Journal of Engineering and Technology
DergiPark
AKADEMİK

Journal of Engineering and Tecnology 7(1) (2026) 1-11

A Multi-Scale Review of Energy Storage Architectures in Smart Grids: An Examination Across Grid, Microgrid, and Building/HVAC Scales

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ARTICLE INFO

Article history:
Submission Date
December 8, 2025

Acceptance Date:
March 24, 2026

Key words:
Smart grids
Energy storage
HVAC
Microgrids

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ABSTRACT

Electricity consumption has grown substantially in recent decades, with buildings and their heating, ventilation, and air conditioning (HVAC) systems accounting for a disproportionately large share of this increase. Concurrently, the rising penetration of variable renewable energy sources and tightening power quality requirements are accelerating the transition toward smart grid infrastructures. In this context, energy storage has emerged as a central enabler of flexibility, both at the system level and within individual buildings.

This paper presents a structured multi-scale literature review on energy storage architectures in smart grids, covering three interconnected levels: the bulk power grid, microgrids, and building/HVAC applications. The review synthesizes contributions addressing technology classification, standards and interoperability, national-scale energy system modeling, smart community applications, and microgrid-level techno-economic analysis. The findings consistently highlight the complementary roles of different storage technologies across scales, the critical importance of regulatory and standards frameworks for safe grid integration, and the significant flexibility potential of building-level storage when coordinated with smart grid control mechanisms. Based on the reviewed evidence, directions for future research are outlined, with particular emphasis on multi-technology optimization, sector-coupled national energy scenarios, and pilot-scale hybrid storage deployments.

1. Introduction

Electricity consumption has increased markedly worldwide over recent decades. According to the International Energy Agency, global electricity demand rose by approximately 1,100 TWh in 2024, corresponding to a growth rate of roughly 4.3% — nearly twice the long-term average (see Fig. 1) [1]. Notably, around 60% of this increase is attributable to buildings [2]. Cooling demand alone is projected to add more than 1,200 TWh to global electricity consumption by 2035 [1]. In the specific case of the European Union, buildings account for approximately 38% of total final energy use, and around 80% of this is associated with HVAC services (see Fig. 2) [3].

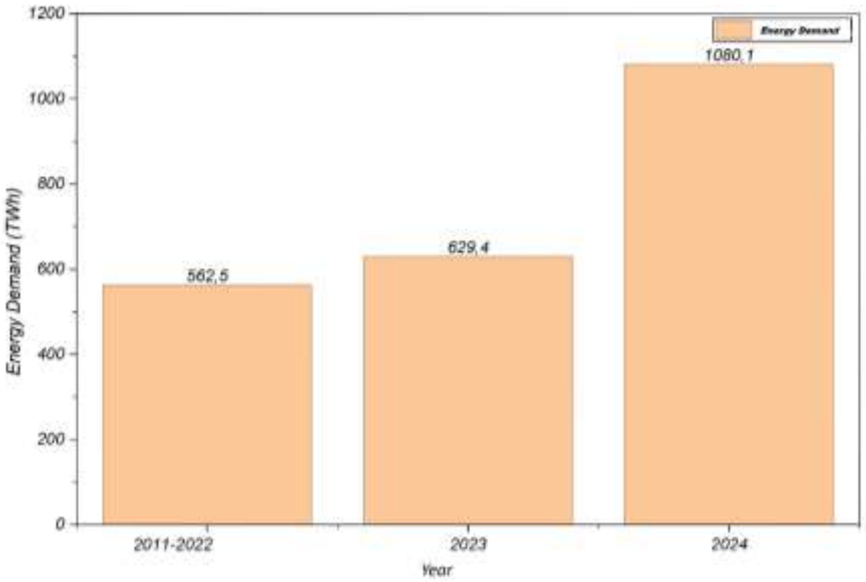

Figure 1. Energy demand in the world by year [1]

These figures make clear that any serious discussion of future electrical systems must extend beyond the traditional grid level to include the building scale and, in particular, HVAC systems. Rising building loads, an increasing share of variable renewable generation (see Fig. 3), and stricter power quality requirements are collectively rendering the traditional unidirectional grid architecture insufficient. Smart grids, which enable bidirectional energy and information flow, have therefore become a structural necessity rather than an optional upgrade [4], [5].

