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EDITORIAL

The road to simplicity: Trimodal thermal energy storage innovation

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Received: April 3, 2025; Accepted: July 8, 2025; Published Online: July 10, 2025; https://doi.org/10.59717/j.xinn-energy.2025.100105

Citation: Chen X. (2025). The road to simplicity: Trimodal thermal energy storage innovation. *The Innovation Energy* 2:100105.

The global energy system has reached a pivotal crossroads, caught between the urgent imperative of energy security and the accelerating demands of decarbonization. Despite global climate commitments, fossil fuels including coal, oil, and natural gas still maintain an 81% share of global primary energy consumption in 2023, locking the world into a dangerous dependency. This carbon-intensive paradigm not only fuels the climate crisis but also creates alarming vulnerabilities. The Russia-Ukraine conflict brutally exposes through cascading energy shocks that rippled across continents. While European nations scrambled to fast-track renewable deployments, developing countries find themselves trapped between energy poverty and unaffordable imports, revealing the unsustainable fragility of current energy architecture. These converging crises make one reality undeniable: the world extremely needs innovative, scalable solutions that can simultaneously address energy security, affordability, and decarbonization.

WHY TES INNOVATION CAN'T WAIT

The global energy landscape is driven by the imperative need to decarbonize industries, enhance energy security, and meet rising demand for sustainable energy at scale. Amid this transition, thermal energy storage (TES) emerges as a critical yet often underestimated solution to bridge the gap between energy supply and demand (Figure 1). Unlike conventional batteries, TES systems store energy in the form of heat or cold, offering unmatched scalability, cost-effectiveness, and compatibility with renewable energy sources like solar energy. However, despite its immense potential, innovation in TES has not kept pace with the accelerating demands of the clean energy transition compared to other storage technologies. The time for innovation is now because the world cannot afford to wait.

The intermittent nature of renewable demands efficient, long-duration storage to ensure energy stability and decarbonize industries such as manufacturing, heating, and cooling. TES can bridge this gap by leveraging materials like molten salts, phase- change materials (PCMs), or even recycled industrial waste to store energy for hours, days, or even seasons. Yet, technological barriers, policy inertia, and limited investment hinder its widespread adoption. Meanwhile, escalating climate disasters underscore the urgency for resilient, low-carbon solutions. Innovation in TES is not just an engineering challenge and is also an economic and environmental imperative. Breakthroughs in materials science, system design, and hybrid TES models can enable ultra-high clean energy capacities, slashing emissions from fossil-fuel-dependent sectors. Governments, researchers, and industry must collaborate to accelerate R&D, standardize regulations, and scale up projects. The race to net zero has begun, and TES is a key player we can no longer ignore. Procrastinating TES innovation risks missing a massive economic opportunity and prolonging reliance on polluting energy sources. The window for action is narrowing.

LIMITATIONS OF CONVENTIONAL TES TECHNOLOGY

Conventional unimodal TES materials exhibit fundamental thermodynamic limitations that constrain their practical applications. Sensible heat storage media like molten salts are restricted by their inherently low TES density and significant thermal losses during extended storage cycles. Phase-change materials (PCMs) for latent heat storage, while offering higher theoretical TES density, face challenges of liquid phase leakage, phase segregation and subcooling that degrade performance over long-term repeated cycles. Despite offering the highest theoretical TES density among TES technologies, thermochemical storage systems face three critical barriers to commercialization.[1-3] Specifically, kinetic limitations in reversible reactions (e.g., metal oxide redox or salt hydration/dehydration) that necessitate catalysts and precise thermal/pressure control to achieve practical reaction rates. Repeated cycling of thermochemical storage materials like Ca(OH)2/CaO and Mg(OH)2/MgO lead to structural degradation, agglomeration, or side reactions. Compared to sensible/latent systems, thermochemical systems require special reactors, gas handling systems (for hydration/dehydration), and precise humidity control, which significantly increases costs and maintenance requirements. Although bimodal systems like latent-sensible and thermochemical-sensible systems have shown some improvements, they still fall short of meeting the stringent requirements for large-scale renewable energy storage. The latest concept innovation in TES technology involves the development of trimodal TES materials that intelligently integrate all three storage mechanisms within a unified matrix, offering the potential to overcome the limitations of unimodal and bimodal TES systems.

