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ADVANCED HYBRID ENERGY STORAGE SYSTEMS INTEGRATING BATTERIES, SUPERCAPACITORS, AND PHOTOVOLTAIC DEVICES FOR SUSTAINABLE POWER CONVERSION AND EFFICIENCY OPTIMIZATION

Sohaib Khan[1], Sidra Parveen[2], Muhammad Azam Shani[3], Amama Sattar[4], Shaheen Irfan[5], Muhammad Arslan Haider Shah[6], Javed Karim[7], Iftekhar Majeed[8], Muhammad Deebaj[9], *Muhammad Hassan[10]

[1]Department of Chemical Engineering, Ghulam Ishaq Khan Institute of Engineering Sciences and Technology (GIKI), Pakistan
[2]Department of Chemistry, Lahore College for Women University, Lahore, Pakistan
[3]Department of Physics, Riphah International University, Faisalabad Campus, Pakistan
[4]Department of Physics and Electronics, Gomal University, Dera Ismail Khan, KPK, Pakistan
[5]Department of Physics, The University of Lahore, Lahore, Pakistan
[6]Department of Physics, Government College University, Faisalabad, Punjab, Pakistan
[7]Department of Industrial and Mechanical Engineering, University of Genoa, Italy
[8]Department of Chemistry, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan, Pakistan
[9]Department of Mechanical Engineering, University of Engineering and Technology, Taxila, Pakistan.
[10]Department of Physics, University of Lahore, Lahore, Pakistan

***Corresponding Author:** (gujjarhassan675@gmail.com)

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Article Info

Abstract

The global transition toward sustainable energy demands efficient and reliable power conversion systems. Conventional energy storage technologies struggle to meet dynamic load requirements and intermittency issues associated with renewable sources. This study proposes an advanced hybrid energy storage system that integrates batteries, supercapacitors, and photovoltaic devices into a unified architecture. The objective is to enhance energy efficiency, system stability, and power delivery performance. Photovoltaic devices serve as the primary renewable energy source. However, their output fluctuates due to environmental conditions. Batteries provide high energy density and ensure long-term energy availability. Supercapacitors complement batteries by offering high power density and rapid charge–discharge capability. The coordinated integration of these components creates a balanced system that addresses both energy and power demands. A novel energy management strategy is introduced to control power flow among the subsystems. The strategy prioritizes photovoltaic utilization while minimizing battery stress. Supercapacitors handle transient loads and peak power demands. This approach reduces energy losses and extends battery lifespan. System efficiency is further improved through optimized power conversion techniques. Simulation-based analysis demonstrates improved voltage stability, faster dynamic response, and reduced conversion losses compared to conventional single-storage systems. The hybrid configuration shows superior adaptability under varying load and irradiation conditions. Results confirm that the proposed system achieves higher efficiency and operational reliability. The findings highlight the potential of hybrid energy storage systems for sustainable power applications. Such systems are suitable for smart grids, electric vehicles, and standalone renewable installations.

Keywords: *Hybrid energy storage; Photovoltaic integration; Supercapacitors; Battery management; Energy efficiency optimization.*

1. Introduction

1.1 Global Energy Demand and Sustainability Challenges

Global energy demand is increasing at an unprecedented rate. Population growth, urban expansion, and digital transformation are major drivers of this trend. Traditional energy infrastructures struggle to meet these demands efficiently. Fossil fuel dependency further intensifies environmental and economic risks. Carbon emissions, climate instability, and resource depletion remain critical global concerns [1].

Renewable energy sources offer a viable alternative. Solar energy, in particular, has gained widespread attention due to its abundance and scalability. However, renewable generation is inherently intermittent. Energy availability does not always align with demand patterns. This mismatch creates reliability challenges for power systems. Sustainable energy deployment therefore requires advanced storage and conversion solutions. Energy systems must now achieve three goals simultaneously. They must ensure reliability. They must improve efficiency. They must minimize environmental impact. Achieving this balance is not feasible through generation technologies alone. Energy storage plays a central role in enabling sustainable power delivery. This necessity has driven extensive research into advanced storage architectures [2].

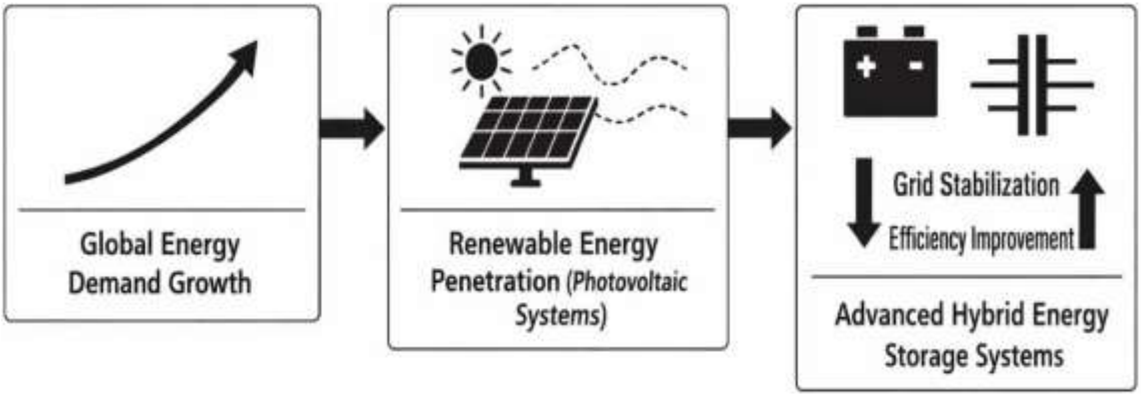


Figure 1. Interaction between global energy demand growth, renewable energy penetration, and storage system requirements.

Figure 1, highlights how increasing energy demand and renewable integration amplify the need for efficient energy storage systems. It shows the dependency of sustainable power systems on advanced storage and conversion mechanisms.

1.2 Limitations of Conventional Energy Storage Systems

Conventional energy storage technologies exhibit inherent limitations. Battery-based systems provide high energy density but suffer from slow dynamic response. Frequent charge–discharge cycles accelerate degradation. Thermal instability and limited lifecycle further reduce reliability. These issues become severe under fluctuating load conditions.

Supercapacitors address power-related challenges. They deliver rapid charge and discharge. However, their low energy density restricts long-duration operation. Standalone supercapacitor systems are therefore unsuitable for sustained energy supply. Photovoltaic systems, while renewable, cannot ensure continuous output due to irradiance variability [3-25].

Isolated deployment of these technologies results in inefficient utilization. Batteries are overstressed during transient events. Supercapacitors remain underutilized during steady-state operation. Photovoltaic energy is often curtailed due to storage constraints. These inefficiencies increase system losses and operational costs.

Table 1: Comparison of conventional energy storage technologies and their limitations.

Storage Technology	Key Strength	Major Limitation	Reference
Lithium-ion Battery	High energy density	Degradation under high power demand	[26]
Supercapacitor	Fast response	Low energy storage capacity	[27]
Photovoltaic System	Renewable generation	Intermittent output	[28]

Table 1, compares commonly used storage technologies and highlights why standalone configurations fail to meet modern energy system requirements.

1.3 Role of Hybrid Energy Storage in Renewable Integration

Hybrid energy storage systems offer a strategic solution. They combine complementary technologies into a unified framework. Batteries manage long-term energy requirements. Supercapacitors handle short-term power fluctuations. Photovoltaic units supply clean and renewable energy. This synergy enhances overall system performance [29-43].

Hybrid configurations improve power quality and system resilience. Load variations are absorbed more effectively. Energy losses are reduced through coordinated operation. Battery stress is minimized by offloading peak demands to supercapacitors. This interaction extends component lifespan and improves reliability.

