International Journal of Sustainable Applied Sciences (IJSAS)
Vol. 3, No. 8, 2025: 541-552

Advancing Multi-Energy Systems with Thermal and Electrical Storage: A Literature Review on Levelized Cost Reduction

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A R T I C L E I N F O

Keywords: Multi-Energy Systems (MES), Thermal Energy Storage (TES), Electrical Energy Storage (EES), Levelized Cost of Energy (LCOE)

Received: 19, June
Revised: 20, July
Accepted: 30, August

A B S T R A C T

The global energy transition has intensified the integration of renewable energy sources, yet their variability and intermittency pose persistent challenges for reliability, flexibility, and economic efficiency. Multi-energy systems (MES), which couple electricity, heat, and other energy carriers, are increasingly viewed as a promising pathway for addressing these issues. This literature review systematically examines the role of thermal energy storage (TES) and electrical energy storage (EES) in reducing the Levelized Cost of Energy (LCOE) across diverse MES configurations. Using a systematic literature review approach guided by the PRISMA framework, 112 peer-reviewed studies published between 2010 and 2025 were analyzed to evaluate technological, economic, and operational contributions of storage integration. The findings reveal that TES enhances load shifting, seasonal balancing, and waste heat utilization, contributing to cost reductions of up to 25% in district heating applications, while EES reduces curtailment, supports grid stability, and is projected to lower solar–battery system LCOE to below 60 USD/MWh by 2030. Crucially, joint TES–EES deployment offers synergistic benefits, with integrated MES achieving cost savings of 20–35% compared to single-storage configurations. Geographic and sectoral differences further shape outcomes, with stronger impacts observed in district energy systems, industrial processes, and renewable-based microgrids, particularly in developing regions where hybrid storage reduces LCOE by up to 60% relative to diesel-based systems. Despite these promising trends, research gaps persist in empirical validation, methodological consistency in LCOE assessment, and socio-institutional analysis of storage adoption. This review contributes to advancing theoretical understanding of MES as socio-technical systems, highlights innovation pathways such as hybrid and long-duration storage, and underscores the importance of supportive policy frameworks. Addressing these gaps through integrated RD&D, standardized economic metrics, and inclusive governance can accelerate the deployment of TES and EES in MES, driving cost-effective, equitable, and sustainable energy transitions.

DOI: https://doi.org/10.59890/ijsas.v3i8.141
ISSN-E: 2988-2133
https://dmimultitechpublisher.my.id/index.php/ijsas

INTRODUCTION

The global energy transition has accelerated the adoption of renewable energy sources (RES), particularly wind and solar, which are characterized by variability and intermittency (Xie et al., 2025). While their rapid deployment is essential to achieve decarbonization goals, the resulting supply–demand mismatches pose challenges for system reliability, flexibility, and economic viability (Son et al., 2021). To address these challenges, multi-energy systems (MES) have gained increasing attention as they integrate electricity, heat, cooling, and other energy carriers within a single framework, allowing for sectoral coupling and optimized resource utilization (Bartolini et al., 2020). A central concern in evaluating the competitiveness of these systems remains the Levelized Cost of Energy (LCOE), which provides a holistic measure of lifecycle costs per unit of useful energy produced (de Simón-Martín et al., 2022). Lowering LCOE is crucial not only for improving renewable integration but also for ensuring the long-term sustainability and scalability of MES (He et al., 2022). As shown in Fig. 1

