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Hybrid battery–supercapacitor storage for PV-based microgrids and smart grids: state-of-the-art applications and open challenges

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ABSTRACT

This paper presents a structured review of hybrid energy storage systems (HESS) for photovoltaic (PV)-based microgrids and smart grids. The review focuses on system architectures, energy management strategies (EMS), and application scenarios. The aim is to provide an application-oriented and integrated perspective. The results show that hybrid systems are most beneficial in PV-based microgrids with high variability and frequent transients. From an architectural perspective, semi-active configurations are suitable for rural and medium-scale systems. In contrast, active architectures are more appropriate for grid-connected systems that require high controllability. In terms of EMS, rule-based and filter-based strategies are well-suited for rural microgrids. Optimization-based and intelligent methods perform better in grid-connected systems with higher computational capability. Furthermore, hybrid systems become economically viable when the reduction in battery degradation and replacement costs offsets the additional investment in power electronics and control complexity. This condition is typically observed in systems with high PV penetration and strict power quality requirements. The main contribution of this review is a unified framework linking HESS architectures, EMS strategies, and application conditions. These insights offer practical guidance for the design and deployment of efficient and resilient HESS in next-generation PV-based microgrids.

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1. INTRODUCTION

The increasing penetration of photovoltaic (PV) generation in microgrids and smart grids plays a key role in enabling sustainable and low-carbon energy systems [1], [2]. However, PV output is inherently intermittent due to fluctuations in solar irradiance [3], [4]. This variability introduces challenges in maintaining power balance, voltage regulation, and frequency stability, especially in PV-dominated and rural microgrids [5], [6]. Therefore, energy storage systems must be capable of handling both energy buffering and fast transient dynamics [7], [8].

Battery energy storage systems (BESS), particularly lithium-ion technologies, are widely used due to their high energy density and technological maturity [9], [10]. However, their performance degrades under frequent high-power fluctuations and rapid cycling conditions [11]–[13]. This degradation reduces battery

lifetime and increases lifecycle costs [14], [15]. In contrast, supercapacitors offer high power density, fast response, and long cycle life, but their low energy density limits long-term energy support [12], [16]–[18].

Hybrid battery–supercapacitor energy storage systems (HESS) have emerged to address these complementary limitations [19], [20]. By decoupling energy and power functions, HESS can improve system flexibility and performance. These systems enhance dynamic response, reduce battery stress, and increase overall reliability. As a result, HESS is increasingly considered for PV-based microgrids and smart grids [21], [22].

Although many studies have investigated HESS, existing literature often remains fragmented. Most works focus on specific control strategies, converter topologies, or isolated application scenarios. A comprehensive, application-oriented review remains limited. In particular, systematic links between hybrid architectures, energy management strategies (EMS), and PV-based microgrid applications are often missing. This gap is more evident in studies addressing grid-support services and real-world deployment challenges.

Therefore, this paper presents a focused review of hybrid battery–supercapacitor energy storage systems for PV-based microgrids and smart grids. The review covers fundamental concepts and system architectures. It also discusses EMS designed to handle PV variability. Applications in microgrids, rural electrification, and smart grid environments are examined. Finally, comparative performance insights, open challenges, and future research directions are highlighted. This review aims to support researchers and system designers in developing efficient, reliable, and resilient PV-based hybrid energy storage solutions.

2. HYBRID BATTERY–SUPERCAPACITOR CONCEPTS AND ARCHITECTURES

Hybrid battery–supercapacitor energy storage systems are designed to address the limitations of single-storage technologies in PV-based microgrids [23]. Batteries provide high energy density and are suitable for long-duration energy balancing [24]. In contrast, supercapacitors offer high power density and rapid dynamic response [25]. Their complementary characteristics underpin HESS, which aim to meet both energy and power requirements in renewable energy applications [12], [26].