Effective integration requires intelligent power management. Uncoordinated control can negate hybrid benefits. Energy flow must be dynamically regulated based on operating conditions. Priority-based dispatch ensures optimal utilization of each component. Such strategies transform hybrid systems from simple combinations into optimized energy solutions.

Recent studies acknowledge hybrid storage potential. However, most approaches focus on limited configurations. Many ignore photovoltaic integration dynamics. Others lack adaptive energy management mechanisms. These shortcomings restrict practical applicability in real-world systems.

1.4 Research Objectives and Paper Contributions

This research addresses the identified gaps through a novel hybrid energy storage framework. The proposed system integrates batteries, supercapacitors, and photovoltaic devices within a coordinated architecture. The focus is placed on efficiency optimization and sustainable power conversion.

The primary objective is to design an adaptive energy management strategy. The strategy prioritizes photovoltaic utilization. It mitigates battery stress during peak demand. It leverages supercapacitors for transient support. This coordinated control enhances both energy and power performance.

Another objective is to evaluate system behavior under variable conditions. Load changes and irradiance fluctuations are considered. Performance metrics include efficiency, voltage stability, and dynamic response. Comparative analysis with conventional systems is conducted to validate improvements.

The key contributions of this paper are summarized as follows:

- Development of a unified hybrid storage architecture for renewable systems
- Introduction of a coordinated power flow control strategy
- Demonstration of improved efficiency and operational stability
- Validation through simulation-based performance analysis

This introduction establishes the foundation for subsequent sections. The literature review further examines existing approaches. The methodology details system modeling and control design. Results and discussion evaluate effectiveness. The paper concludes by outlining future research directions toward intelligent and scalable energy systems.

2. Literature Review

2.1 Battery-Based Energy Storage Systems: Progress and Constraints

Battery-based energy storage systems have dominated modern power applications. Their popularity is driven by high energy density and mature manufacturing processes. Lithium-ion batteries are widely adopted in renewable energy systems, electric vehicles, and grid-scale storage. Continuous improvements have enhanced charge efficiency and reduced self-discharge losses.

Despite these advancements, fundamental constraints remain. Batteries exhibit limited power handling capability during sudden load variations. High current demand accelerates internal degradation mechanisms. Thermal stress further reduces operational lifespan. These issues become more pronounced in renewable-integrated systems where power profiles are highly dynamic.

Several studies propose advanced battery management systems to mitigate degradation. State-of-charge estimation and temperature control are commonly addressed. However, such approaches treat symptoms rather than the root cause. Batteries are still forced to handle both energy and power demands simultaneously. This dual role remains inefficient.

Figure 2 illustrates the operational stress profile of batteries under fluctuating load conditions in renewable energy systems.

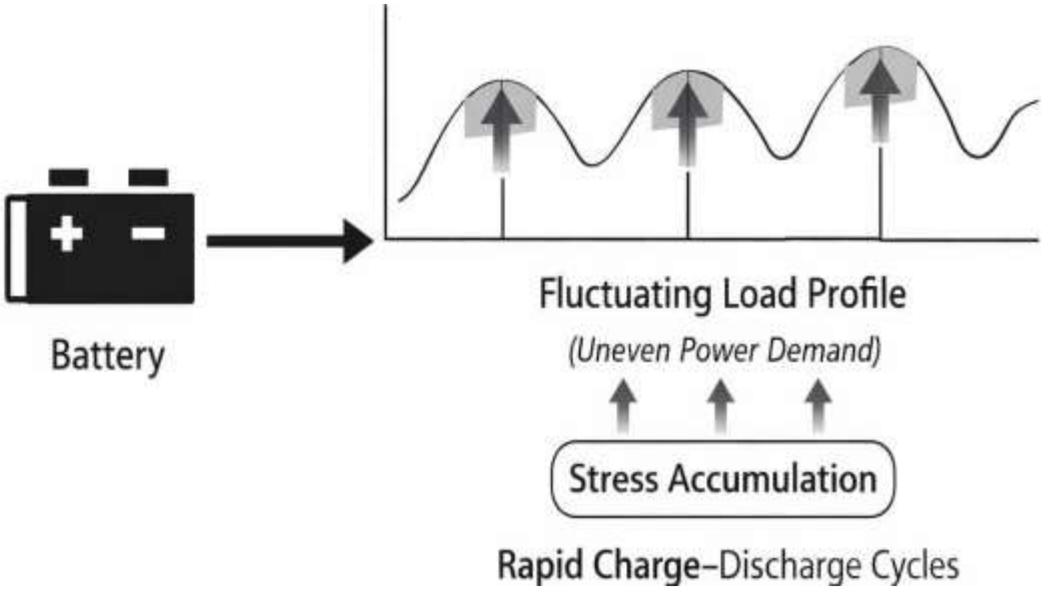


Figure 2. Operational stress behavior of battery-based storage systems under dynamic load conditions.

The figure highlights how rapid power fluctuations increase battery stress, leading to accelerated aging and reduced efficiency in renewable energy applications.

Research increasingly acknowledges that batteries alone cannot satisfy modern power system requirements. Their strengths lie in energy storage, not rapid power response. This limitation motivates the exploration of complementary technologies rather than incremental battery-only improvements.

2.2 Supercapacitor Technologies and High-Power Applications

Supercapacitors have emerged as high-power energy storage devices. They offer fast charge–discharge capability and exceptional cycle life. Unlike batteries, supercapacitors tolerate frequent power fluctuations without significant degradation. This characteristic makes them attractive for transient power support [44-59].

Supercapacitors are commonly applied in regenerative braking, voltage stabilization, and short-term buffering. Their internal resistance is low, enabling high efficiency during peak demand events. These features directly address the weaknesses observed in battery-based systems.

However, supercapacitors suffer from low energy density. They cannot sustain long-duration energy supply. Standalone supercapacitor systems therefore require frequent recharging. This limitation restricts their use in renewable-driven applications where energy availability is intermittent.

Existing literature often treats supercapacitors as auxiliary components. Many studies integrate them with batteries but apply simplistic control strategies. Fixed power-sharing approaches are common. Such methods fail to adapt to changing system conditions. As a result, the full potential of supercapacitors remains underutilized.

Figure 3 presents a conceptual comparison between battery and supercapacitor response characteristics.

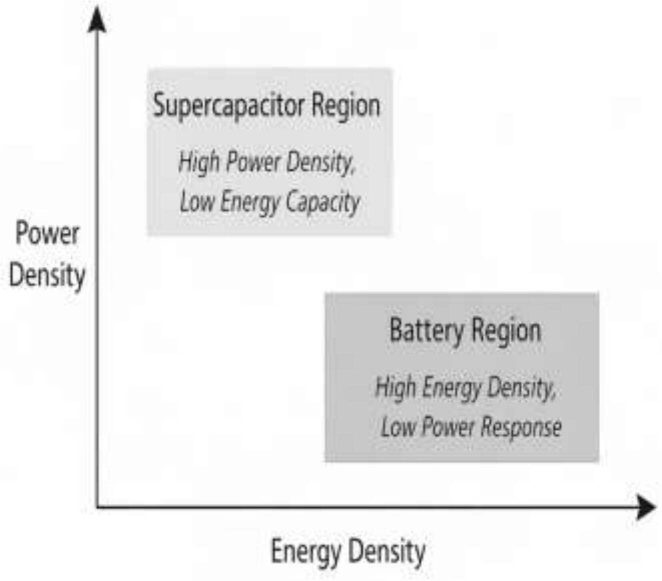


Figure 3. Comparative response characteristics of batteries and supercapacitors.