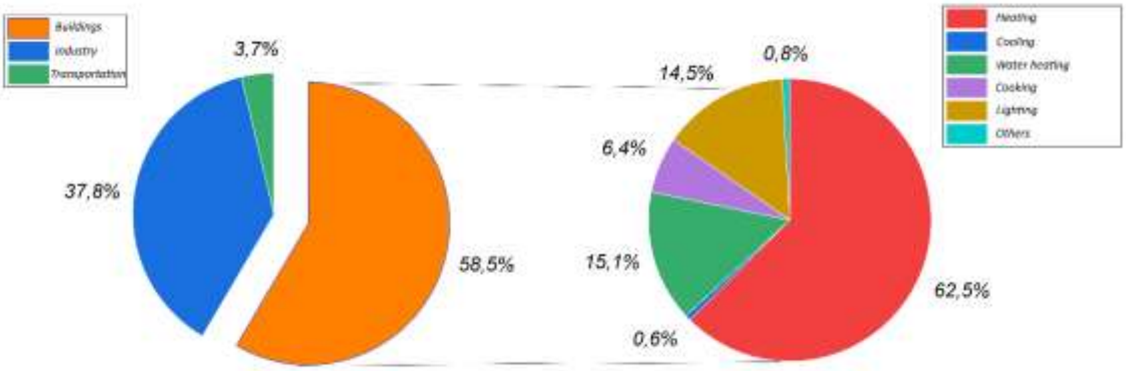

Figure 2. The share of the building sector and HVAC systems in final energy use in the European Union in 2023 [3]

As illustrated in Fig. 4, smart grids integrate advanced metering infrastructure, two-way communication, distributed generation, demand-side management, and energy storage into a coordinated system. Storing energy during periods of high renewable output and releasing it during peak demand or low generation periods offers substantial technical and economic advantages [5], [6]. Crucially, energy storage is not confined to the bulk grid level. Building-integrated solutions — including electrical battery systems, thermal storage tanks, and phase change materials (PCM) — can reduce grid load and operating costs by providing local flexibility. When coordinated with smart grid controls and demand-side management programs, such solutions support peak load shaving, load shifting, and increased self-consumption of on-site renewable energy. Fig. 5 provides a classification of the principal energy storage technologies referenced throughout this review [7].

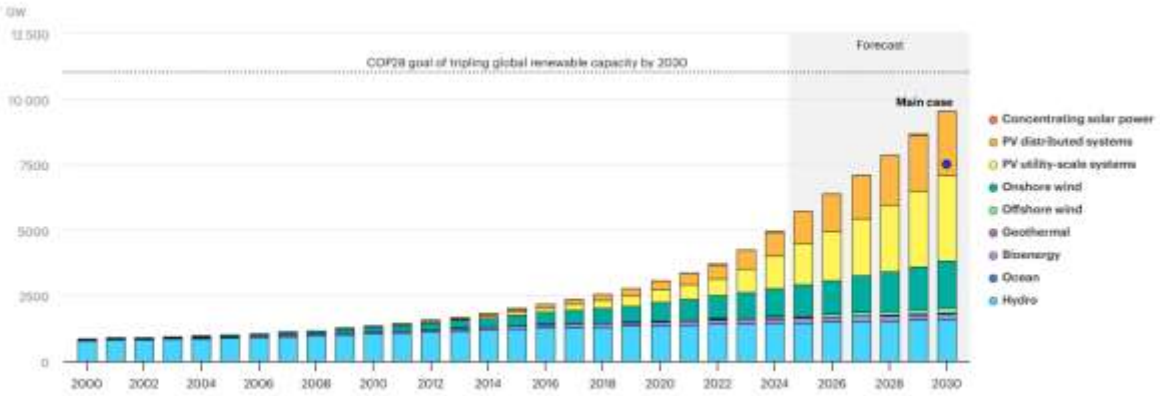

Figure 3. Renewable energy facility capacities by year (GW) [6]