2.1. Characteristics of batteries and supercapacitors

Batteries and supercapacitors exhibit fundamentally different operating characteristics, particularly in terms of energy capacity, power capability, and response time [27]. Batteries are designed to store relatively large amounts of energy. Therefore, it is well suited to medium- to long-duration applications such as energy balancing, load shifting, and backup supply in PV-based systems. Lithium-ion batteries, widely used in microgrids, offer high energy density and good round-trip efficiency [28]. However, their electrochemical nature limits their ability to respond efficiently to rapid power fluctuations [27]. Frequent exposure to high-power transients and deep charge-discharge cycling accelerates aging mechanisms. It's leading to capacity fade and increased internal resistance [29], [30].

In contrast, supercapacitors are characterized by very high power density, fast charge–discharge capability, and exceptionally long cycle life [31]. These properties enable supercapacitors to handle short-duration high-power events such as PV output smoothing, load transients, and fast grid-support actions with minimal degradation [32], [33]. Their main drawback is their low energy density, which limits their ability to provide sustained energy over long periods [18]. As a result, supercapacitors are unsuitable as standalone storage devices for PV-based microgrids [34]. The strong opposition between the energy-oriented nature of batteries and the power-oriented behaviour of supercapacitors underpins hybrid battery–supercapacitor systems [20]. From this hybrid system, each device can operate in its optimal performance range [35].

2.2. Principle of hybridization: energy–power decoupling

The core principle of battery–supercapacitor hybridization is energy–power decoupling [36]. In a hybrid system, low-frequency power components associated with energy balancing are assigned to the battery. High-frequency components caused by PV intermittency and load transients are handled by the supercapacitor [16]. This separation reduces stress on the battery and mitigates rapid charge–discharge cycles [37]. As a result, battery lifetime is extended and overall system efficiency is improved [38].

Energy–power decoupling is particularly relevant in PV-based microgrids, where fast irradiance variations and fluctuating loads are common [39]. Without hybridization, batteries must respond to both short-term and long-term power demands, which accelerates degradation [40], [41]. Hybrid systems address this issue by exploiting the fast dynamics of supercapacitors while preserving the energy capacity of batteries [39].

2.3. Architectures of hybrid battery–supercapacitor systems

Hybrid battery–supercapacitor systems can be broadly classified into passive, semi-active, and active architectures based on the degree of power-electronic interfacing and control complexity [42]. These architectures differ in how power is shared between the battery and the supercapacitor, as well as in their

flexibility, efficiency, and implementation cost. Therefore, the selection of an appropriate architecture depends on the system scale, application requirements, and performance objectives in a PV-based microgrid [42].

From an application perspective, passive architectures are generally suitable for low-cost and small-scale systems where simplicity and reliability are prioritized over performance optimization. However, their limited controllability restricts their ability to handle dynamic PV fluctuations effectively.

Semi-active architectures employ a bidirectional direct current (DC–DC) converter for one storage device, while the other is directly connected to the DC bus [43]. This configuration improves power flow controllability and enhances the utilization of supercapacitors for transient power support [42]. As a result, semi-active systems are well suited for medium-scale microgrids, including rural electrification applications. They provide a balanced trade-off between control capability, system complexity, and cost [43], [44].

Active architectures are more suitable for large-scale or grid-connected microgrids. These systems require precise power control and high operational performance [42]. Using dedicated converters for each storage device enables full controllability and optimal energy–power decoupling. However, this type has a higher cost and increased control complexity [44].

2.4. Relevance for photovoltaic-based microgrids

In PV-based microgrids, energy storage systems must manage variability across multiple timescales. Hybrid battery–supercapacitor systems are well suited for this role because they integrate complementary dynamic characteristics within a single framework [45]. Supercapacitors respond rapidly to short-term disturbances, such as cloud-induced PV fluctuations and sudden load changes [41]. While batteries handle slower energy balancing and backup functions [24]. This approach allows each storage device to operate within its optimal range, improving voltage regulation, frequency stability, and overall power quality, particularly in islanded microgrids with limited inertia [46].

The suitability of HESS architectures depends strongly on the microgrid operating scenario. For remote and rural microgrids, semi-active configurations offer a practical trade-off between cost, robustness, and performance. In contrast, grid-connected and high-PV-penetration systems benefit from active architectures due to their superior controllability and ability to support advanced grid services. Passive configurations remain relevant for low-demand applications where cost constraints dominate, and system dynamics are less critical.