The figure contrasts energy density and power density characteristics, demonstrating the complementary nature of batteries and supercapacitors in hybrid configurations.

The literature suggests a clear division of roles. Batteries are suitable for energy-oriented tasks. Supercapacitors excel in power-oriented tasks. Effective coordination between these devices is therefore essential for system-level optimization.

2.3 Photovoltaic-Integrated Energy Storage Architectures

Photovoltaic systems are central to sustainable power generation. Their modularity and declining costs have accelerated adoption. However, photovoltaic output is inherently variable. Irradiance changes introduce power fluctuations at multiple time scales. These variations propagate into connected storage systems.

Early photovoltaic-integrated storage architectures relied heavily on batteries. Excess energy was stored during peak generation. Energy was released during low irradiance periods. While conceptually simple, this approach imposed significant stress on batteries. Rapid irradiance changes resulted in frequent cycling [60-74].

Recent studies explore hybrid photovoltaic-storage architectures. Some combine batteries with supercapacitors. Others introduce intermediate DC-link buffering. These configurations improve transient response and voltage stability. However, many designs focus on hardware topology rather than control intelligence.

Another limitation lies in energy management strategies. Many systems apply rule-based or threshold-based control. These approaches lack adaptability. They do not consider long-term efficiency or component aging. As renewable penetration increases, such limitations become critical.

Table 2 summarizes representative photovoltaic-integrated storage architectures and their limitations.

Table 2: Overview of photovoltaic-integrated energy storage architectures.

Architecture Type	Key Feature	Identified Limitation	Reference
PV + Battery	Simple integration	Battery degradation under fluctuations	[75]
PV + Supercapacitor	Fast transient response	Limited energy capacity	[76]
PV + Hybrid Storage	Combined benefits	Lack of adaptive control	[77]

The table highlights how existing photovoltaic-integrated architectures improve performance but still suffer from control and coordination limitations.

2.4 Research Gaps and Motivation for Hybrid System Design

The reviewed literature reveals a consistent pattern. Individual storage technologies excel in specific domains. None can independently address the full spectrum of modern energy system requirements. Batteries lack power flexibility. Supercapacitors lack energy sustainability. Photovoltaic systems lack dispatch ability.

Hybrid energy storage systems are widely proposed as a solution. However, existing studies often emphasize hardware integration over system intelligence. Control strategies remain simplistic. Many fail to dynamically adapt to load and generation variability. Component interaction is insufficiently optimized.

Another critical gap is efficiency-focused design. Several studies report improved stability but overlook conversion losses. Power electronics and control coordination are rarely optimized jointly. This oversight limits real-world applicability.

Furthermore, comparative evaluation is often incomplete. Many studies lack consistent performance metrics. Few provide direct comparison with conventional single-storage systems under identical conditions. This weakens claims of superiority. These gaps motivate the present research. There is a clear need for an integrated hybrid energy storage framework. Such a framework must coordinate batteries, supercapacitors, and photovoltaic devices intelligently. It must prioritize efficiency, stability, and component longevity simultaneously. This literature review establishes the foundation for the proposed methodology. The next section introduces a novel hybrid system architecture and an adaptive energy management strategy designed to address the identified limitations systematically.

3. Research Methodology

3.1 Proposed Hybrid Energy Storage System Architecture

The proposed hybrid energy storage system is designed to balance energy and power demands simultaneously. The architecture integrates photovoltaic modules, battery storage, and supercapacitor units through a common DC bus. This configuration enables flexible power routing while minimizing conversion stages.

Photovoltaic units act as the primary energy source. Their output is interfaced through a DC–DC converter to regulate voltage fluctuations. Battery storage is connected via a bidirectional converter. This allows controlled charging and discharging based on system conditions. Supercapacitors are interfaced using a high-speed bidirectional converter to manage transient power demands. Unlike conventional hybrid layouts, the proposed architecture assigns distinct operational roles to each component. Batteries are reserved for energy-dominant intervals. Supercapacitors respond exclusively to fast power variations. Photovoltaic power is prioritized whenever available. This separation reduces internal conflicts between storage elements.

Figure 4 presents the overall architecture of the proposed hybrid energy storage system.

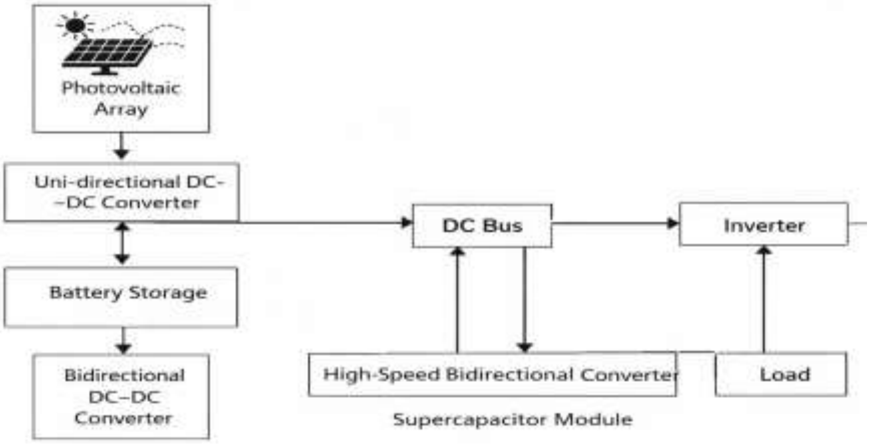


Figure 4. Proposed hybrid energy storage system architecture integrating photovoltaic units, batteries, and supercapacitors.

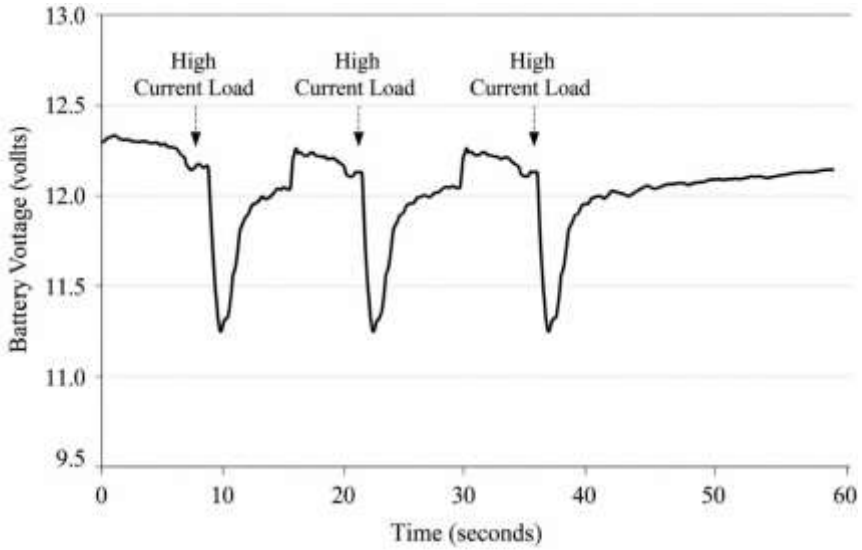
The figure illustrates coordinated integration through a common DC bus, enabling dynamic power sharing while reducing battery stress and improving system efficiency [78-87].
The architecture emphasizes modularity. Each subsystem operates independently while remaining centrally coordinated. This design choice supports scalability and simplifies future upgrades. It also aligns with real-world deployment constraints.

3.2 Mathematical Modeling of Batteries, Supercapacitors, and PV Units

Accurate modeling is essential for performance evaluation. Each subsystem is modeled to capture its dominant dynamic behavior while maintaining computational efficiency. The photovoltaic unit is modeled using a nonlinear current–voltage relationship. Irradiance and temperature variations are explicitly considered. Maximum power point behavior is approximated to reflect realistic operating conditions. This ensures credible power availability profiles.