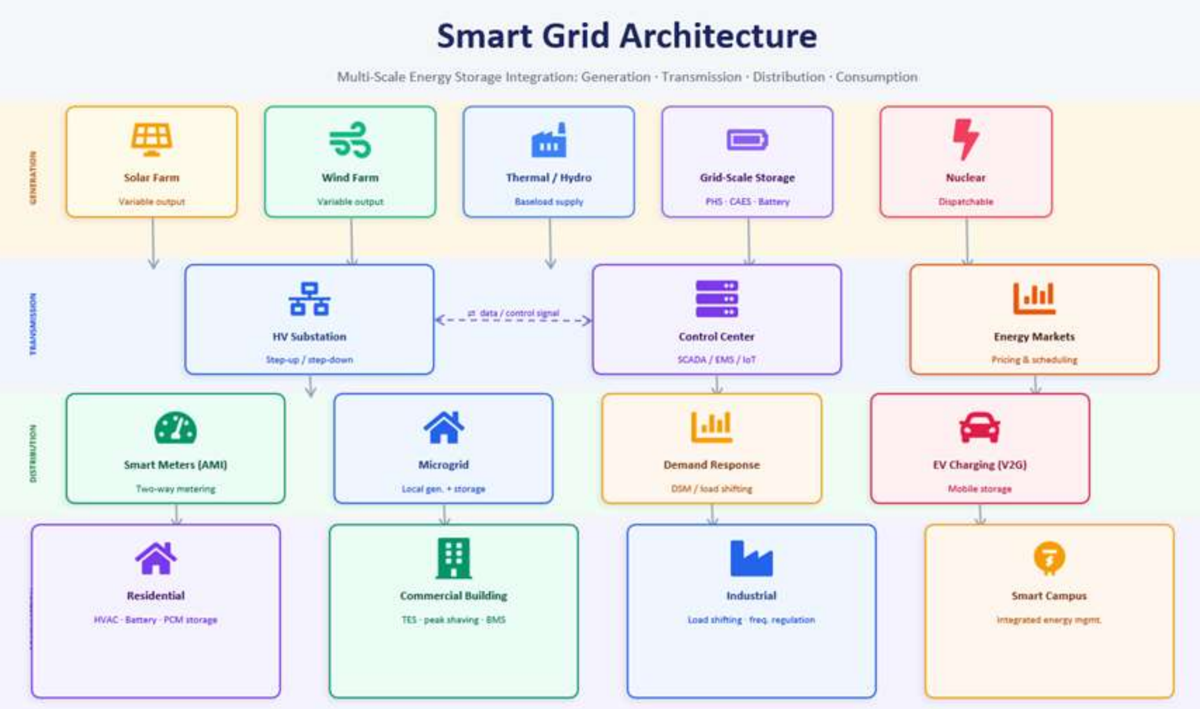

Figure 4. A view of Smart Grid

Building on these trends, this study examines how energy storage can be deployed across the different layers of the power system to address rising, building-driven electricity demand and the growing share of variable renewables. Specifically, the paper reviews energy storage architectures in smart grids at three interconnected scales: (i) the bulk grid level, where large-scale storage supports system balancing and reliability; (ii) the microgrid level, where storage enhances local flexibility, resilience, and renewable integration; and (iii) the building/HVAC level, where both electrical and thermal storage can mitigate peak loads and improve power quality.