In addition, hybrid battery–supercapacitor systems improve reliability and operational sustainability in PV-based microgrids [23]. By absorbing high-power transients, supercapacitors reduce stress on batteries and power electronic converters, thereby slowing battery degradation and extending service life [47]. This benefit is especially important for remote and rural electrification systems, where access for maintenance and replacement costs is a critical concern [47]. Furthermore, the flexibility of the hybrid architecture allows microgrids to provide fast grid support services while maintaining energy sufficiency. Thus, hybrid storage is a practical and robust solution for microgrids with high PV penetration and emerging smart grid applications [23]. A comparative summary of the suitability of HESS architectures in various PV-based microgrid scenarios is presented in Table 1.

Table 1. Comparison of HESS architectures for different PV-based microgrid scenarios [41]–[45], [48]

Architecture type	Configuration complexity	Control capability	Cost level	Key advantages	Limitations	Suitable applications
Passive	Very low (no DC–DC converter)	Limited	Low	Simple design, high reliability, low-cost	Poor power sharing control, limited dynamic performance	Small-scale, low-cost, standalone PV systems
Semi-active	Moderate (one bidirectional converter)	Medium	Medium	Balanced cost-performance, improved transient handling	Limited flexibility compared to active systems	Rural microgrids, medium-scale systems
Active	High (two converters)	High	High	Full controllability, optimal power allocation, supports advanced EMS	High cost and complexity	Grid-connected, large-scale, smart grids

3. ENERGY MANAGEMENT STRATEGIES FOR PV-BASED HESS

EMS play an important role in realizing the benefits of hybrid battery–supercapacitor energy storage systems in PV-based microgrids [23]. The primary objective of EMS is to coordinate power sharing between the battery and the supercapacitor under varying PV generation and load conditions [49]. An effective EMS must simultaneously mitigate PV power fluctuations, protect battery health, and maintain stable microgrid operation [50]. Thus, EMS design directly influences system efficiency, reliability, and lifetime [51], [52].

3.1. Rule-based and filter-based strategies

Rule-based EMS are among the most widely adopted approaches due to their simplicity and ease of implementation [42]. These methods rely on predefined logical rules derived from system states such as state of charge (SoC), power demand, and PV output [53]. Typically, the battery supplies low-frequency power, while the supercapacitor handles high-frequency transients. Although rule-based strategies are computationally efficient and suitable for real-time control, their performance strongly depends on expert knowledge and fixed thresholds [54].

Filter-based strategies extend rule-based concepts by explicitly decomposing power signals into frequency components [55]. Low-pass filters are commonly used to separate slow-varying energy demands from fast PV and load fluctuations [43]. In this framework, the battery supplies the filtered low-frequency component, whereas the supercapacitor compensates for high-frequency variations. Filter-based EMS are intuitive and effective for smoothing PV output. However, improper filter design may lead to suboptimal power sharing or delayed responses under rapidly changing conditions [56].

3.2. Optimization-based energy management

Optimization-based EMS aims to achieve optimal power allocation [43]. On the other hand, it can also minimize the cost function while accounting for battery degradation, power loss, and operational constraints [57]. Model predictive control (MPC) is a prominent example, as it incorporates system dynamics and forecasts of PV generation and load demand [58]. By optimizing control actions over a prediction horizon, MPC can improve battery lifetime and overall system performance [57].

Heuristic optimization techniques, such as particle swarm optimization and genetic algorithms, have also been applied to HESS. These methods are attractive for complex, nonlinear systems where analytical models are difficult to obtain [59]. However, optimization-based EMS generally require higher computational resources and accurate system models. This limits their applicability in low-cost or resource-constrained microgrids, particularly in rural electrification scenarios [60].

3.3. Intelligent and data-driven strategies

Recent studies have explored intelligent and data-driven EMS to enhance adaptability under uncertain operating conditions [61]. These approaches employ techniques such as fuzzy logic, neural networks, and reinforcement learning to learn optimal power-sharing behaviors from data [62], [63]. Intelligent EMS can adapt to changing system characteristics and operating environments without relying on fixed rules or detailed physical models [64].