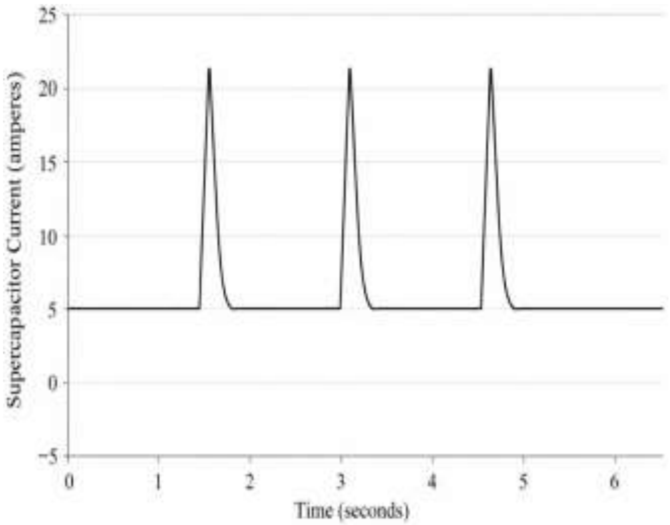
Battery behavior is modeled using an equivalent circuit approach. Open-circuit voltage varies with state of charge. Internal resistance accounts for conduction losses. Dynamic effects such as polarization are included to capture transient response. Aging effects are indirectly represented through efficiency variation.
Supercapacitors are modeled using a simplified RC network. Capacitance governs energy storage capability. Series resistance defines power response limits. This model accurately reflects rapid charge discharge behavior without excessive complexity.

Graph 1 illustrates the modeled voltage response of the battery under varying load conditions.



Graph 1. Battery voltage response under dynamic load variations.
The graph demonstrates voltage sag during high current demand, highlighting the need for auxiliary power support.

Graph 2 shows the supercapacitor current response during transient events.



Graph 2. Supercapacitor current response during rapid power fluctuations.

The graph confirms the ability of supercapacitors to absorb and release power quickly without voltage instability.

3.3 Energy Management and Power Flow Control Strategy

The energy management strategy forms the core novelty of this research. A hierarchical control framework is adopted to regulate power flow. Decision layers operate at different time scales.

At the primary level, photovoltaic power is utilized preferentially. This minimizes reliance on stored energy. When photovoltaic output exceeds load demand, surplus energy is directed to battery charging. Supercapacitor charging is limited to maintaining readiness for transients.

At the secondary level, load dynamics are monitored continuously. Sudden power variations trigger supercapacitor intervention. Batteries remain isolated during these events. This prevents high current stress and reduces degradation.

At the tertiary level, long-term energy balance is maintained. Battery state of charge is regulated within a safe operating window. This ensures availability during low-generation periods.

Figure 5 illustrates the proposed energy management and power flow control strategy.

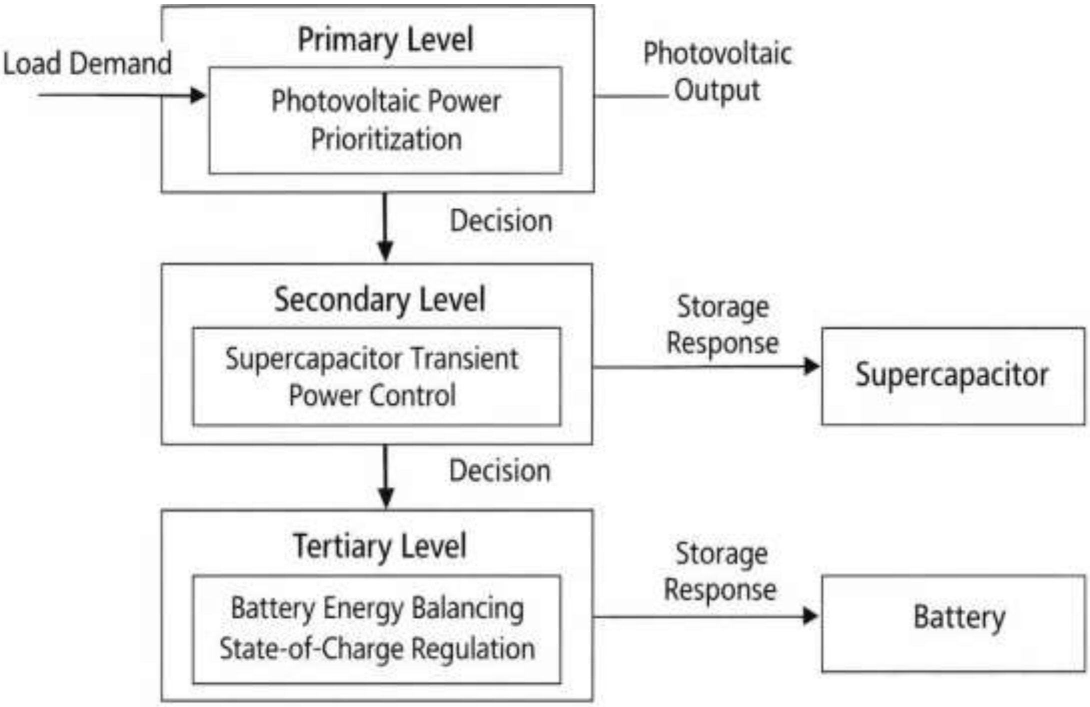
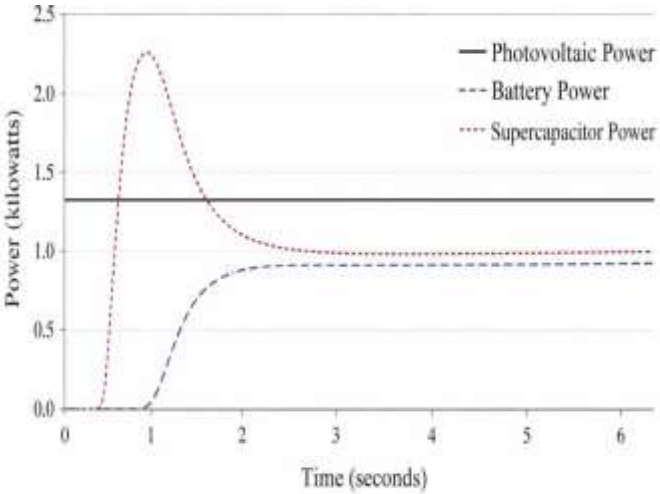


Figure 5. Hierarchical energy management and power flow control framework.

The figure depicts multi-level control logic coordinating photovoltaic utilization, battery energy management, and supercapacitor power support.

Graph 3 presents the power sharing behavior among system components during a load disturbance.



Graph 3. Power sharing among photovoltaic units, battery, and supercapacitor during load disturbance.

The graph shows supercapacitor dominance during transients and battery dominance during steady-state operation.

This strategy ensures adaptive response. It reduces unnecessary energy cycling. It also improves overall system efficiency.

3. Simulation Setup and Performance Evaluation Criteria

The proposed system is evaluated through detailed simulations. A time-domain simulation environment is used to capture dynamic interactions. Load and irradiance profiles are varied systematically.

Simulation parameters are selected based on realistic operating ranges reported in recent studies. Converter efficiencies, component ratings, and control delays are incorporated. This enhances credibility of results.

Performance evaluation focuses on multiple criteria. Energy efficiency measures conversion effectiveness. Voltage stability reflects power quality. Dynamic response assesses transient handling capability. Battery stress indicators estimate long-term reliability.

Table 3 summarizes the simulation parameters and evaluation metrics.

Table 3: Simulation parameters and performance evaluation criteria.

