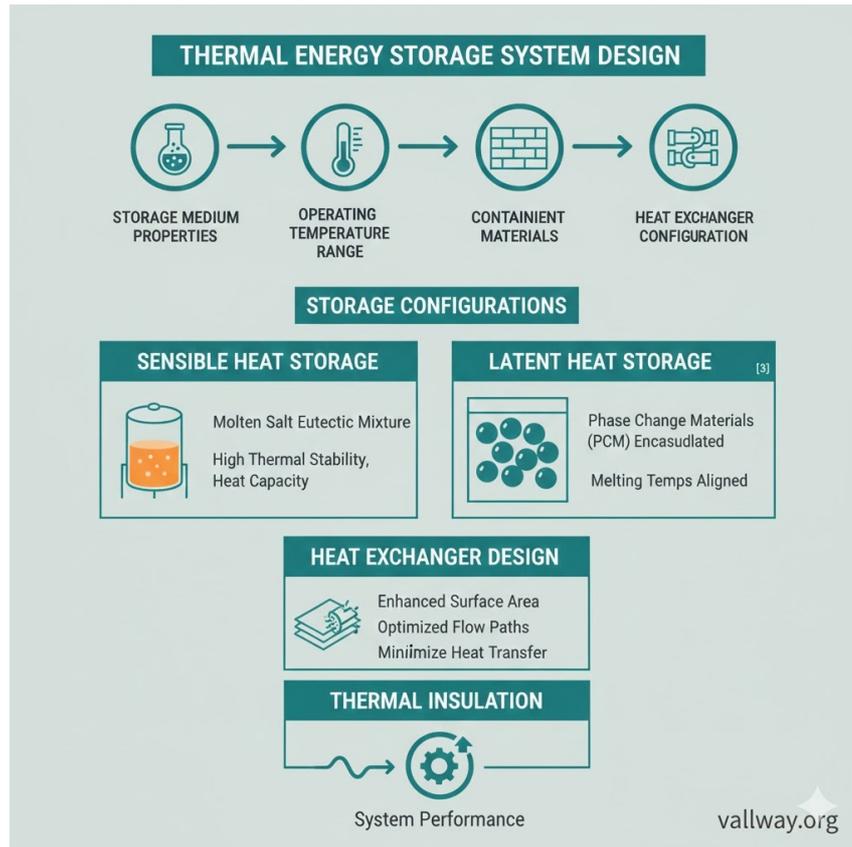


Fig. 1 Thermal Energy Storage Systems

3. Experimental Methodology and Instrumentation

Experimental evaluation was conducted using a controlled test rig designed to simulate solar thermal input and power plant operating conditions. The system was instrumented with temperature sensors, flow meters, and data acquisition units to monitor thermal behavior during charging and discharging cycles. Charging experiments involved supplying thermal energy at controlled rates to evaluate storage capacity and heat transfer efficiency. Discharging tests assessed energy retrieval efficiency and temperature stability under variable load conditions. Repeated cycling experiments were performed to evaluate thermal reliability and material stability over extended operation [4].

4. Heat Transfer and Thermodynamic Performance Analysis

Heat transfer performance was analyzed by evaluating temperature gradients, heat flux, and thermal response time. The molten salt system exhibited rapid heat absorption and stable temperature profiles, indicating effective sensible heat storage. The phase change material system demonstrated enhanced energy density due to latent heat absorption during phase transition. Thermodynamic efficiency was calculated based on energy input and output measurements. The results indicated that optimized system configurations achieved high round-trip efficiency, making them suitable for integration into solar power plants. Comparative analysis highlighted the strengths and limitations of each storage approach [5].

5. Field Simulation and Solar Plant Integration Assessment

To assess practical feasibility, experimental conditions were extended to simulate field operation scenarios. Variable heat input profiles mimicking diurnal solar patterns were applied. The thermal energy storage systems successfully buffered fluctuations in solar input, maintaining stable output temperatures during discharge periods. Integration analysis demonstrated that thermal energy storage significantly improved plant capacity utilization and reduced startup losses. These findings underscore the value of storage systems in enhancing solar plant operational flexibility.

6. Energy Efficiency and Economic Considerations

Energy efficiency analysis revealed that thermal energy storage systems contribute to improved overall plant efficiency by reducing curtailment and enhancing dispatchability. Preliminary economic evaluation suggested that increased capital costs associated with storage systems are offset by improved energy output and reduced reliance on auxiliary energy sources [6].

7. Challenges and Future Research Directions

Challenges related to material degradation, thermal losses, and system scaling were identified. Future research should focus on advanced materials with higher thermal conductivity, improved encapsulation techniques, and integration with hybrid renewable systems.

8. Conclusion

This study provides a comprehensive experimental evaluation of thermal energy storage systems for solar power plant integration. Both sensible and latent heat storage configurations demonstrated strong performance, enhancing energy availability and system reliability. The findings support the broader adoption of thermal energy storage technologies as a critical component of sustainable solar power generation, contributing to energy security and environmental sustainability.

References

1. G. L. Morrison and J. A. Taylor, "Solar thermal power systems," *Renewable Energy*, vol. 34, pp. 189–198, 2009.
2. D. Laing et al., "Thermal energy storage for solar power plants," *Energy Procedia*, vol. 49, pp. 120–129, 2014.
3. A. Gil et al., "State of the art on high-temperature thermal energy storage," *Renewable and Sustainable Energy Reviews*, vol. 14, pp. 31–55, 2010.
4. H. Michels and R. Pitz-Paal, "Cascaded latent heat storage," *Solar Energy*, vol. 81, pp. 829–837, 2007.
5. S. Jegadheeswaran and S. Pohekar, "Performance of latent heat storage," *Renewable and Sustainable Energy Reviews*, vol. 13, pp. 2225–2244, 2009.
6. IRENA, *Thermal Energy Storage Technology Brief*, International Renewable Energy Agency, 2013.



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