Despite their potential advantages, data-driven EMS face challenges related to the availability of training data, computational complexity, and robustness. In PV-based microgrids, particularly in remote areas, limited data and processing capacity may limit their deployment [65]. Therefore, intelligent EMS is often combined with conventional strategies to balance performance and implementation feasibility [66].

3.4. Comparative assessment and application context

Each EMS category presents distinct trade-offs between performance, complexity, and implementation requirements [65]. Rule-based and filter-based strategies are well-suited for rural microgrids due to their simplicity, robustness, and low computational cost [66]. These methods can operate reliably under limited data availability and constrained hardware resources. However, their performance is limited in highly dynamic or large-scale systems.

In contrast, optimization-based EMS are more suitable for grid-connected microgrids where higher computational capability and system modeling are available. These approaches enable improved power allocation, battery protection, and overall system efficiency. Intelligent and data-driven methods further enhance adaptability and performance under uncertain and dynamic conditions. However, their deployment is often constrained by data requirements and real-time implementation challenges [67].

Rule-based and filter-based EMS are generally optimal for rural microgrids. While optimization-based and intelligent EMS are more suitable for grid-connected systems. This distinction arises from differences in system scale, data availability, and computational resources. In practice, hybrid or hierarchical EMS that combine simple rules with limited optimization are increasingly adopted. Such approaches provide a balanced solution between performance and practical implementation in PV-based HESS.

4. APPLICATIONS IN MICROGRIDS AND SMART GRIDS

HESS battery–supercapacitor have been increasingly deployed in microgrids and smart grids to address operational challenges associated with high PV penetration [23]. High PV integration introduces multi-timescale power variability, including rapid irradiance-induced fluctuations and slower diurnal variations. By leveraging the complementary characteristics of batteries (high energy density) and supercapacitors (high

power density and fast response), hybrid systems enhance power quality, operational flexibility, and system reliability. The specific role of hybrid storage depends strongly on the operating mode and deployment context [40]. The integrated conceptual relationship between PV generation, hybrid storage architectures, EMS categories, and their system-level impacts is illustrated in Figure 1.

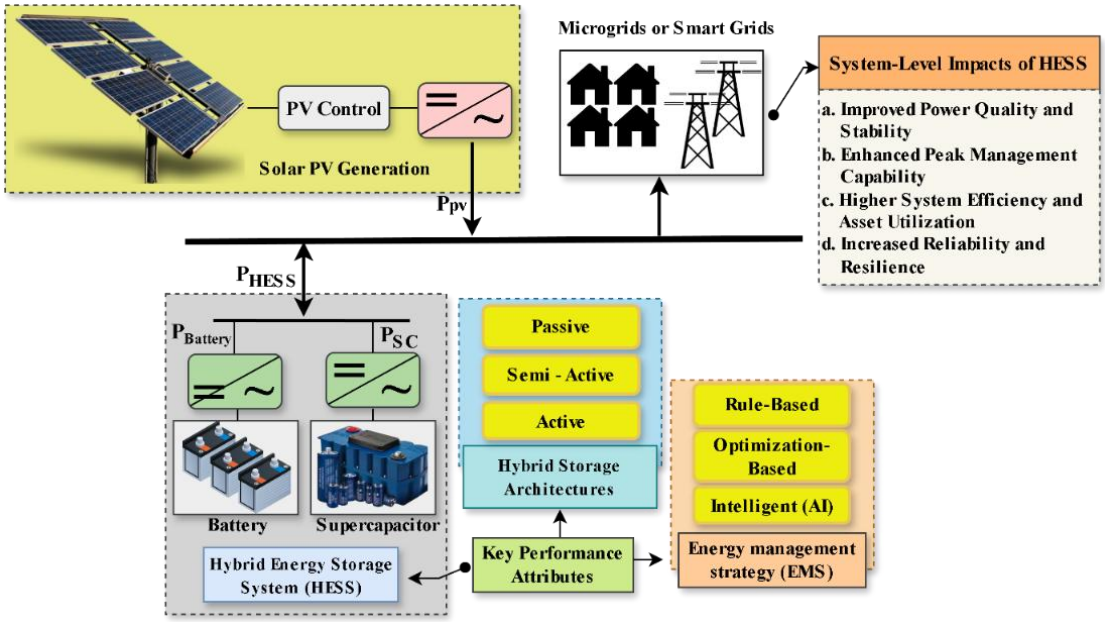


Figure 1. Overview of hybrid battery–supercapacitor for PV-based microgrids and smart grids