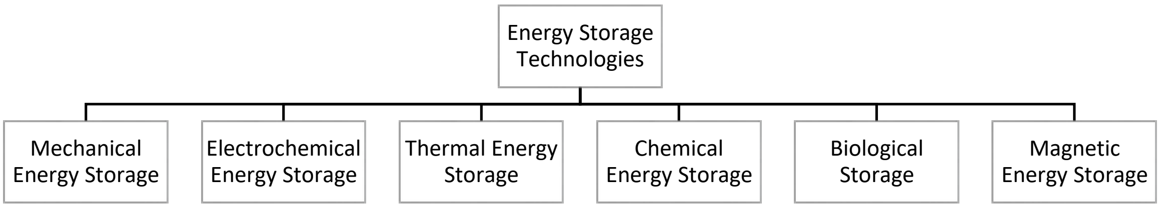

Figure 5. Energy storage Technologies [9]

The remainder of the paper is organized as follows. Section 2 describes the methodology and search strategy employed in the review. Section 3 presents the literature review across the three scales. Section 4 discusses the findings and draws cross-scale conclusions. Section 5 outlines directions for future research.

2. Methodology

2.1 Review Approach

This study adopts a structured literature review methodology. Unlike a fully systematic review — which requires exhaustive database searches, and quantitative synthesis — a structured review approach is appropriate when the research objective is to examine a well-defined thematic scope through carefully selected representative studies. This approach has been widely used in engineering and energy systems literature to map the state of knowledge across interconnected sub-domains without aiming for statistical representativeness. The primary objective of this review is not to quantify aggregate findings across a large corpus of studies, but rather to examine how energy storage architectures are conceptualized, designed, and evaluated at three distinct scales — bulk grid, microgrid, and building/HVAC — and to identify the technical, regulatory, and economic dimensions that are common across these scales..

2.2 Search Strategy

The literature search was conducted using Web of Science, Scopus, and Google Scholar. Searches were performed using the following keyword combinations:

- "energy storage" AND "smart grid"
- "energy storage" AND "microgrid" AND "flexibility"
- "thermal energy storage" AND "smart energy system"
- "battery storage" AND "building" AND "peak shaving"
- "HVAC" AND "demand flexibility" AND "storage"
- "smart grid standards" AND "energy storage"

The search was limited to peer-reviewed journal articles, conference proceedings, and authoritative institutional reports. No strict publication year cutoff was applied; however, priority was given to studies published after 2013, reflecting the period of significant acceleration in smart grid deployment and storage integration research. Foundational or frequently cited works published before this period were retained where necessary to provide contextual grounding.

2.3 Inclusion and Exclusion Criteria

Studies were considered eligible for inclusion if they met all of the following criteria:

- The study addresses energy storage technologies, architectures, or integration strategies at one or more of the three scales examined in this review (bulk grid, microgrid, building/HVAC).

- The study provides quantitative results, comparative analysis, or a systematic technology assessment — rather than purely qualitative or descriptive commentary.
- The study is published in an indexed, peer-reviewed venue or is an official report from a recognized institution (e.g., IEA, Eurostat).

Studies were excluded if they focused exclusively on power electronics design, storage materials science, or smart grid communication protocols without addressing storage architecture or system-level integration. Studies dealing with storage in contexts unrelated to electricity systems were also excluded.

2.4. Study Selection and Scope

Following the application of the above criteria, the studies included in this review were selected on the basis of thematic complementarity and methodological diversity. The aim was not to achieve statistical representativeness across the field, but rather to ensure that each major dimension of the multi-scale storage architecture examined here — technology classification, regulatory and standards frameworks, national-scale energy system modeling, smart grid and community-level applications, and microgrid-level techno-economic analysis — is addressed by at least one substantive contribution. Where a single study provided particularly focused and quantitative treatment of a given dimension, it was given primary analytical weight; in all cases, additional recent literature was incorporated to contextualize, extend, or critically evaluate the primary findings.

