# Development of a Hybrid Solar Cell–Battery System with Integrated Supercapacitor and AI-Based Energy Management – A Literature Review

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**Abstract: Hybrid energy storage systems (HESS) that combine batteries and supercapacitors are increasingly deployed in off-grid photovoltaic (PV) systems to handle both steady-state energy needs and transient power surges. Concurrently, AI-enabled energy management strategies have emerged to coordinate power sharing and to extend storage lifetime. This review synthesizes recent and closely related studies focusing on PV battery supercapacitor architectures and advanced energy management approaches. Control strategies and reported outcomes are summarized, and cross-cutting insights on sizing, protection constraints, and AI-based control are highlighted. A reference architecture and research agenda for off-grid applications are presented.**

***Keywords:*** *Hybrid Energy Storage, Supercapacitor, Battery, Photovoltaic Microgrid, Energy Management System, AI, Off-Grid.*

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## I. INTRODUCTION

Solar PV is a viable option for electrifying remote communities and building resilient microgrids. However, solar PV output is inherently intermittent. Batteries provide the necessary energy capacity but suffer accelerated degradation when forced to handle high-frequency, high-amplitude power fluctuations. Supercapacitors (SCs) have high power capacity and long life, and they support batteries by handling quick changes in power. The hybridization of batteries and SCs is therefore a natural design pattern in off-grid PV systems. Beyond hardware, modern Energy Management Systems (EMS) increasingly incorporate data-driven and model-based intelligence, rule-based logic, model predictive control (MPC), reinforcement learning (RL), or model-free adaptive control to split power across sources and storage while enforcing state-of-charge (SoC), current and voltage limits, and DC-bus stability. This review focuses on recent papers that analyze or validate PV battery SC systems and AI-enabled EMS, highlighting design choices that increase efficiency and extend battery longevity.

## II. SCOPE AND METHOD

In this review, recent research on hybrid energy storage systems (HESS) integrating photovoltaic (PV) batteries and supercapacitor (SC) systems, and energy management techniques, especially those pertinent to off-grid systems, is coherently synthesized. The review addresses research that presents innovative system topologies, converter configurations, and sophisticated control systems aimed at advancing system dependability, power quality, and storage longevity.

In selecting studies for review, three core criteria were prioritized: direct relevance of the study to PV-battery-SC grids or HESS frameworks, the articulation of control or management of the system's energy processes, and the provision of measurable metrics such as maintained DC-link voltages, diminished current flow, or tangible changes in system lifecycle metrics.

Numerous key studies were scrutinized per the prior criteria, focusing on the context of application, system topology, control mechanism, evaluation paradigm, and the results detailing system performance measurement, or the overall quality of findings.

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## III. OVERVIEW OF HESS

Hybrid Energy Storage Systems (HESS) are advanced as 'go-to' options for resolving the issues posed by solar photovoltaic (PV) generation variability as well as the limitations posed by single-storage technologies in off-grid microgrids. Most HESS consist of an 'energy dense' lithium-ion battery and a 'power dense' supercapacitor (SC). The battery provides long-duration energy while the SC provides quick energy and power stabilization. It provides power surge stabilization and current stress isolation during battery operation. In addition, the SC improves the overall efficiency and reliability of the system.

The integration of DC–DC converters and an inverter facilitate power conversion while a Maximum Power Point Tracking (MPPT) controller ensures the optimized utilization of solar energy. Multi-layered Energy Management System (EMS) is in control of system operation, where fast control loops regulate system stability at the converter level while supervisory layers impose State of Charge (SoC) and current limits. Advanced algorithms like Model Predictive Control (MPC) and Reinforcement Learning (RL) optimize control of the dispatch strategies based on forecasted historical data and current real-time conditions, improving system resilience. This improves battery lifespan.

## IV. PERFORMANCE ANALYSIS OF HESS

Hybrid Energy Storage Systems (HESS) are becoming increasingly important for incorporating solar photovoltaic (PV) generation into standalone and grid-tied microgrids. HESS designs combine a high energy component, usually a lithium-ion battery, and a high power component like a supercapacitor (SC), flywheel, or superconducting magnetic energy storage (SMES) system. This setup alleviates the intermittency of a PV system, augments the quality of the power delivered, and reduces the rate of battery wear. Batteries are energy dominant for long periods, while SCs are dominant during rapid transient intervals, achieving a balanced efficiency for longevity of the system overall.

Thanks to their high-power density (5-10 kW/kg), near instantaneous battery cycling, and over a million cycles of discharge-charge cycles, supercapacitors will mitigage the cycling stress on a battery. Many authored works note the frosting of battery aging and excessive battery wear when SCs are incorporated to buffer high-frequency load variations, with up to a 19% increase in lifetime reported in some. Not only is SC integration capable of extending battery life, but it is also able to assist in the regulation of DC-link voltage, transient response, and power quality, and hence SCs should be considered a fundamental component in high performance HESS designs.

The type of converter used in a HESS determines the price, complexity, and performance. Cost and complexity decrease in passive topologies, which connect the batteries and SCs directly to the DC bus, but they also increase the limited flexible control. Semi-active topologies interface one of the battery or SCs with a DC-DC converter, which offers a middle control and price adjustment. Maximally integrated systems, in which both SCs and batteries are connected to control converters, offer fine control, improved fault tolerance, and expansion capabilities. More elaborate converters in the multi-level or isolated categories increase complexity, but allow modularity, higher voltage ranges, and other features.