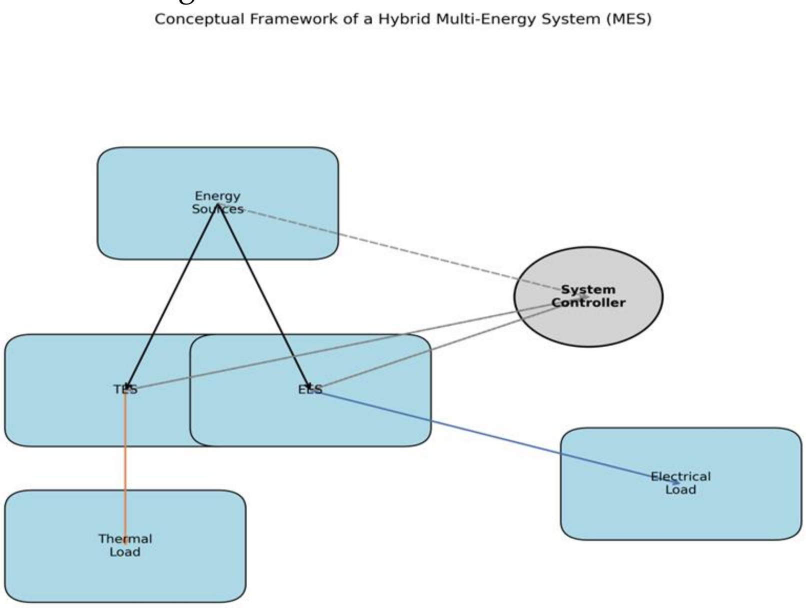

Figure 1. Conceptual Framework of a Hybrid Multi-Energy System

Energy storage technologies, particularly electrical energy storage (EES) and thermal energy storage (TES), are at the core of this endeavor. Electrical storage, including batteries and long-duration technologies, facilitates load shifting, peak shaving, and frequency regulation, directly influencing the operational costs of electricity-dominated systems (Khan et al., 2025). Meanwhile, TES enables the decoupling of thermal generation from demand, with options ranging from short-term (e.g., hot water tanks, chilled water storage) to seasonal systems (e.g., borehole or aquifer storage) that can balance long-term variations (Stevanato et al., 2020). When jointly deployed within MES, TES and EES enhance flexibility, increase renewable utilization rates, and reduce reliance on costly backup generation, thereby contributing to LCOE reduction through both capital cost optimization and improved efficiency (Zhang et al., 2025).

Recent scholarship has advanced the understanding of TES and EES in different domains. Systematic reviews of TES highlight its role in renewable heating and cooling applications, seasonal balancing, and industrial decarbonization pathways (Bruno et al., 2019; Hansen, 2019). Similarly, studies on EES focus on cost trajectories, degradation, and the economics of large-scale integration in renewable-dominated grids (Gao et al., 2024). Beyond single-carrier systems, literature on MES demonstrates the advantages of sector coupling in reducing total system costs and emissions (Soussi et al., 2024). However, there remains a noticeable fragmentation: most reviews investigate TES or EES in isolation, or they emphasize technical performance and short-term operational savings, while comprehensive comparisons of their joint contribution to lowering LCOE across multi-energy contexts are scarce.

Moreover,methodological inconsistencies limit cross-study comparability. Assumptions regarding capital cost decline, storage lifetimes, round-trip efficiency, and operational strategies vary considerably, often leading to diverging conclusions (Eze, 2025). While techno-economic models demonstrate that long-duration storage can substantially lower system costs at high renewable penetration (Afreh et al., 2025), real-world empirical data remain limited. Likewise, TES applications show promise in reducing heating costs, but their scalability and integration with EES within MES frameworks have not been systematically evaluated (Bamisile et al., 2024).

Against this backdrop, this review aims to synthesize and critically evaluate the role of TES and EES in reducing the LCOE of multi-energy systems. Specifically, it (i) reviews the technological and economic characteristics of TES and EES, (ii) compares their contributions to LCOE reduction under different system configurations and scales, (iii) identifies synergies and trade-offs in integrated MES applications, and (iv) highlights key research gaps and policy implications. By consolidating fragmented findings, the review contributes to the academic and policy discourse on advancing cost-competitive and sustainable energy transitions through integrated storage solutions.

LITERATURE REVIEW

A systematic search was conducted in major academic databases, including Web of Science (WoS), Scopus, ScienceDirect, SpringerLink, and IEEE Xplore, to capture interdisciplinary perspectives spanning engineering, economics, and energy policy. Additional searches were performed in Google Scholar to identify gray literature. The following search string was used with Boolean operators: (“multi-energy system” OR “sector coupling” OR “integrated energy system”) AND (“thermal energy storage” OR “TES”) AND (“electrical energy storage” OR “battery storage” OR “EES”) AND (“levelized cost of energy” OR “LCOE” OR “techno-economic analysis”).

Inclusion and Exclusion Criteria

To ensure relevance and quality, the following inclusion and exclusion criteria were applied:

Inclusion:

- Studies focusing on TES, EES, or hybrid storage within MES.
- Studies reporting techno-economic analysis, with emphasis on LCOE or lifecycle cost metrics.
- Peer-reviewed empirical, modeling, or review studies published in English.