The review covers studies addressing storage at three interconnected scales: the bulk power grid, microgrids, and building/HVAC systems. At the bulk grid level, the focus is on system balancing, large-scale storage integration, and the role of standards in enabling safe and interoperable deployment [4], [8], [9], [10]. At the microgrid level, the review examines flexibility, economic performance, and energy management strategies [11], [12], [13], [14], [15], [16]. At the building and HVAC scale, both electrical and thermal storage solutions are considered, with attention to demand flexibility, peak load management, and sector coupling [17], [18], [19], [20]. Cross-cutting themes — including technology classification, battery degradation, and hybrid storage architectures — are addressed where they bear on multiple scales simultaneously [5], [6], [7], [21], [22], [23], [24].

Contextual and statistical data were drawn from IEA reports[1], [2], [25] and Eurostat [3], supplemented by a general reference work on smart grid architecture[26]. It is further noted that data-driven approaches are increasingly complementing physical storage architectures in smart grid management; recent work on hybrid deep learning models for electricity demand forecasting illustrates this growing intersection and is referenced accordingly [27].

3. Literature Review

3.1 Energy Storage Technologies in Smart and Microgrids

Energy storage technologies deployed in smart grids and microgrids span a wide range of physical principles and application scales. Kocaman [5] provides a foundational classification of these technologies under four main categories: electrical, mechanical, chemical/electrochemical, and thermal storage. Electrical storage systems — including capacitors, ultracapacitors, and superconducting magnetic energy storage (SMES) — are primarily suited to short-duration, high-power applications that support power quality and protect against sudden voltage drops. Mechanical storage technologies such as pumped hydroelectric storage (PHS), compressed air energy storage (CAES), and flywheel systems are better suited to long-duration storage and load-curve smoothing at larger scales. The chemical and electrochemical category covers battery technologies including lead-acid, lithium-ion, and nickel-cadmium cells, as well as hydrogen storage and fuel cells, which are widely applicable in both grid-scale and distributed settings due to their high energy density and increasingly mature technology levels. Thermal storage addresses sensible and latent heat methods — including hot and cold water tanks and phase change material (PCM) systems — and is positioned as a complementary flexibility tool in heating, cooling, and renewable integration contexts.

This classification is consistent with and reinforced by more recent literature. Tan et al. [21] provide a comprehensive assessment of energy storage technologies from the perspective of smart grid integration, covering hybrid storage configurations and their application functions across grid, user, and renewable energy generation sides. The authors emphasize that no single technology is universally optimal, and that the appropriate storage solution depends critically on application-specific requirements including discharge duration, power response time, cycle life, and cost. Njema et al.[22] further examine recent advances in battery development, noting that lithium-ion batteries currently dominate grid-scale deployment due to their high energy density and flexible form factor, but highlight ongoing challenges related to degradation, safety, and resource supply chains. Battery degradation in particular is a concern for long-term techno-economic performance: as cycling depth and frequency increase, capacity fade reduces both storage availability and the economic value of installed capacity [23]. Together, these studies establish that a nuanced, application-aware approach to technology selection is essential for any storage architecture intended to serve multiple functions within a smart grid.

3.2 Smart Grid Standards and Energy Storage

Koç et al. [4] evaluate energy storage applications in smart grids from a standards and interoperability perspective. Their study examines the IEEE 2030 series, developed to ensure the interoperability of electric power systems, communication technologies, and end-user loads within a smart grid environment. The 2030.2 and 2030.3 substandards focus specifically on the technical specifications, performance criteria, and test procedures for energy storage systems. The IEEE 1547 series, which governs the connection of distributed energy resources to the grid, defines connection conditions, protection requirements, and test methods applicable to both distributed generation and storage units. Koç et al. argue that these standards provide a critical framework for the safe and predictable operation of storage systems, particularly in demand-side management and distributed storage applications, transforming storage from a power electronic component into a grid element with clearly defined technical rights and obligations.