4.1. Islanded and grid-connected microgrids

In islanded microgrids, HESS play a critical role in maintaining system stability. The absence of grid support and limited system inertia make islanded operation highly sensitive to PV intermittency and sudden load disturbances [23]. Supercapacitors provide rapid transient power to support voltage and frequency regulation, while batteries deliver sustained energy for load balancing and backup supply. This coordinated multi-timescale operation significantly improves dynamic performance and reduces instability risks under fluctuating operating conditions [68].

In grid-connected microgrids, hybrid storage enhances operational flexibility and strengthens interaction with the utility grid [44]. Batteries are typically employed for energy arbitrage and peak shaving, whereas supercapacitors mitigate short-term power fluctuations and smooth PV output prior to grid injection. Hybrid systems also facilitate compliance with grid codes by reducing ramp-rate violations and improving voltage regulation performance [69].

Compared to battery-only systems, hybrid configurations offer superior transient response capability and reduced electrochemical stress, particularly under high PV penetration scenarios. Overall, hybrid battery–supercapacitor systems provide a flexible and scalable control solution that improves both technical performance and economic operation in diverse microgrid configurations.

4.2. Rural electrification and remote areas

Hybrid battery–supercapacitor systems are particularly attractive for rural electrification and remote microgrids, where maintenance access and component replacement may be limited [47]. In such environments, system reliability and longevity are critical design priorities. By absorbing high-power transients and sudden load variations, supercapacitors reduce current spikes and depth-of-discharge fluctuations experienced by batteries and power electronic interfaces. This mitigation of stress mechanisms can extend system lifetime and reduce life-cycle costs [70].

Rural microgrids often exhibit highly variable load profiles, limited generation diversity, and weaker grid infrastructure [71]. Hybrid storage enhances system resilience by enabling fast dynamic response while preserving sufficient energy capacity for prolonged supply periods. This capability is particularly valuable in off-grid and weak-grid conditions, where supply interruptions can have significant socio-economic impacts [72], [73]. Compared to conventional single-storage solutions, hybrid systems provide improved reliability under uncertain operating conditions, making them well suited for sustainable rural electrification initiatives.

4.3. Rural electrification and remote areas

One of the most established applications of hybrid battery–supercapacitor systems is PV power smoothing. Rapid PV output fluctuations caused by cloud transients are effectively compensated by supercapacitors due to their near-instantaneous response capability [50]. Meanwhile, batteries manage slower variations associated with daily irradiance cycles and longer-term energy balancing requirements [41]. This coordinated response reduces power oscillations and enhances voltage stability at the point of common coupling (PCC) [74].

Hybrid storage is also widely applied for load leveling and peak shaving in both microgrids and smart grids [75]. During peak demand periods, batteries supply energy to reduce grid stress and minimize energy procurement costs. Supercapacitors, on the other hand, support short-duration peaks and high ramp-rate events, thereby preventing excessive high-rate cycling of batteries [76].

This coordinated strategy improves overall system efficiency, enhances asset utilization, and supports grid-support services such as frequency regulation and power quality improvement [45]. Compared to battery-only systems, hybrid configurations demonstrate superior performance in handling multi-timescale variability while mitigating accelerated battery degradation. Across various applications, hybridization consistently improves PV smoothing, voltage stability, and battery lifetime compared to battery-only systems. Studies on battery-supercapacitor HESS in PV-based microgrids reviewed from various configurations, including grid-connected systems and EMS deployments are summarized in Table 2.