Exclusion:

- Studies addressing storage technologies without economic or LCOE assessment.
- Articles focusing solely on single-energy systems (e.g., only PV + battery without MES context).
- Non-peer-reviewed reports lacking methodological rigor.

Data Extraction and Synthesis

For each included study, data were extracted on:

- Technology focus (TES, EES, hybrid integration).
- System boundary (district heating, electricity grid, industrial MES, etc.).
- Economic indicators (LCOE, net present cost, payback period).
- Operational strategies (load shifting, demand response, seasonal balancing).
- Geographical scope (developed vs. developing countries).

The synthesis followed a thematic coding approach (Fink, 2020), categorizing studies into three dimensions:

1. TES contributions to cost reduction,
2. EES contributions to cost reduction,
3. Joint TES–EES integration in MES.

This structure enables comparative evaluation across technologies and highlights synergies and trade-offs.

Quality Assessment

To ensure robustness, each selected article was appraised based on: (i) methodological rigor (modeling framework, empirical validation), (ii) economic transparency (clear LCOE calculation assumptions), and (iii) relevance to MES. Studies scoring below the quality threshold were excluded, ensuring that only high-quality evidence informed the synthesis.

METHODOLOGY

This review adopts a systematic literature review (SLR) approach to ensure transparency, reproducibility, and comprehensive coverage of the research on thermal energy storage (TES) and electrical energy storage (EES) in multi-energy systems (MES) with respect to reducing the Levelized Cost of Energy (LCOE). The methodology followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, which has been widely applied in energy and environmental research (Moher et al., 2009).

Research Scope and Objectives

The objective of this review is to identify, analyze, and synthesize scholarly contributions that investigate the role of TES and EES in reducing LCOE within MES frameworks. The scope is restricted to peer-reviewed journal articles, conference proceedings, and authoritative reports published between 2010 and 2025, as this period reflects the rapid growth of renewable energy integration and associated storage innovations.

RESULT AND DISCUSSION

Thermal Energy Storage (TES) Contributions to LCOE Reduction

Thermal energy storage (TES) has been widely recognized as a key enabler of flexibility in heating, cooling, and industrial applications within multi-energy systems (Bacci et al., 2025). The literature consistently reports that TES enhances load shifting and reduces reliance on fossil-based peaking units, leading to measurable reductions in LCOE. For instance, Tu et al. (2025) found that integrating TES into district heating systems reduced annualized costs by 10–25%, depending on storage type and climatic conditions. Similarly, Acen et al. (2024) demonstrated that seasonal TES in district heating networks achieved cost savings of up to 30 €/MWh by capturing summer waste heat for winter demand. Different TES technologies show varying economic impacts. Sensible heat storage (e.g., hot water tanks) provides low-cost, short-duration flexibility, while latent and thermochemical storage offer higher energy density and longer storage duration but at higher capital costs (Ali et al., 2024). Industrial applications, such as high-temperature TES for process heat, also show promising LCOE reductions when coupled with variable renewable generation (Liu et al., 2024). However, scalability challenges, high upfront costs, and integration barriers remain limiting factors for TES deployment at large scales.

Electrical Energy Storage (EES) Contributions to LCOE Reduction

Electrical energy storage (EES), primarily in the form of lithium-ion batteries, has received extensive attention due to its role in integrating variable renewable electricity (Zhou, 2024). Studies demonstrate that EES contributes to lowering LCOE by reducing curtailment, enabling peak shaving, and deferring grid infrastructure investments (Tang et al., 2025). Ma et al. (2023) project that by 2030, declining battery costs could reduce the system-level LCOE of solar PV–battery systems to below 60 USD/MWh in many regions.