The significance of such regulatory frameworks is underscored by broader analyses of smart grid architecture. Aly et.al. [8] highlights that the integration of renewable energy sources into smart grids, supported by AMI, DCS, SCADA, machine learning, and energy storage systems, has significant potential to enhance grid reliability, operational efficiency, resilience, and sustainability, while still facing technical, economic, regulatory, and contextual limitations. Complementing this, Ethirajan et al. [28] reviews the past two decades of progress in integrating renewable energy sources into smart grids and emphasizes that bidirectional communication, automation, energy storage, demand-side participation, and data management significantly enhance grid reliability, flexibility, and sustainability. The study also highlights cybersecurity, data management, standardization, and interoperability as key factors for the wider deployment of smart grids. Li et al. [10] further analyze the optimal planning and benefit evaluation of energy storage systems in smart grids, emphasizing their critical role in addressing renewable energy intermittency, improving grid stability, and supporting grid-side, user-side, and renewable-side applications. It also highlights that effective storage deployment requires both techno-economic optimization and comprehensive evaluation of system benefits.

3.3 Thermal Energy Storage and the Smart Energy System Approach

Christensen et al. [17] examine the role of thermal energy storage (TES) in future smart energy systems at a national scale, using Denmark as the case study and EnergyPLAN software as the modeling tool. Their analysis considers sector-coupled scenarios in which the electricity, heat, gas, and transport sectors are modeled jointly. The results show that in low-renewable-penetration scenarios, TES reduces fossil fuel consumption by 0.6–3 TWh, while in high-renewable scenarios its primary function shifts toward absorbing surplus electricity. A key quantitative finding is that economic benefits diminish when TES capacity exceeds approximately 150 GWh, indicating that storage sizing must be aligned with national energy policy objectives and economic optimization rather than being treated as an unlimited flexibility resource.

This national-scale perspective connects directly to building-level thermal storage applications, which are often discussed in isolation but belong to the same flexibility continuum. Recent work has confirmed and extended this connection across both scales. Yang et al. [18] conducted a study on a district-heated office building in Finland demonstrated that short-term thermal energy storage can effectively reduce daily peak heating demand, particularly during the heating season when morning ventilation start-up causes sharp load increases. The findings showed that integrating a stratified thermal storage tank into the district heating substation significantly decreased peak loads, while additional peak reduction could be achieved by limiting the district heating mass flow without compromising indoor thermal comfort. These results indicate that short-term thermal energy storage is not only beneficial at the building scale for lowering peak demand and operational costs, but also valuable for improving the operational flexibility of district heating networks. In parallel, a recent European review on latent thermal energy storage highlighted the growing importance of phase change material (PCM)-based systems in HVAC applications for both commercial and residential buildings. The review emphasized that latent thermal energy storage can enhance energy efficiency, reduce peak loads, and improve overall system flexibility by storing and releasing thermal energy more effectively within heating and cooling processes. It further noted that PCM-integrated HVAC systems have considerable potential to support low-carbon building operation across different climatic conditions in Europe, although challenges such as high initial cost, material selection, standardization, and long-term performance assessment still limit large-scale deployment. Together, these studies show that thermal energy storage, whether in short-term sensible form or latent form, is a promising strategy for improving building energy performance and supporting more flexible and sustainable heating and cooling systems [19]. Active and passive PCM system applications have been reviewed in detail by Talu et al. [29], who demonstrate that low thermal conductivity remains the primary challenge limiting PCM performance across both system types, and that heat transfer enhancement strategies are central to ongoing research efforts in this area. Huylo et al. [20] further evaluate peak shaving potential using thermal energy storage in a combined heat and power and district energy model, demonstrating that TES dispatch strategies can be optimized across both economic and grid service objectives simultaneously. Taken together, these findings reinforce the argument advanced by Christensen et al. [17] that thermal storage is not merely a building-level efficiency measure but a strategically significant component of smart energy system architecture at every scale.