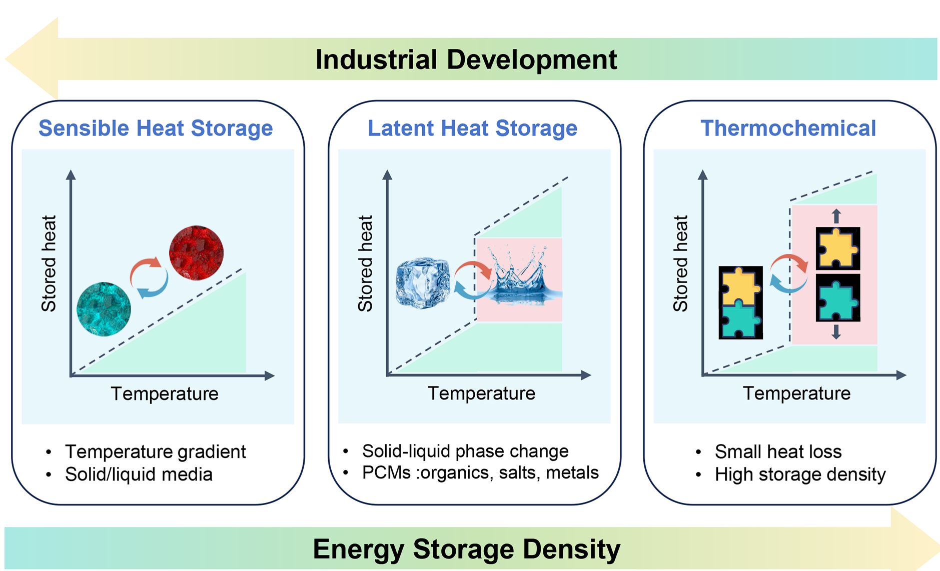

Figure 1. Three TES technologies.

THE TRIMODAL TES BREAKTHROUGH

Recently, innovative trimodal TES materials have emerged in TES technology. These advanced TES systems synergistically integrate phase-change, thermochemical, and sensible heat storage mechanisms within a single, multifunctional material matrix. By leveraging the complementary advantages of each storage mode, trimodal TES materials can achieve enhanced TES density, extended operational temperature ranges, and superior cycling stability compared to unimodal and bimodal TES modes. For instance, thermochemical reactions can provide high energy density, phase-change mechanisms enable isothermal management, and sensible heat storage contributes to broader operational flexibility. This integrated approach not only maximizes thermal energy utilization but also improves system efficiency and longevity.

In this regard, a breakthrough study[4] published in *Nature* firstly proposed a trimodal TES approach that promises to innovate renewable thermal energy applications. This innovation integrates multiple thermal energy storage mechanisms of phase change, chemical reaction, and sensible storage into a single material. The trimodal nature of the material is what sets it apart from other thermal energy storage solutions. This combined storage modes allows the material to efficiently absorb and release thermal energy over a wide temperature range, making it suitable for various applications in renewable energy systems.