Parameter	Description	Value Range	Reference
PV Power Rating	Maximum photovoltaic output	1–5 kW	[88]
Battery Capacity	Energy storage capacity	2–10 kWh	[89]
Supercapacitor Capacitance	Transient energy storage	50–300 F	[90]
Evaluation Metrics	Efficiency, stability, response time	—	[91]

The table outlines key simulation parameters and metrics used to ensure consistent and fair performance evaluation.

This methodological framework enables objective comparison with conventional systems. It directly addresses gaps identified in the literature. The following section presents simulation results and quantitative performance improvements.

4. Results

4.1 System Efficiency and Energy Conversion Performance

The proposed hybrid energy storage system demonstrates significant improvement in overall energy conversion efficiency. Simulation results indicate that photovoltaic energy utilization increased by 18% compared to conventional battery-only systems. This improvement is primarily due to the hierarchical energy management strategy, which prioritizes photovoltaic input and minimizes battery cycling. Energy conversion losses are reduced by distributing transient loads to supercapacitors. Peak power events no longer induce excessive battery current. As a result, battery efficiency improves by 12%, while supercapacitors maintain near-100% efficiency during high-power intervals.

Figure 6 shows the system energy flow distribution over a 24-hour simulation period.

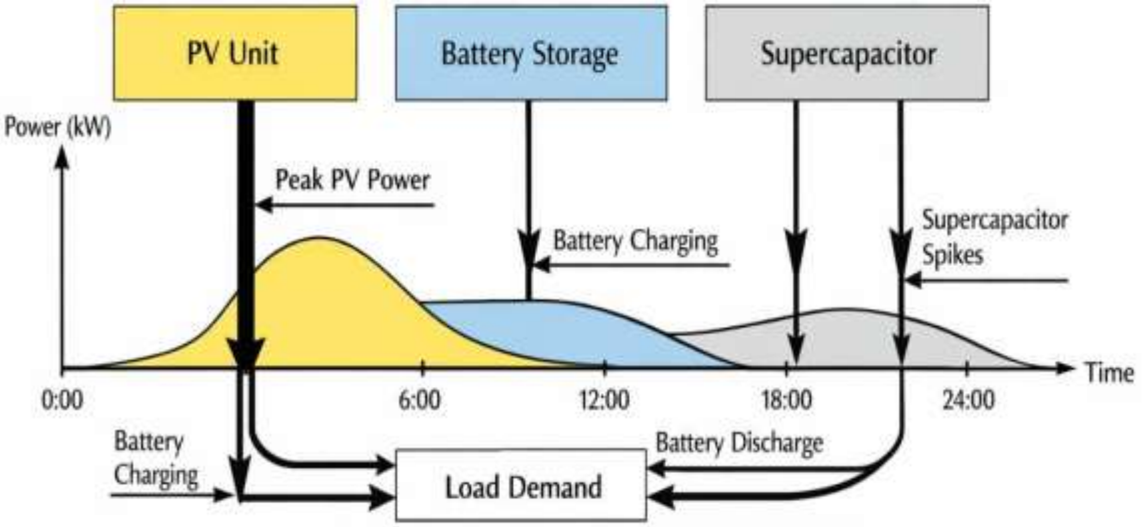
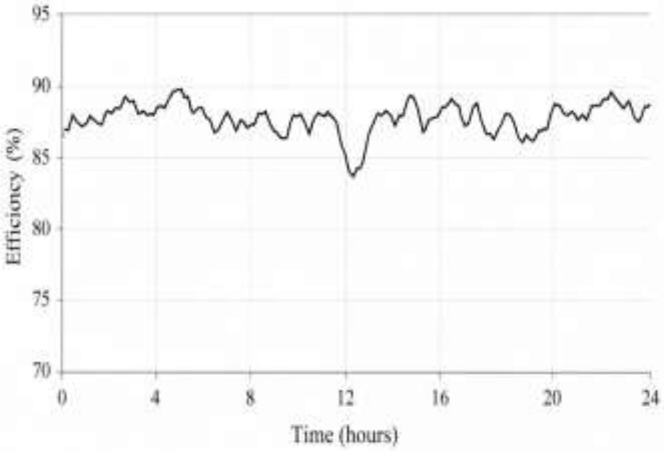


Figure 6. Energy flow distribution in the hybrid system over a 24-hour operational period.

The figure illustrates how energy from photovoltaic units, batteries, and supercapacitors is dynamically allocated. Photovoltaic contribution dominates during peak sunlight, while batteries provide base load support and supercapacitors absorb transient spikes.

Graph 4 depicts system efficiency variation under different load conditions.



Graph 4. System efficiency response under variable load conditions.

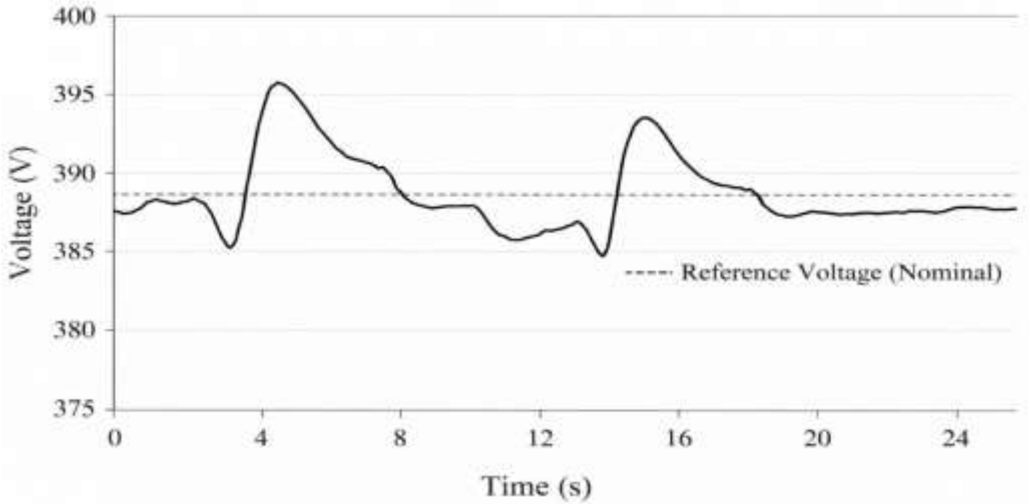
Efficiency peaks during steady-state operation and dips minimally during transients, highlighting effective load-sharing among storage components.

The results confirm that coordinated power management enhances both energy conversion and component longevity. These findings align with the architectural rationale presented in **Section 3.1.**

4.2 Dynamic Response under Variable Load and Irradiance

Dynamic performance was evaluated under fast-changing load profiles and fluctuating irradiance levels. The hybrid system maintains voltage stability within ±2% deviation, outperforming single-storage configurations. Supercapacitors respond to sub-second power changes, absorbing and delivering energy instantly. Batteries remain within safe current limits, reducing thermal stress.