3.4 Energy Storage Technologies and Applications in Smart Grids

Kolokotsa et al. [6] offer a broad review of energy storage technologies in the smart grid context, comparing electrical/electrochemical, mechanical, thermal, and chemical storage options across dimensions of storage duration, power and energy density, efficiency, response time, and typical application areas. A particularly valuable contribution to their work lies in its grounding of technology comparisons in real application cases. In a smart community deployment combining photovoltaic generation, battery storage, and thermal storage tanks, their analysis shows that coordinated storage increases on-site solar self-consumption, reduces peak demand, and diminishes grid energy draw simultaneously. A separate case study involving concentrated solar power (CSP) with a thermocline thermal storage tank demonstrates that the same storage infrastructure can meet both electricity generation and heating or cooling loads, pointing toward the design efficiency gains achievable through hybrid storage architectures. These examples underscore that storage integration and energy management system design must be treated as a joint problem rather than a sequential one.

The techno-economic dimension of this integration challenge has been examined in recent quantitative work. Yang et al. [24] analyze the costs and benefits of battery energy storage systems deployed in smart grids with wind and photovoltaic generation, comparing battery chemistries on capital cost, operational cost, and grid service value. Their results show that the economic case for storage in wind-PV grids is highly sensitive to battery chemistry selection and market design, reinforcing the importance of cost-aware planning in hybrid smart grid architectures. At the system level, Wu et al. [12] review energy management systems and control strategies for renewable-based microgrids, identifying optimization approaches — including rule-based, model predictive, and metaheuristic methods — that enable storage assets to serve multiple simultaneous functions such as frequency regulation, peak shaving, and renewable integration. The convergence of these findings confirms that the design principles identified by Kolokotsa et al. [6] remain valid and are being progressively operationalized through increasingly sophisticated control and planning frameworks.

3.5 Energy Storage Solutions in Microgrids: Flexibility and Economy

Oymak et al. [11] present a numerical analysis comparing energy storage solutions in microgrids with respect to flexibility and economic performance. The study models different storage configurations for a sample microgrid and evaluates key indicators including net present cost, levelized cost of energy, generator utilization rate, and carbon emissions. The findings show that appropriately sized storage systems improve grid independence, reduce peak demand, and lower fuel consumption. Beyond technical flexibility, the results demonstrate significant economic contributions in the form of deferred investment, reduced operating costs, and emission reductions — confirming that storage at the microgrid scale is a multi-benefit asset rather than a single-function resource.

Recent work has broadened this analysis in two important directions. Liu et al. [13] review microgrid energy management systems comprehensively, classifying microgrid types and storage configurations and surveying both optimization-based and heuristic approaches to energy scheduling. Their review shows that battery degradation modeling — frequently omitted in earlier techno-economic studies — significantly affects long-term cost projections and optimal dispatch strategies, a finding with direct implications for investment sizing decisions. Aziz et.al [14] address this gap directly by developing a grid-connected microgrid energy management model that explicitly incorporates battery degradation constraints alongside standard economic and technical objectives. Their results demonstrate that degradation-aware scheduling can extend battery service life while maintaining economic performance, providing a more realistic basis for comparative storage assessments. Nguyen-Esparza et.al. [15] further survey optimization strategies for microgrid energy management, emphasizing that multi-objective approaches capable of simultaneously handling cost, emissions, and reliability constraints are essential for practical deployment. Punitha et al. [16] complement these findings by reviewing microgrid architecture challenges comprehensively, identifying control complexity and storage sizing uncertainty as the most persistent barriers to widespread adoption. Taken together with the work of Oymak et al. [11], these contributions indicate that the economic case for microgrid storage is robust across methodologies, but that its full realization depends on operational strategies that account for long-term battery behavior and multi-objective system requirements.

