

Editorial

# The Convergence Era of Energy Storage: Towards Integrated, Circular, and Multi-Modal Energy Systems

Rajan Jose

Battery Research Center of Green Energy, Ming Chi University of Technology, New Taipei City 24301, Taiwan;  
rjose@mail.mcut.edu.tw

**How To Cite:** Jose, R. The Convergence Era of Energy Storage: Towards Integrated, Circular, and Multi-Modal Energy Systems. *Energy Storage Technologies* 2025, 1(1), 1.

For over a century, energy systems were built around centralized fossil-fuel infrastructures designed for predictable and dispatchable power flows. Emergence of sustainability concerns and consequent accelerating transition to net-zero pathways, driven by renewable energy penetration, electrification of industry and mobility, decentralized grid architectures, and rapid digitalization, have transformed the role of energy storage from a supporting utility to a central pillar of sustainable development. As the world moves towards renewable electricity systems and diversified energy vectors, no single storage technology can meet the diverse operational, economic, and environmental demands of the future. We are thereby entering the convergence era of energy storage, where multi-modal, integrated, and circular energy storage frameworks will define energy security, resilience, and sustainability.

**Energy Storage Technologies (EST)** is envisioned to provide this mission by serving as a scientific and technological platform for researchers, innovators, and decision-makers working across the wide spectrum of energy storage including electrochemical, thermal, mechanical, chemical, gravitational, hybrid systems, and emerging paradigms yet to be conceived (Figure 1). With this inaugural issue, EST positions itself not merely as another repository of research articles, but as a catalyst for integrated thinking, a place where disciplinary boundaries dissolve and where materials science, engineering, policy, and sustainability come together to shape the next generation of energy infrastructures.

Historically, research communities have advanced energy storage technologies in disconnected and separated technologies as batteries and supercapacitors in electrochemistry circles, hydrogen and ammonia within chemical engineering, flywheels and compressed air among mechanical engineers, pumped hydro in energy systems domains, and so on. These siloed technologies, while valuable in deepening the knowledge as well as delivering their respective share to the total energy storage mix, are seemingly insufficient for the modern energy transition considering a large population and their energy needs, as well as variability of availability of various forms of ambient energy. Intermittency challenges of solar and wind require both short-duration and long-duration storage; grid resilience requires fast response, while industrial decarbonization requires seasonal and storage of thermal energy at high temperatures. The needs of data centers are distinct from the needs of heavy transportation, residential microgrids, or utility-scale balancing. This plurality demands convergence across technologies, not competition between them. For example, (i) battery-hydrogen coupling smooths renewable energy over-production by using batteries for short-term balancing and hydrogen systems for long-term/seasonal storage. This hybrid approach effectively manages the inherent volatility and intermittency of solar and wind power, enhancing grid stability and energy utilization; combined thermal-mechanical storage, such as molten-salt with compressed air, for industrial energy management; metal-air and redox metal loops for long-duration storage with circular material cycles; and so on. Such integrations represent more than technological combinations; they signal a systems-level paradigm where **EST** intends to lead. We encourage submissions that explore these intersections from experimental, theoretical, modelling, economic, and policy-oriented research that highlight the value of integrated solutions in real-world contexts.





**Figure 1.** Cartoon showing focal themes of energy storage technologies and merging of strategies of convergence, integration, and circular.

The future of energy storage is inseparable from the sustainability and circularity of materials. For instance, for electrochemical energy storage, traditional resource-intensive pathways, such as cobalt-rich cathodes, fluorinated electrolytes, graphite derived from fossil precursors, and metal mining with high environmental burdens, face mounting scrutiny. As the energy systems scale-up, so does the material footprint of storage technologies. Circular and resource-efficient materials will shape the competitive advantage of future storage solutions: (i) sodium-, potassium-, magnesium-, and aluminum-based electrochemical systems, leveraging abundant elements in place of high materials and energy footprint energy carrier such as lithium, (ii) biomass-derived carbons with low carbon footprints replacing fossil-based carbons in electrodes, (iii) solid-state electrolytes that enable longer life cycles and safer architectures, (iv) thermal storage materials with high recyclability and stability, (v) hydrogen carriers such as liquid organics, metal hydrides designed for reusability, and (vi) second-life and upcycled materials integrated into larger storage systems. At **EST**, we place strong emphasis on materials circularity, recycling processes, second-life strategies, carbon accounting, and both static and dynamic lifecycle assessment (LCA). Innovation must extend beyond performance metrics to include resource ethics, carbon neutrality, and end-of-life value recovery. We see these sustainability dimensions not as peripheral considerations, but as core scientific challenges that must shape the next generation of storage design.