Table 2. Summary of battery–supercapacitor HESS in PV-based microgrids

Ref	Year	Application	Microgrid mode	EMS type	Main contribution
[50]	2024	PV smoothing and DC bus stability	Standalone DC microgrid	Data-driven EMS	Model-free control for HESS
[77]	2024	Power management in DC microgrid	DC microgrid	Rule/fuzzy/hybrid	Adaptive load control for HESS
[41]	2019	Power smoothing and battery stress	DC microgrid	SoC-based control	Smooths power fluctuation and extend battery life
[23]	2025	Grid-isolated microgrid stability	Grid-isolated DC microgrid	Fuzzy logic-based EMS	Enhances stability and resilience
[78]	2024	Decentralized control in low-voltage direct current (LVDC) microgrid	LVDC microgrid	Decentralized control	Decoupled high/low frequency allocation
[79]	2022	HESS energy management and bus stability	DC microgrid	Optimized droop/EMS	Improved voltage stabilization
[80]	2021	HESS and reactive control	Microgrid	Direct reactive power control (DRPC) and fuzzy logic controls	The load profile, power management
[81]	2025	Grid-connected PV/wind HESS	Microgrid	Meta-heuristic algorithms	Cost and efficiency optimization in energy system design
[24]	2024	Power fluctuation suppression	DC microgrids	The moving average filtering (MAF)	Decompose the low-frequency component and high-frequency component in HESS

5. COMPARATIVE PERFORMANCE, CHALLENGES, AND FUTURE PERSPECTIVES

5.1. Performance comparison and practical insights

Hybrid battery-supercapacitor configurations demonstrate superior performance in handling multi-timescale power variability compared to battery-only energy storage systems [81]. In battery-only systems, the battery must respond to both fast transients and long-term energy demands. This leads to frequent high-rate charge–discharge cycles and accelerated aging. Hybridization alleviates this burden by assigning fast power fluctuations to the supercapacitor [25].

One of the most significant benefits of hybrid systems is extending battery life. By absorbing high-power transients, supercapacitors reduce peak currents and variations in depth of discharge experienced by batteries [82], [83]. This mitigation of electrochemical stress slows degradation mechanisms and improves long-term capacity retention. As a result, hybrid systems often exhibit lower replacement frequency and improved operational sustainability [12].

Hybrid storage also enhances PV power smoothing and dynamic response. Supercapacitors provide near-instantaneous power support during cloud transients and sudden load changes. This capability improves voltage regulation and frequency stability, particularly in low-inertia and islanded microgrids [45]. In contrast, battery-only systems show slower response and limited effectiveness in managing rapid fluctuations [40].

However, these performance gains come with trade-offs. Hybrid systems introduce additional power electronic converters and more complex EMS. This increases system complexity, control effort, and upfront

cost [41]. Therefore, the design of hybrid storage systems requires an appropriate balance between performance gains and economic feasibility. Hybridized systems are most beneficial in applications with high PV penetration, frequent transients, or stringent power quality requirements, such as PV-based microgrids and smart grids [42].

5.2. Technical and system-level challenges

Hybrid battery-supercapacitor systems face several technical challenges that limit their widespread adoption. Optimal sizing remains a key issue, as both PV generation and load demand are highly variable [84]. Oversizing can increase capital costs, while undersizing reduces performance and reliability [85]. In addition, accurate sizing methods must account for the stochastic behavior of PVs, load uncertainties, and degradation [81].

Another critical challenge lies in modeling that considers degradation and predicts lifespan. While hybridization reduces stress on batteries, quantifying how much it extends their lifespan under real-world operating conditions remains challenging [86]. Most existing models rely on simplifying assumptions and may not capture complex aging mechanisms. Therefore, more accurate models for determining degradation are needed to support long-term planning and techno-economic assessments [87].

On the other hand, EMS strategies also face challenges in scalability and real-time implementation. Advanced optimization and intelligent EMS offer high performance. However, this requires reliable forecasting, computing resources, and robust communication infrastructure [88]. These requirements may be difficult to meet in small-scale or rural microgrids. Furthermore, ensuring reliable and interoperable operation of electronic power converters remains a practical concern, especially in harsh environmental conditions [89].