The developed trimodal TES material by Karolina Matuszek *et al.*4 is a eutectic mixture of boric acid and succinic acid, which was simple and scalable to be synthesized by grinding them together in a mortar and pestle until a homogenous mixture. This remarkably straightforward solid-state synthesis method eliminates the need for complex equipment, toxic solvents, or energy-intensive processing while maintaining promising scalability from lab-scale to industrial quantities, offering unprecedented advantages in manufacturing feasibility and cost-effectiveness compared to conventional TES material production techniques. The key feature of this eutectic mixture is its trimodal TES mechanisms. The first mode involves the phase change from solid to liquid, which absorbs thermal energy. The second mode occurs through a thermochemical reaction within the liquid state, further increasing the energy storage capacity. The third mode, sensible storage, contributes to the overall energy uptake by absorbing heat within the operating temperature range of the material. Specifically, differential scanning calorimeter analysis revealed that the eutectic mixture exhibits multiple endothermic transitions during heating. The first transition occurs between 143°C and 144°C, while the second transition occurs between 150°C and 156°C, corresponding to the melting and dehydration of the eutectic mixture. These combined phase change and reaction transitions result in a high thermal energy uptake of 380 J/g ± 5% at the melting point of 148°C ± 1°C. The sensible heat component further contributes an extra 14 J/g, thus yielding a total ultra-high thermal energy storage density of 394 ± 5% J/g.

Moreover, the sustainability and cost-effectiveness are significant advantages for its large-scale applications. The solvent-free method for yielding eutectic mixture can be scaled up to produce ton-level quantities, making it suitable for industrial production. Boric acid (44 wt% of the eutectic mixture) is economical (priced at 0.7 USD per kilogram) and boasts minimal environmental toxicity. It can be sourced from diverse boron ores or naturally occurring boron brines, with the potential to reduce greenhouse gas emissions by using renewable heat sources for extraction. Succinic acid (56 wt% of the eutectic mixture) is also a mature bio-based substance with biodegradability and low cost (priced at 2.5 USD per kilogram). The cost of the eutectic mixture is expected to be about 1.7 USD per kilogram, significantly lower than large-scale lithium battery technology. Boric acid waste can also be repurposed for incorporation in building materials, thereby enhancing the overall sustainability. Remarkably, trimodal TES material maintains long-term thermal stability and reversibility over 1,000 heating and cooling cycles, with only a slight decrease of 4% in thermal energy uptake in the first 300 cycles, followed by stabilization at 395 ± 5% for the remaining 700 cycles.

Compared with other TES technologies, such as molten salt tower systems, Carnot batteries, and carbonate-hydroxide thermochemical systems, trimodal TES material is competitive in terms of thermal efficiency, cost-effectiveness, and deployment scalability. This economic and reliable trimodal TES solution represents a significant step forward in the field of renewable energy storage applications. The potential impact of trimodal TES material on renewable energy applications is profound. Its high-density capacity, low cost, environmental friendliness, and thermal stability make it a compelling alternative to traditional energy storage technologies. It is appropriate for utilization in combination with renewable energy sources, such as solar energy, which are intermittent and require reliable storage solutions to balance supply and demand.

CURRENT CHALLENGES AND FUTURE SOLUTIONS

While trimodal TES materials demonstrate exceptional thermal energy density, several critical challenges must be addressed: (1) Low thermal conductivity limits charge/discharge rates, (2) Fixed operational temperature ranges restrict versatility, (3) Industrial-scale production requires validation of homogeneity and stability, and (4) Fossil fuel-dependent boric acid extraction undermines sustainability. These limitations necessitate innovative solutions to realize the full potential of trimodal TES systems for renewable energy integration. Artificial intelligence (AI) is revolutionizing TES technology through multiple approaches.[5] Machine learning enables rapid screening of material combinations to optimize TES density and thermal conductivity, while computer vision-guided process control ensures precision in large-scale production. Digital twin technology accelerates durability assessment by simulating material performance degradation under long-term service conditions in a short period of time, significantly shortening the R&D cycle. These AI-driven innovations have also demonstrated significant reductions in both development timelines and process carbon footprints. Future trimodal TES research priorities include AI-driven multi-scale interface engineering for enhanced heat transfer, intelligent control systems for seasonal TES management, and automated life cycle assessment tools.

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FUNDING AND ACKNOWLEDGMENTS

The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The author declares no competing interests.