Energy storage no longer resides at a single spatial or temporal scale. From nanoscale ion transport phenomena to gigawatt-scale pumped hydro installations, energy storage solutions must be designed across orders of magnitude to meet diverse application needs. At small scales, we witness solid-state ionic conductors with sub-nanometer diffusion channels, fast-charging electrode architectures, nanostructured thermal storage media, and micro-supercapacitors for wearables and IoT systems. At intermediate scales, energy storage is transforming electric mobility (EVs, electric aviation, maritime electrification), industrial thermal management, commercial energy demand smoothing, hydrogen production from curtailed renewable generation. At large scales, entire infrastructures evolve: long-duration energy storage continuous powering of renewable grids, compressed air and gravity storage for regional balancing, hydrogen-based seasonal storage for national energy security, integrated storage in smart cities and national energy networks. This multi-scale dimension is central to the identity of **EST**. We encourage submissions that explore how innovations at one scale affect constraints and opportunities at another by linking materials science to device engineering, device performance to grid modelling, and grid modelling to national policy.

Energy storage is also rapidly merging with the digital backbone of modern society. Artificial intelligence, digital twins, and real-time data analytics are redefining how storage systems are designed, operated, and maintained. Digitalization enables (i) predictive maintenance for large-scale battery farms, (ii) AI-assisted

electrolyte and material discovery, (iii) digital twins for hydrogen and thermal systems, (iv) autonomous operation of distributed storage assets in smart grids, (v) cybersecurity frameworks for storage-integrated energy networks. We envision **EST** as a venue for pioneering research in these emerging domains by bridging physical storage technologies with computational intelligence. As energy systems become cyber-physical ecosystems, the role of AI becomes indispensable not only for performance optimization but also for safety, reliability, and resilience.

Energy storage is no longer a purely technical domain; it has become a societal instrument. Nations pursuing industrial competitiveness, energy independence, and climate mitigation increasingly view energy storage as a strategic infrastructure. Yet global inequalities persist. Access to clean, reliable energy storage remains limited in many regions, despite abundant renewable resources. Sustainable and inclusive energy transitions require affordable materials and manufacturing routes, decentralized storage solutions for underserved communities, robust policies that ensure global participation, knowledge transfer across developed and developing economies. **EST** aims to support this global dialogue by encouraging research that addresses affordability, socio-economic impacts, regulatory considerations, and scalability in emerging markets.

With the launch of **EST**, we extend an invitation to the global community working in the energy storage systems. Our aim is to (i) bridge disciplinary divides by welcoming work across electrochemical, thermal, mechanical, gravitational, hydrogen, and hybrid storage systems; (ii) support fundamental and applied research that advances understanding from atoms to grids; (iii) promote sustainability and circularity as central elements of technological innovation; (iv) encourage modelling, techno-economic analysis, digitalization, and lifecycle assessment as essential complements to experimental and engineering studies; (v) facilitate global engagement, ensuring diverse perspectives and needs are represented. As energy storage technologies underpin the future of clean energy transitions, the need for bold, integrated, and scientifically rigorous research has never been superior. **EST** intends to play a meaningful role in shaping this future by providing a platform where multidisciplinary advances converge into actionable knowledge.

Looking ahead, the pages of **EST** will reflect the vast and expanding landscape of energy storage research. We will publish high-impact original articles, insightful reviews, emerging perspectives, and visionary commentaries that inspire progression across all domains of storage technologies. As the world moves deeper into an era defined by decarbonization, decentralization, and digitalization, the role of energy storage will only grow in complexity and importance. This inaugural editorial represents our commitment to fostering a unified and forward-looking community, i.e., one that embraces diversity in technologies, interdisciplinarity in methods, and sustainability in ethos. We look forward to receiving contributions that not only push scientific boundaries but also contribute to shaping a resilient and circular energy future for generations to come.

With this first issue, we welcome you to **Energy Storage Technologies**: a journal dedicated to advancing the science, engineering, and societal impact of energy storage in its many forms.

Let the convergence era begin!

### Conflicts of Interest

The author declares no conflict of interest.

### Use of AI and AI-Assisted Technologies

During the preparation of this work, the author used Chat GPT and Google Gemini to collect facts relating to the interrelationship between energy storage technologies. After using these tools, the author reviewed and edited the content as needed and take full responsibility for the content of the published article.