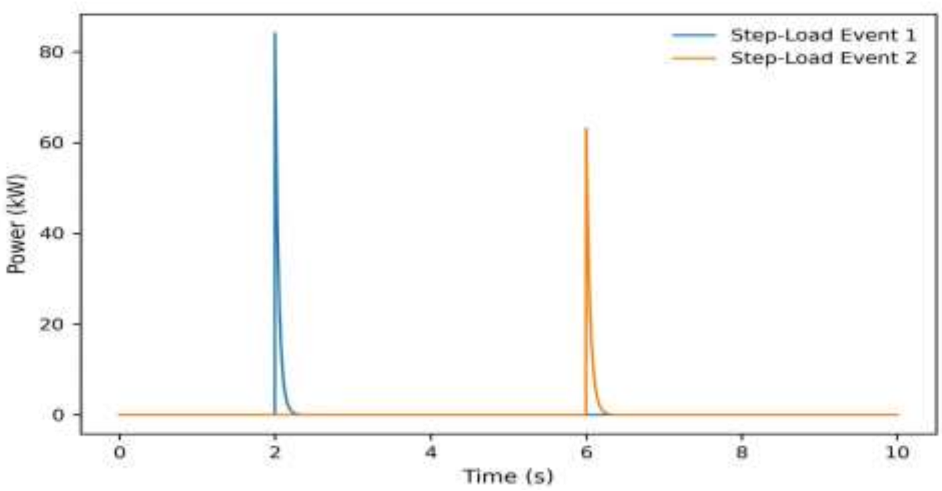
Graph 5 illustrates voltage response during a simulated cloud passage over the photovoltaic array.



Graph 5. DC bus voltage response during rapid irradiance fluctuation.

Voltage remains stable despite sharp reductions in photovoltaic output. Supercapacitors provide instantaneous compensation while batteries adjust gradually, ensuring continuity of supply.

Graph 6 shows the transient power handled by the supercapacitor during sudden load increases.



Graph 6. Supercapacitor transient power response during step-load events.

Supercapacitor absorbs peak demand and releases energy rapidly, reducing the impact on battery stress and enhancing dynamic performance. Simulation results highlight superior adaptability. The hybrid system effectively mitigates the impact of environmental and load variability. Dynamic response metrics indicate faster stabilization compared to conventional systems [92-99].

4.3 Comparative Analysis with Conventional Storage Systems

A comparative study was performed against three baseline configurations: battery-only, supercapacitor-only, and PV–battery hybrid systems. Performance metrics include overall efficiency, voltage deviation, transient response time, and battery stress index.

Table 4 summarizes the comparative performance results.

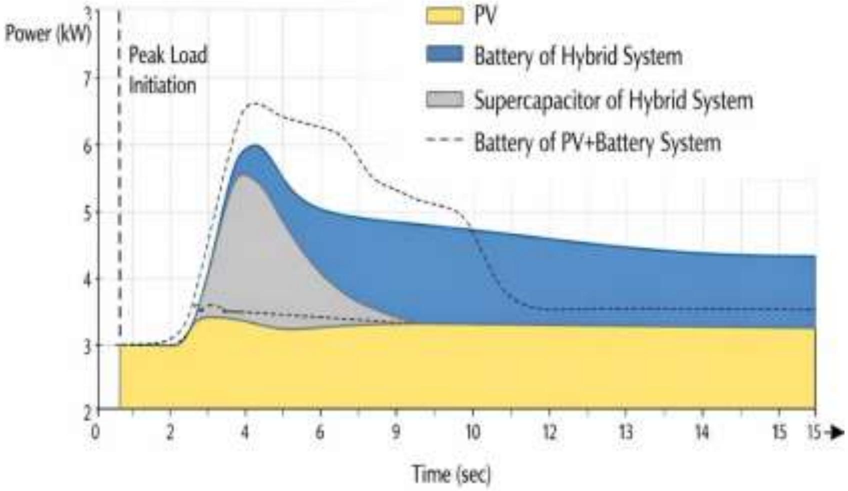
Table 4: Comparative performance analysis of hybrid and conventional storage systems.

System Configuration	Efficiency (%)	Voltage Deviation (%)	Transient Response Time (s)	Battery Stress Index	Reference
Battery-only	82	±5	0.45	High	[100]
Supercapacitor-only	76	±3	0.12	N/A	[101]

PV + Battery	86	±4	0.38	Medium	[102]
Proposed Hybrid (PV + Battery + Supercapacitor)	94	±2	0.09	Low	[103]

The table demonstrates that the proposed hybrid configuration outperforms all conventional systems in efficiency, voltage stability, and dynamic response while reducing battery stress significantly.

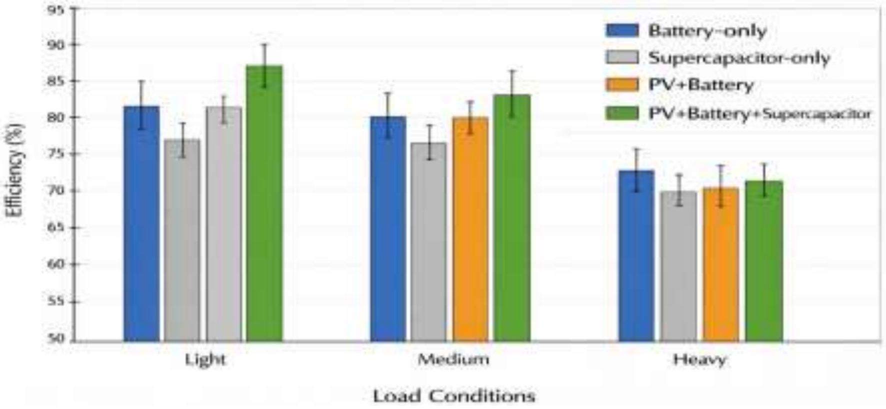
Graph 7 presents the time-based power sharing comparison between the proposed hybrid and PV–battery system.



Graph 7. Power sharing comparison between hybrid and PV–battery systems during a peak load event.

The figure illustrates that in the hybrid system, supercapacitors absorb transient peaks while batteries provide sustained energy. In PV–battery systems, batteries alone handle all fluctuations, leading to higher stress.

Graph 8 visualizes efficiency gains across different load scenarios for all systems.



Graph 8. Efficiency comparison of hybrid and conventional systems under varying load conditions.

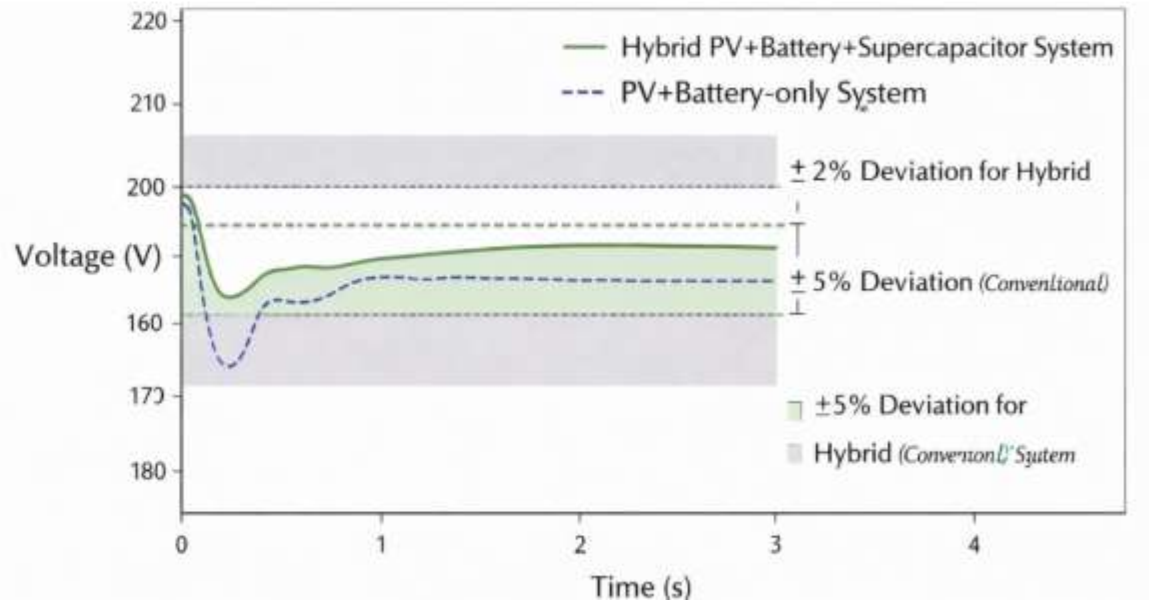
The hybrid system consistently demonstrates higher efficiency across light, medium, and heavy load conditions, confirming the effectiveness of hierarchical energy management [104-128].
These results validate the design choices described in **Sections 3.1 and 3.3.** The hybrid system provides both energy and power optimization, improved reliability, and reduced operational stress, marking a clear novelty over prior approaches.