4. Discussion and Conclusion

The reviewed literature demonstrates that energy storage architecture in smart grids is inherently multi-layered and cannot be adequately addressed at a single scale or through a single technology lens. Across the three scales examined; bulk grid, microgrid, and building/HVAC, a consistent set of themes emerges: the need for technology-specific deployment strategies, the critical enabling role of standards and regulatory frameworks, the growing importance of sector coupling, and the tension between short-term economic optimization and long-term performance.

At the bulk grid level, the reviewed studies highlight that standards such as IEEE 2030 and IEEE 1547 are not merely technical specifications but foundational governance instruments that determine the conditions under which storage can participate in grid services [4], [17], [18], [19]. Without clear interoperability and market participation rules, the technical capabilities of storage assets cannot be fully utilized. This regulatory dimension is frequently underweighted in purely engineering-focused analyses.

At the microgrid scale, the evidence consistently supports the multi-benefit nature of storage investments: appropriately designed systems simultaneously improve flexibility, reduce peak demand, defer network investment, and lower emissions [11], [24], [25]. However, the accuracy of techno-economic assessments is substantially affected by whether battery degradation is explicitly modeled[16], [26]. Studies that omit degradation dynamics tend to overestimate long-term economic returns and underestimate replacement costs, leading to suboptimal sizing decisions.

At the building and HVAC scale, both electrical and thermal storage contribute meaningfully to demand flexibility and peak load reduction. TES in particular emerges as a cost-effective and highly scalable option, with performance documented at scales ranging from individual building substations to national energy systems [17], [20], [21], [22]. The sector-coupled modeling approach of Christensen et al. [17] is especially instructive in showing how building-level and district-level TES decisions have upstream effects on national system costs and renewable integration capacity.

Overall, energy storage systems remain among the few technical components capable of simultaneously advancing the objectives of flexibility, economic efficiency, and environmental sustainability across all levels of the power system. However, fully realizing this potential requires coordinated action across technological development, standards evolution, market design, and operational strategy — domains that are rarely addressed together in individual research contributions.

IEA data consistently show that most of the increase in global electricity demand is driven by building heating and cooling loads, and that buildings account for a significant share of final energy consumption in the EU [1], [3], [25]. This reinforces the conclusion that energy storage architecture must be addressed not only at the grid level but also at the building scale. Storage solutions integrated with HVAC systems and coordinated through smart grid control frameworks offer a powerful and underutilized toolkit for peak load shaving, load shifting, and renewable energy integration.

5. Recommendations for Future Research

The reviewed literature and the cross-scale framework presented point to several key directions for future research:

1.Multi-technology optimization studies: Optimization models that simultaneously address investment and operating costs — including batteries, TES, pumped hydro, hydrogen, and PCM-based solutions — are needed. Such models can guide the [17]determination of the optimal storage mix for different climates, demand profiles, and grid configurations.

2.Detailed modeling at the building and HVAC scale: Detailed simulation and experimental studies are needed to examine how PCM applications integrated with the building envelope, thermal storage tanks, and on-site battery systems can be optimized in conjunction with smart meters and dynamic pricing signals.

3.Country-scale smart energy system scenarios: Similar to the approach of Christensen et al. for Denmark, national scenario studies that address the electricity, heat, and transportation sectors together — including TES and other storage types — are needed for Turkey and comparable emerging economies.

4.Degradation-aware techno-economic frameworks: Given the demonstrated sensitivity of long-term economic projections to battery degradation assumptions[14], [23], future studies should adopt degradation-aware modeling as a standard rather than optional component of storage investment analysis.

5.Hybrid storage technology and pilot applications: Smart campus or neighborhood-scale pilot projects that combine photovoltaic, wind, storage, and heating/cooling systems can serve as important test environments for both technology integration and behavioral response to dynamic pricing

Acknowledgement

A preliminary version of this work, limited to an abstract and without a full paper, was presented at the "5th International Batman Energy Summit, November 2025".

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