5.3. Economic, policy, and future research directions

From an economic perspective, the higher capital expenditure of hybrid systems remains a major barrier. Although hybridization can reduce operational costs and extend battery lifetime, its impact on the levelized cost of storage depends on system design and application conditions [90]. Life-cycle cost analysis, including maintenance and replacement savings, is essential for accurate evaluation [80]. Hybrid systems become economically viable under conditions of high PV variability and frequent transients. These conditions lead to intensive cycling in battery-only systems. As a result, battery degradation costs increase significantly.

In practical applications, hybridization is particularly beneficial in systems with high PV penetration and strict power quality requirements. Under these conditions, the value of improved dynamic performance and extended battery life becomes more significant. Conversely, in low-dynamic or cost-constrained systems, battery-only solutions may remain more economical. Therefore, economic justification depends on balancing performance gains with system cost and operational demands.

Policy and regulatory frameworks also influence the economic viability of hybrid systems. Existing grid codes and market structures often do not fully recognize fast-response services provided by supercapacitors [91]. Supportive policies that value ancillary services and hybrid storage capabilities can improve economic feasibility. This is especially important for accelerating deployment in smart grid applications.

Future research should focus on improving techno-economic modeling and decision-making frameworks for hybrid systems. AI-based energy management and predictive maintenance can further reduce operational costs [92]. Advances in storage technologies may also reduce cost gaps between batteries and supercapacitors. Additionally, integrating digital twins can enhance system optimization and lifecycle management in PV-based microgrids [50].

6. CONCLUSION

This review provides a structured and application-oriented analysis of hybrid battery–supercapacitor energy storage systems for PV-based microgrids and smart grids. The findings confirm that hybridization is most beneficial in systems with high PV variability, frequent power transients, and intensive cycling conditions. Under these conditions, battery-only systems experience accelerated degradation, making hybrid configurations a more reliable and sustainable solution. Thus, hybrid systems are particularly justified in high-dynamic and high-PV-penetration environments.

From an architectural perspective, semi-active HESS configurations offer the best trade-off for rural and medium-scale microgrids due to their balance between cost and performance. In contrast, active architectures are better suited to grid-connected and large-scale systems that require precise power control and advanced functionality. Passive configurations remain relevant only for low-cost and low-dynamic applications. This mapping highlights that architecture selection must be aligned with system scale and operational requirements.

In terms of EMS, rule-based and filter-based EMS are most appropriate for rural microgrids due to their simplicity, robustness, and low computational requirements. Optimization-based and intelligent EMS, on the other hand, are better suited for grid-connected systems where higher computational capability and data availability enable improved performance. Hybrid or hierarchical EMS approaches provide a practical compromise by combining simplicity and adaptability. This demonstrates that EMS selection is strongly dependent on system constraints and application context.

From a techno-economic perspective, hybrid systems become economically viable when the reduction in battery degradation, maintenance, and replacement costs offsets the additional investment in power electronics and control complexity. This condition is typically encountered in systems with high variability, strict power-quality requirements, or long operational lifetimes. In contrast, for low-dynamic or cost-constrained systems, battery-only solutions may remain more economical. Therefore, economic justification depends on a balance between performance gains and lifecycle cost.

The main contribution of this review is a unified framework linking HESS architectures, EMS strategies, and application scenarios in PV-based microgrids. Unlike existing studies that treat these aspects separately, this work offers a clear mapping between system design choices and operational conditions. This integrated perspective enables more informed decision-making for both researchers and system designers. It also highlights critical gaps in techno-economic modeling, real-time EMS implementation, and system-level optimization.

Future research should focus on developing scalable and cost-effective EMS, improving degradation-aware models, and advancing hybrid storage technologies. In addition, integrating digital twins and data-driven monitoring can enhance system optimization and predictive maintenance. Addressing these challenges will be essential to fully realize the potential of hybrid energy storage in next-generation PV-based microgrids and smart grids.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

The research related to human use has been complied with all the relevant national regulations and institutional policies in accordance with the tenets of the Helsinki Declaration and has been approved by the authors' institutional review board or equivalent committee.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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