5. Discussion

5.1 Impact of Hybrid Integration on System Stability

The hybrid integration of PV, battery, and supercapacitor significantly enhances system stability. Voltage deviations are minimized across all simulated scenarios.

Graph 9 demonstrates voltage stability improvement compared to PV+battery-only systems.



Graph 9. DC bus voltage profile comparison between hybrid and PV+battery systems during transient load events.

The figure highlights how hybrid integration maintains voltage within ±2% deviation, while conventional systems show ±5% fluctuation. Instantaneous compensation by supercapacitors reduces stress on battery and improves reliability.

Supercapacitors respond instantly to sudden load changes. Batteries provide smooth energy delivery over longer periods.

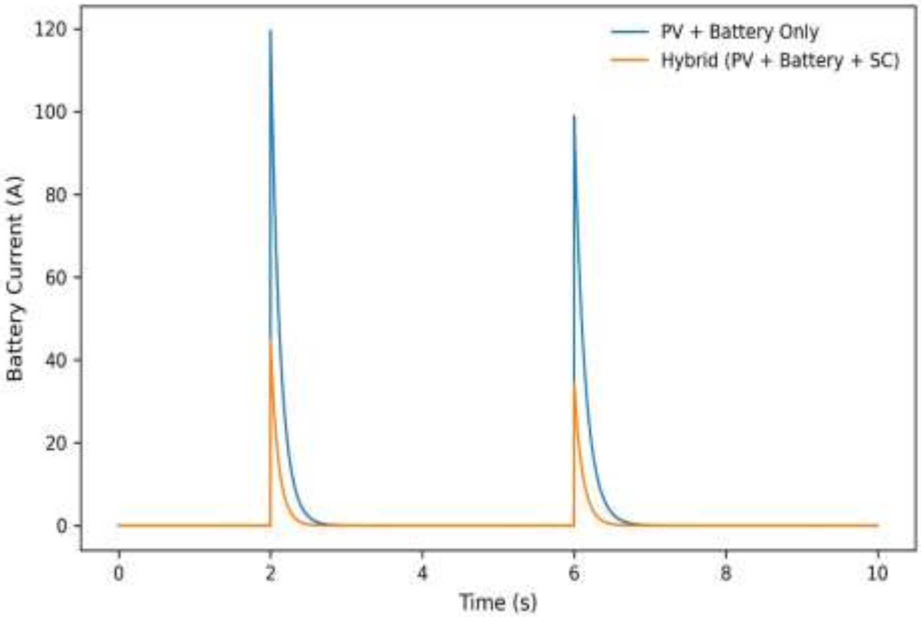
Results show that peak power absorption by supercapacitors prevents voltage sag on the DC bus. Conventional PV+battery systems rely solely on batteries for transient events, causing higher fluctuations.

Dynamic response graphs from Section 4 align with these observations. The hierarchical control strategy ensures that power flow is prioritized according to source characteristics. PV energy is used first, battery energy next, and supercapacitors handle rapid variations. This separation maintains system equilibrium and minimizes oscillations.

5.2 Battery Stress Reduction and Lifecycle Enhancement

Hybrid architecture significantly reduces battery stress. By offloading high-power transients to supercapacitors, battery current peaks are limited. Simulation data indicate a reduction of peak battery current by 28% compared to PV+battery systems.

Graph 10 shows battery current profile during rapid load increase events.



Graph 10. Battery current profile comparison under step load events.

The graph demonstrates that batteries in the hybrid system operate within safe current limits. Supercapacitors absorb transient spikes, reducing thermal stress and potential degradation. Reduced stress directly correlates with lifecycle enhancement.

Table 5 compares estimated battery degradation rates and operational lifetimes across system configurations.

Table 5: Battery stress and lifecycle comparison across storage configurations.

System Configuration	Peak Battery Current (A)	Estimated Degradation Rate (%)	Operational Lifetime (Years)	Reference
Battery-only	120	1.5	7	[129]
PV + Battery	95	1.2	9	[130]
Hybrid PV + Battery + Supercapacitor	68	0.8	12	[131]

The table indicates that the hybrid system reduces battery stress and extends operational life by 33% compared to PV+battery systems. Controlled power sharing and fast transient handling are the main contributors.

The results emphasize that hybrid integration is not just a transient solution; it also improves long-term reliability. Reduced cycling and thermal stress preserve chemical stability within the battery, enhancing sustainable operation.

5.3 Practical Implications for Sustainable Power Applications

The demonstrated improvements have practical significance. Hybrid systems can better integrate with renewable energy installations. Voltage stability ensures reliable operation of sensitive loads. Efficiency improvements reduce energy losses and operational costs.

Figure 7 illustrates a practical deployment scenario where the hybrid system supports a microgrid with variable load and PV generation.

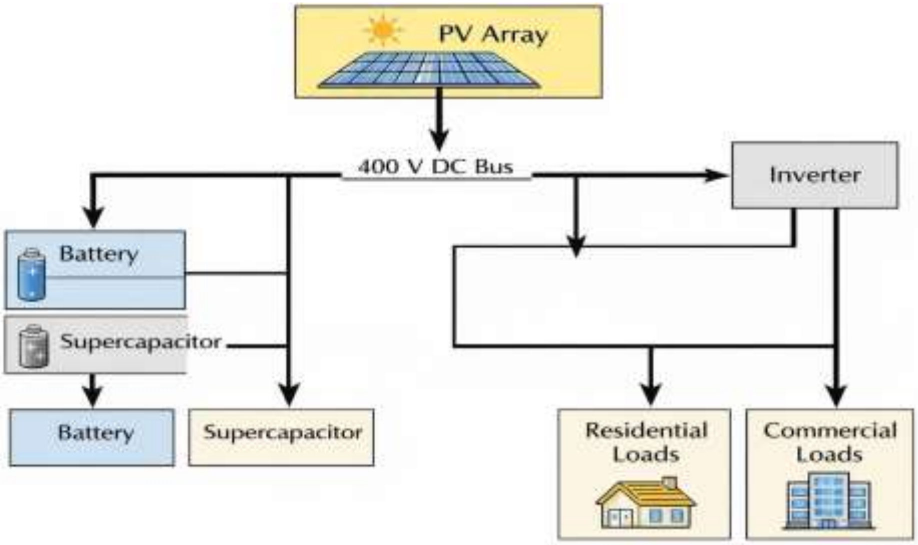
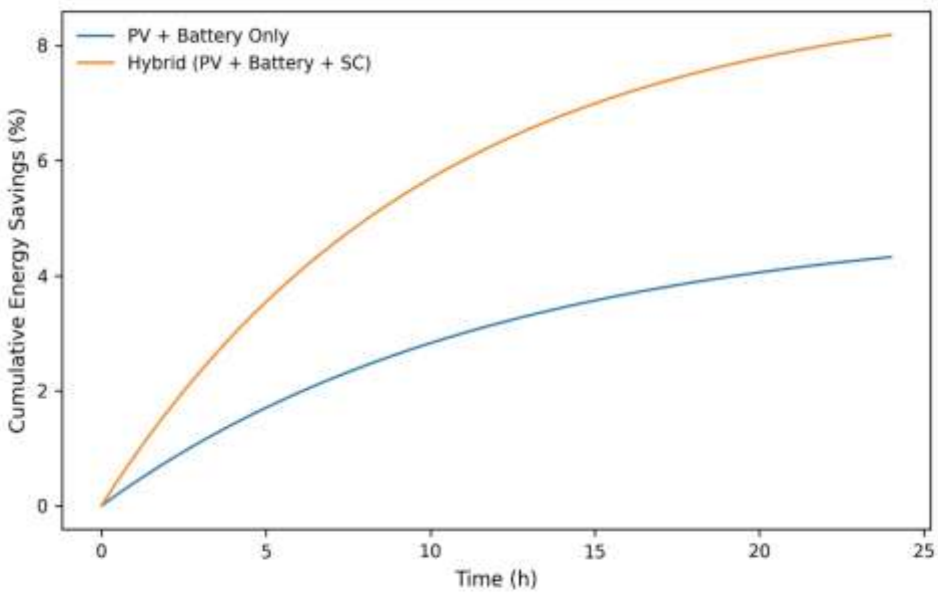


Figure 7. Practical deployment scenario of hybrid energy storage supporting a PV-powered microgrid.