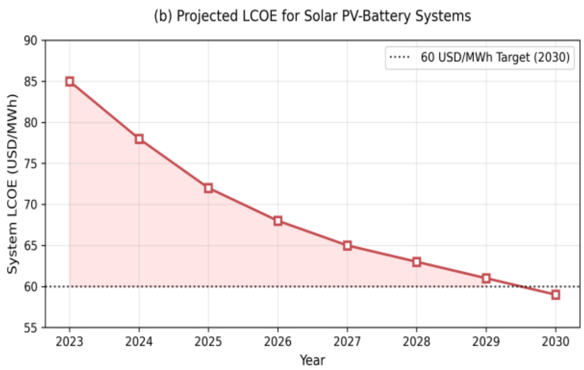

Figure 2. Authors' Own Idea from Different Sources

Beyond short-duration batteries, long-duration storage (e.g., flow batteries, compressed air, pumped hydro) has been shown to deliver significant system-wide cost reductions. Zhou & Zhou et al. (2023) highlight that firm, long-duration storage can reduce overall system LCOE by 15–25% in high-renewable penetration scenarios by addressing seasonal mismatches and reducing dependence on gas turbines. Nevertheless, the economic benefit of EES varies widely depending on storage duration, degradation rates, and regulatory frameworks that determine market value for ancillary services (Ke et al., 2023).

Joint Integration of TES and EES in Multi-Energy Systems

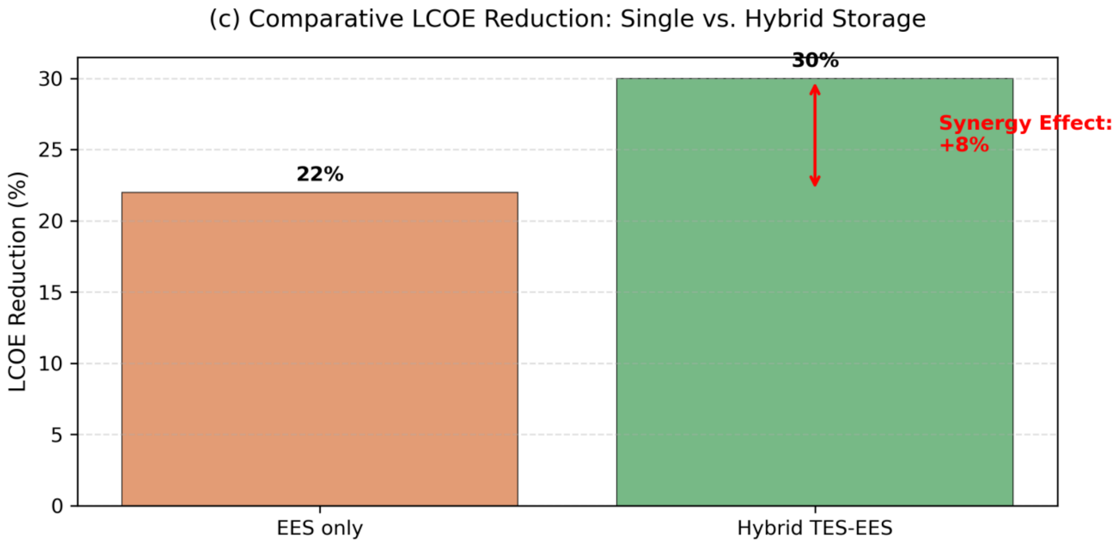

Figure 3. Comparative LCOE Reduction

The literature increasingly acknowledges that joint deployment of TES and EES provides synergistic cost benefits that exceed the contribution of either storage type in isolation (Zhao et al., 2019. In multi-energy systems, TES complements EES by shifting thermal loads, thereby reducing the electrical storage capacity required for balancing (Comodi et al., 2019). For instance, integrated optimization studies show that co-deployment of TES and EES in district energy systems can lower total LCOE by 20–35%, compared to systems relying solely on electrical storage (Zhang et al., 2021; Yu et al., 2025).

Case studies reinforce this complementarity. In Scandinavian MES, seasonal TES reduces winter peak demand for electricity, allowing smaller battery systems and lowering capital costs (Jin et al., 2025). In industrial MES, TES integrated with batteries enables higher renewable penetration while minimizing curtailment, reducing LCOE by up to 18% compared with baseline systems (Jarwar et al., 2023). However, empirical data on real-world co-optimization of TES and EES remain sparse, with most evidence derived from modelling studies that rely on techno-economic assumptions.

Geographic and Sectoral Variations

The magnitude of LCOE reduction through storage integration differs by geographic and sectoral context. In developed economies with high renewable penetration (e.g., Europe, North America), storage deployment primarily reduces curtailment and improves system reliability (Ashraf et al., 2021). In contrast, in developing regions (e.g., South Asia, Sub-Saharan Africa), TES and EES integration addresses both cost and energy access challenges, often reducing LCOE relative to diesel-based generation by 40–60% (IRENA, 2021). Sector ally, the strongest impacts are found in district heating/cooling, industrial processes, and renewable-based microgrids.

