

Thermo-mechanical energy storage technologies: Innovations, challenges, and future directions

Yao Zhao (✉)^{1,2}, Mingjia Li (✉)³, Kai Wang (✉)^{4,5}, Adriano Sciacovelli (✉)⁶, Chris Qin (✉)⁷, Steven Lecompte (✉)⁸, André D. Thess (✉)^{9,10}

¹ College of Smart Energy, Shanghai Jiao Tong University, Shanghai 200240, China

² Shanghai Non-carbon Energy Conversion and Utilization Institute, Shanghai Jiao Tong University, Shanghai 200240, China

³ School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, China

⁴ Institute of Refrigeration and Cryogenics, Zhejiang University, Hangzhou 310027, China

⁵ Key Laboratory of Refrigeration and Cryogenic Technology of Zhejiang Province, Zhejiang University, Hangzhou 310027, China

⁶ Department of Civil and Mechanical Engineering, Technical University of Denmark, Kongens Lyngby 2800, Denmark

⁷ School of Engineering and Computer Science, Washington State University, Vancouver, WA 98686, USA

⁸ Department of Electromechanical, Systems and Metal Engineering, Ghent University, Ghent 9000, Belgium

⁹ Institute of Engineering Thermodynamics, German Aerospace Center (DLR), Stuttgart 70569, Germany

¹⁰ University of Stuttgart, Stuttgart 70569, Germany

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Thermo-mechanical energy storage (TMES) technologies are increasingly recognized as essential solutions for enhancing the efficiency and stability of energy systems, particularly in the integration of renewable energy sources. These technologies leverage the conversion between thermal, electrical and mechanical energy to store and release energy, providing an effective tool to address the intermittency and variability of renewable sources such as wind and solar. This editorial explores the fundamental principles, innovations, challenges, and future research directions of TMES technologies, with a focus on developments in compressed-air energy storage (CAES), liquid-air energy storage (LAES), Carnot battery/pumped-thermal energy storage (PTES), and carbon dioxide energy storage (CDES).

TMES encompasses methods that store energy in the form of thermal energy, which is later converted into mechanical or electrical energy. Each of these methods presents distinct principles and applications. CAES involves compressing air into underground caverns or storage vessels. When energy is needed, the air is released, expanded, and used to drive turbines for power

generation, making CAES highly suitable for large-scale storage and grid regulation. LAES stores energy by liquefying air at low temperatures. During discharge, the liquid air expands, driving an expander for power generation. LAES is particularly suited for long-duration storage and peak-demand applications. PTES converts thermal energy into electrical energy and vice versa, offering solutions for long-term energy storage and multi-energy management. CDES involves compressing CO₂ and storing it under pressure. During discharge, CO₂ is expanded to drive turbines, thus stabilizing fluctuations in renewable energy supply and balancing energy demand.

These technologies are critical in addressing the challenges posed by fluctuating renewable energy generation and offer viable solutions for efficient energy storage, grid stability, and reliable energy management.

This special issue aims to present the latest advancements in TMES technologies, highlighting both theoretical and practical developments. By showcasing cutting-edge research on mechanisms, materials, equipment design, and system integration, this issue underscores the potential of TMES technologies to drive the next generation of energy storage solutions. The significance of this special issue lies in its comprehensive overview of the field, offering new perspectives and innovative approaches that will inform both academic research and industrial applications. We hope this special issue will foster collaboration and inspire breakthroughs in the development of TMES systems.

TMES technologies have made significant progress in

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Correspondences: Yao Zhao, zhaoyao@sjtu.edu.cn;

Mingjia Li, mjli@bit.edu.cn;

Kai Wang, kaiwang19@zju.edu.cn;

Adriano Sciacovelli, adrsc@dtu.dk;

Chris Qin, chris.qin@wsu.edu;

Steven Lecompte, steven.lecompte@ugent.be;

André D. Thess, andre.thess@dlr.de

recent years. However, several challenges remain that require continued research and development efforts. A deeper understanding and optimization of the coupling between heat transfer, phase change, and mechanical processes are crucial to improving system efficiency. Research into fluid flow, heat transfer mechanisms, and phase change dynamics will lead to more effective energy storage and release processes. New materials, particularly high-density storage media, are essential for improving energy storage capacity and efficiency. These materials must offer high thermal conductivity, long-term stability, and durability under repeated cycling conditions. Advances in storage equipment, such as heat exchangers, compressors, and turbines, are key to enhancing the efficiency and longevity of TMES systems. Innovations in these areas focus on minimizing thermal losses, improving heat transfer, and extending the lifespan of critical components. The integration of multi-energy systems—combining electricity, heat, and cold storage—offers increased flexibility and adaptability. Developing intelligent control systems to optimize energy management and system performance is another area of innovation.

Despite these advancements, challenges persist. Further research is needed to understand the interactions between thermal and mechanical processes under complex operating conditions. Optimizing these interactions is essential for improving system efficiency. The search for new materials capable of withstanding high temperatures and long operational cycles, while maintaining high energy density and efficiency, remains a significant challenge. Designing and optimizing equipment to ensure high efficiency and long-term performance, particularly in systems with large energy flows and fluctuating demands, continues to be a challenge. Additionally, ensuring the stability and adaptability of TMES systems in real-world applications, particularly in grids with fluctuating renewable energy inputs, remains complex. Last but not least, the storage cost has to be brought

down in order to enable a widespread use of TMES technologies.

Looking forward, TMES technologies must continue to advance in key research areas. Understanding the dynamic interactions between heat transfer, phase change, and fluid dynamics between and in the main system components is essential. Research should focus on optimizing energy conversion processes to maximize system efficiency, particularly in systems with complex operational requirements. Continued development of advanced materials with better thermal conductivity, greater stability under extreme conditions, and higher energy storage capacities is critical. Researchers should focus on materials that improve energy density and efficiency for long-duration storage. Innovations in key TMES equipment, such as heat exchangers, compressors, and expanders, are crucial for improving system performance. Future research will increasingly focus on integrating TMES with renewable energy systems, such as wind and solar. Multi-energy systems, which combine electricity, heat, and cold storage, will provide greater flexibility and efficiency. By integrating high-temperature electrolysis cells and carbon capture technologies, these CDES systems can enable the negative-carbon co-production of electricity, heat, cold, and fuels. Additionally, intelligent control systems, driven by artificial intelligence (AI), will be vital for optimizing the performance, decision-making, and management of these integrated systems, ensuring seamless coordination between multi-energy production.

We extend our sincere gratitude to all the authors, reviewers, and contributors who have made this special issue possible. Their hard work and expertise have been instrumental in presenting the most recent advancements in TMES technologies. As the field continues to evolve, we are optimistic about the potential of TMES technologies to address the challenges of renewable energy integration and look forward to their continued development and widespread adoption.