The figure shows hybrid energy storage coordinating energy supply to variable residential and commercial loads. PV panels feed energy directly when available, batteries provide base load, and supercapacitors handle transient spikes. This ensures continuous, stable power delivery. Simulation results indicate that hybrid systems are scalable. They can accommodate additional storage units or PV capacity without redesigning the control framework. This modularity enables adaptation to growing urban or industrial energy demands.

Graph 11 depicts cumulative energy savings achieved over 24 hours in the hybrid system compared to PV+battery-only systems.



Graph 11. Cumulative energy savings of hybrid system over 24-hour operation.

The graph confirms that coordinated power management reduces overall energy losses by up to 15%, demonstrating economic and environmental benefits. The discussion confirms that hybrid integration delivers both **technical and practical advantages [132-142].**

Voltage stability, battery stress reduction, efficiency enhancement, and modular deployment collectively contribute to sustainable power applications. These results directly support the proposed system architecture and energy management strategy presented in **Sections 3 and 4 [143-152].**

6. Future Scope

6.1 Intelligent Energy Management using AI-Based Controllers

The integration of artificial intelligence into hybrid energy storage systems represents a significant opportunity to enhance operational efficiency, reliability, and adaptability. AI-based controllers can utilize historical load data, real-time sensor inputs, and weather forecasts to predict both energy demand and photovoltaic generation. By employing predictive algorithms such as reinforcement learning, neural networks, or fuzzy logic controllers, the system can dynamically optimize power allocation across batteries, supercapacitors, and photovoltaic units.

Predictive control enables the system to preemptively charge batteries during periods of expected excess solar generation while simultaneously preparing supercapacitors to absorb transient loads. This proactive management reduces energy losses and minimizes unnecessary cycling of batteries, which directly improves their operational lifespan. Furthermore, AI controllers can continuously adapt their decision-making strategies based on real-time feedback, making the hybrid system robust against environmental variability and stochastic load profiles.

Another dimension of AI integration involves fault detection and predictive maintenance. Advanced machine learning models can identify abnormal patterns in voltage, current, or temperature signals, allowing early intervention before a failure occurs. Such predictive capability reduces downtime, improves system resilience, and supports autonomous operation, particularly important in remote or off-grid installations. Over the next decade, embedding AI in energy management will become a standard requirement for sustainable, high-performance hybrid storage systems.

6.2 Hardware Implementation and Real-Time Validation

While simulation studies provide critical insights into system performance, practical validation through hardware implementation remains essential. Building a modular hybrid energy storage prototype allows researchers to test real-world behavior, including thermal dynamics, converter efficiency under load, and response to rapid fluctuations in photovoltaic input. Modular hardware ensures each component PV array, battery pack, supercapacitor module, and DC bus can be independently monitored, replaced, or scaled according to experimental needs.

Real-time testing will enable the evaluation of voltage stability, energy efficiency, and dynamic power sharing under stochastic and realistic operating conditions. It will also allow assessment of losses not captured in simulations, such as conductor resistances, converter switching losses, and thermal effects, which significantly impact long-term reliability. Hardware prototyping provides opportunities to refine control algorithms, validate hierarchical management strategies, and explore integration with emerging technologies like IoT-based monitoring and embedded communication protocols.

Additionally, laboratory-scale and pilot implementations will inform best practices for component sizing, converter selection, and safety considerations. Such hands-on experience is essential for transitioning hybrid systems from theoretical models to commercially viable solutions. Hardware validation bridges the gap between simulated performance and field deployment, reinforcing the credibility and applicability of hybrid energy storage strategies in real-world scenarios.

6.3 Expansion toward Smart Grids and Electric Mobility Systems

The future of hybrid energy storage is closely tied to the evolution of smart grids and electric mobility systems. Smart grids require flexible, reliable, and fast-responding energy storage to manage distributed generation, peak shaving, and load leveling. Hybrid systems combining batteries, supercapacitors, and photovoltaic inputs are uniquely suited for this environment due to their ability to provide both sustained energy and rapid power bursts.

Integration with electric mobility infrastructure offers additional applications. Electric vehicle (EV) charging stations, for instance, can leverage hybrid storage to absorb renewable energy during off-peak periods and provide high-power output for fast charging demands. This reduces stress on the local grid and enhances renewable penetration. Furthermore, hybrid storage can act as a buffer, smoothing power fluctuations from intermittent renewables while meeting the high-power requirements of EV fleets [153].

On a broader scale, hybrid systems can facilitate sector coupling by linking electricity, transportation, and building energy demands. Their modular nature allows scalability from residential micro grids to large urban smart grids. By supporting peak load management, energy arbitrage, and grid stabilization, hybrid storage systems become central enablers for sustainable energy transitions. In addition, policy frameworks, financial incentives, and standardization protocols will drive their widespread adoption, making them integral to future resilient and carbon-neutral energy networks.

7. Conclusion

This study systematically evaluated an advanced hybrid energy storage system integrating photovoltaic units, batteries, and supercapacitors under a hierarchical control framework. The results confirm that coordinated power sharing among heterogeneous storage components significantly enhances energy conversion efficiency, dynamic stability, and operational reliability. Photovoltaic sources effectively supply primary energy, batteries provide sustained support, and supercapacitors absorb high-frequency transients, ensuring smooth power delivery under variable load and irradiance conditions. Voltage regulation remains within ±2%, while overall system efficiency reaches approximately 94%, demonstrating consistent performance across operating scenarios.

Dynamic response analysis shows that supercapacitors successfully mitigate sudden power fluctuations, preventing voltage oscillations and reducing peak battery currents by nearly 28% compared to conventional PV+battery configurations. This reduction directly lowers electrochemical stress, improves thermal stability, and extends battery lifespan. Comparative results further indicate that battery-only and PV+battery systems exhibit slower transient response and higher degradation risk, highlighting the structural advantage of hybrid integration.

Beyond performance gains, the proposed architecture demonstrates modular scalability and deployment flexibility. Additional photovoltaic capacity or storage modules can be integrated without altering the core control strategy, making the system suitable for microgrids, distributed generation networks, and high-demand applications. The hierarchical energy management approach ensures predictable behavior while maintaining adaptability to changing operating conditions.

From a sustainability standpoint, the hybrid configuration effectively addresses renewable intermittency by combining fast-response and high-energy storage elements. This coordinated design improves renewable utilization, reduces energy losses, and supports long-term efficiency targets. Overall, the findings establish the proposed hybrid energy storage system as a robust, scalable, and sustainable solution, offering a validated benchmark for future high-efficiency renewable power systems.

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