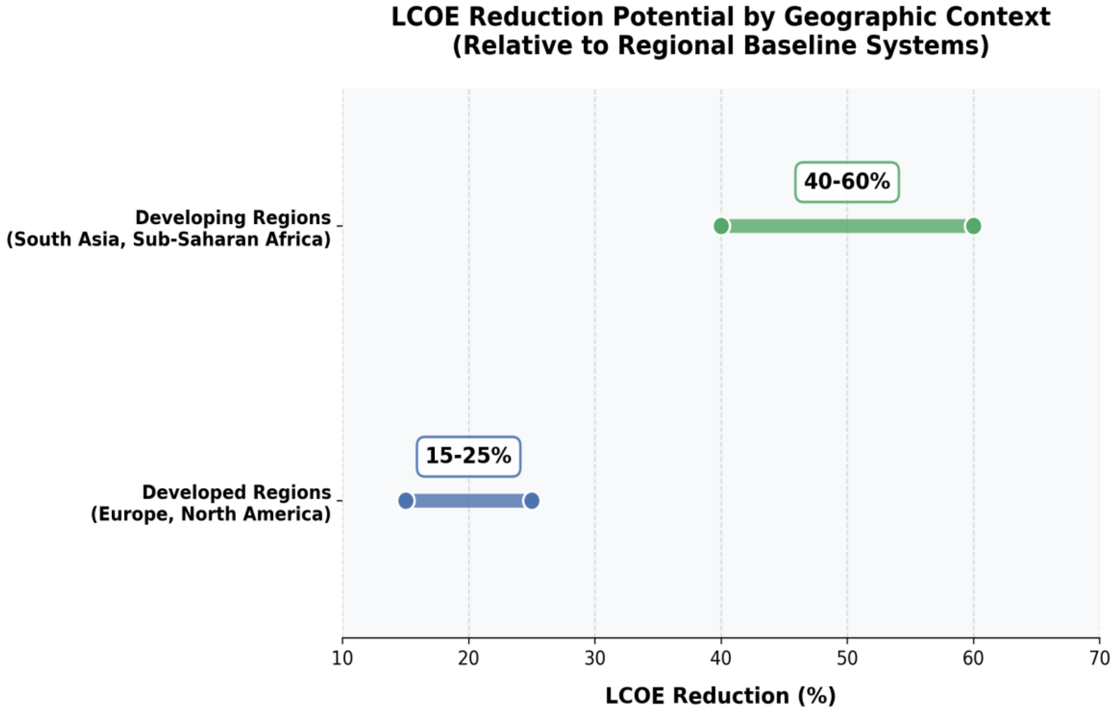

Figure 4. LCOE Reduction Potential by Geographic Context

The findings of this review demonstrate that both thermal energy storage (TES) and electrical energy storage (EES) play decisive yet distinct roles in reducing the Levelized Cost of Energy (LCOE) in multi-energy systems (MES), with TES primarily lowering costs in thermal-dominated sectors through demand decoupling and utilization of waste heat and renewables, while EES reduces costs in electricity-dominated systems by mitigating intermittency, avoiding curtailment, and supporting grid services (Vecchi, 2023). Importantly, their co-deployment generates complementary flexibility that amplifies cost savings in high-renewable contexts (Pawlak, 2024). Theoretically, this review contributes by advancing integration perspectives that highlight MES as socio-technical systems where sectoral coupling unlocks added value, by underscoring the need for consistent LCOE-based economic evaluation frameworks, and by reframing flexibility as a systemic and economic driver rather than a purely technical characteristic. Innovation trends further reveal strong synergies from sectoral coupling (e.g., TES in district heating and industrial processes, EES in electricity systems), the emergence of hybrid storage systems (PV–battery–TES), the rising significance of long-duration storage for seasonal balancing, and the application of advanced optimization algorithms to enhance MES operations (Miro et al., 2016; Evens et al., 2022). From a policy perspective, the literature underscores the necessity of supporting hybrid storage deployment through integrated incentives, standardizing LCOE calculation methodologies to reduce cross-study inconsistencies (Magni et al., 2022), creating regulatory frameworks that allow TES and EES to participate in flexibility and capacity markets, and prioritizing deployment in developing regions where hybrid MES can significantly reduce LCOE compared to diesel-based systems while advancing SDG 7 (IRENA, 2021). Nevertheless, critical research gaps persist, including the scarcity of empirical data from operational projects, limited cross-sectoral case studies of integrated TES–EES deployment, static approaches to LCOE modeling that neglect cost dynamics, and a lack of socio-institutional analyses examining governance, social acceptance, and regulatory arrangements. Together, these insights reinforce that while TES and EES hold substantial promise for advancing cost-competitive MES, future scholarship and policy must address these gaps to translate technological potential into sustainable real-world outcomes.

CONCLUSIONS AND RECOMMENDATIONS

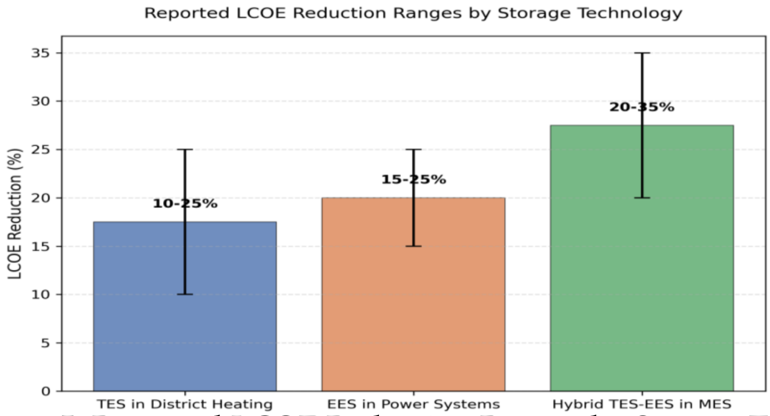

Figure 5. Reported LCOE Reduction Ranges by Storage Technology

This review demonstrates that integrating thermal energy storage (TES) and electrical energy storage (EES) within multi-energy systems (MES) is crucial for reducing the Levelized Cost of Energy (LCOE) and facilitating cost-competitive, low-carbon energy transitions. TES delivers notable cost savings in heating, cooling, and industrial applications by decoupling supply and demand, enabling seasonal balancing, and enhancing the utilization of waste heat and renewables, while EES supports electricity-dominated systems by smoothing intermittency, reducing curtailment, and providing critical grid services (IRENA, 2021) Importantly, their joint deployment offers complementary flexibility that amplifies economic benefits, with integrated systems achieving LCOE reductions of up to 35% relative to single-technology storage solutions (Jarwar et al., 2023) Despite these advances, inconsistencies in LCOE calculation methods, reliance on techno-economic modelling rather than empirical validation, and limited attention to socio-institutional dynamics constrain the comparability and applicability of existing findings.

From a policy standpoint, several implications emerge. First, governments should move beyond siloed support for single storage technologies and instead incentivize hybrid storage portfolios, such as PV–battery–TES systems, that maximize cost synergies across sectors. Second, the establishment of standardized LCOE assessment frameworks is essential to ensure methodological consistency, improve cross-country comparability, and provide more reliable signals to investors and policymakers (Schmidt et al., 2019). Third, regulators should enable TES and EES participation in flexibility and capacity markets, recognizing their role in demand-side management, ancillary services, and seasonal balancing, thereby monetizing their value beyond energy arbitrage. Fourth, dedicated funding for research, development, and demonstration (RD&D) should accelerate technological innovation in long-duration TES and EES, coupled with real-world pilot projects to validate modelled cost savings. Finally, in developing regions, where affordability and access remain pressing challenges, policies should prioritize the deployment of hybrid MES as a low-cost alternative to fossil-based generation, leveraging concessional finance and capacity-building initiatives to align with global sustainability targets, such as SDG 7 (IRENA, 2021).

In conclusion, TES and EES are not merely supportive technologies but central levers in lowering LCOE and enhancing the resilience and flexibility of future energy systems. Yet their transformative potential depends on bridging the gap between technological innovation and institutional readiness. Addressing the identified research gaps, particularly through empirical evidence, dynamic LCOE modelling, and socio-institutional analyses, will be critical for translating theoretical potential into practice. By advancing integrated storage deployment within MES through coherent policies, standardized assessments, and inclusive governance, the global energy transition can be accelerated toward a more sustainable, equitable, and cost-effective trajectory.

FURTHER STUDY

This research has limitations, so further research on this topic is still needed.

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