Energy management strategies (EMS) are traditionally divided into classical, optimization based, or intelligent. Classical strategies like frequency splitting with low-pass and high-pass filters, droop control, and state of charge (SoC) based hysteresis rules are efficient but rigid and will pivot control when conditions of the system change. Optimisation strategies, like model predictive control (MPC) and other heuristic methods (ie. Particle Swarm Optimisation (PSO), genetic algorithms (GA)), allow the system to balance multiple goals, and control battery degradation, and even system costs and power quality. Intelligent strategies offer systems with artificial neural networks (ANN), fuzzy logic controllers (FLC) and other hybrid control methods.

For optimal performance, cost, and lifespan, it's important to understand the sizing methodologies for HESS components. The simplest equations will calculate the power and energy ratings in analytical methods, but these methods oftentimes lack detail. Monte Carlo simulations are statistical methods which account for the variability in solar irradiance, and also for load profiles. For capacity allocation, PSO and GA which are search-based optimization techniques, and pinch analysis with Ragone-plot-guided design, which are more focused on the graphical approach, give insight on the trade-off involved with design, selection, and sizing of the devices.

Evaluations on performance have shown and described the advantages of hybrid systems when compared to systems that are purely battery powered. Some of the advantages include peak battery current reduction of up to 50%, improved power quality, and regulation of transient voltage. HESS becomes more cost effective since the initial cost of integrating supercapacitors is recovered in the long run because the system saves money due to the reduction of battery replacements and extended battery life. More systems are evaluated with a broader view because of the increasing use of metrics, including lifecycle cost, LCOE, and reliability indices.

Practical implementation of HESS still has numerous challenges. Many works cite MATLAB/Simulink-based simulations and simplified rule-based approaches to field-deployable EMS designs. The integration of safety and computational challenges such as formal verification and fail-safe design in AI-based reinforcement learning and model-free adaptive control will hinder further implementation. Future works are projected to center around co-optimizing EMS, sizing, and converter design to ensure off-grid applications are maintained resilient and cost-optimized lifetime and minimized.

HESS systems that use batteries and supercapacitors have been proven to improve the power quality, battery lifespan, and microgrid resilience, and the systems continue to improve with advancements in the algorithms for EMS and smart control techniques. However, challenges in cost-optimization and validation for real-world applications still persist. The combination of the various optimization methods, energy management systems powered by AI, and innovative scalable designs for hardware will continue to advance research centered around energy storage for PV microgrids.

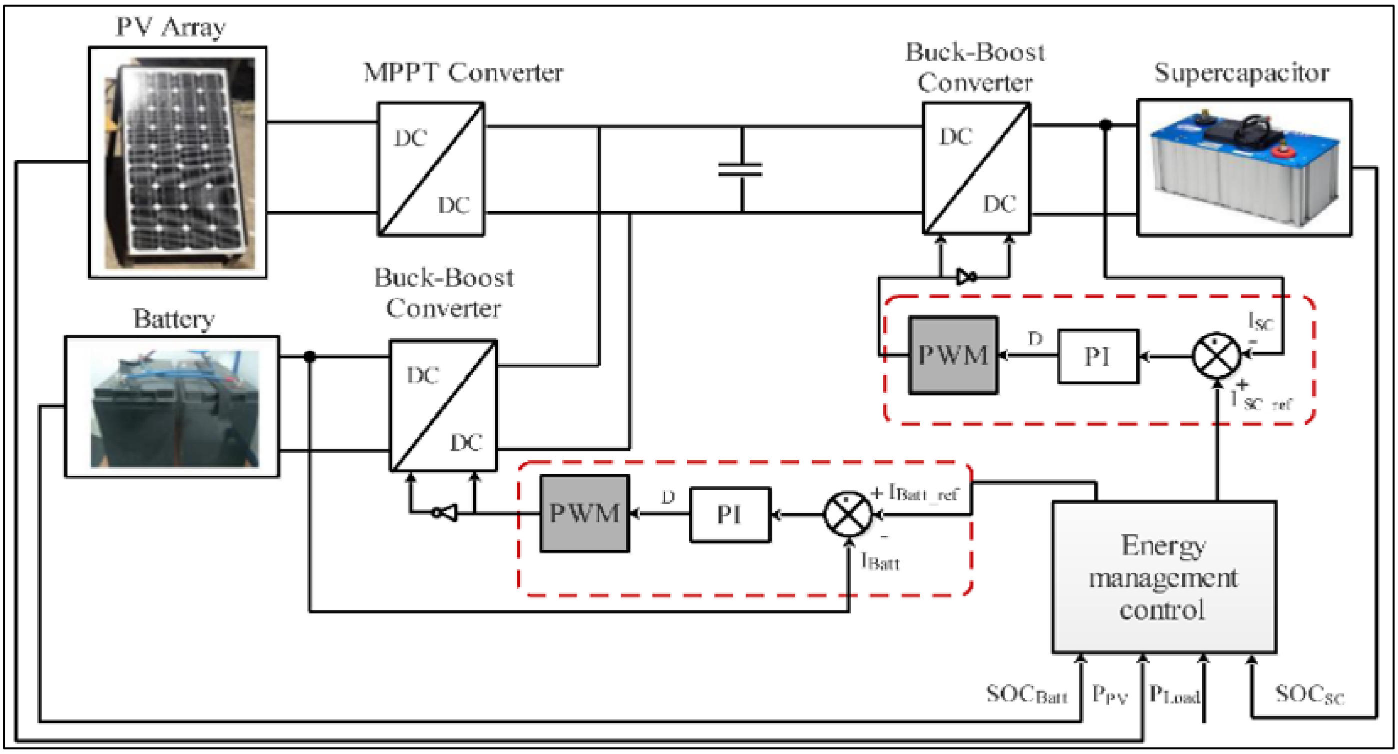


Fig 1 PV-HESS Block Diagram.

Table 1 HESS in Different Applications

| **Application** | **Topology** | **EMS / Control** | **Evaluation** | **Research Outcomes** |
|---|---|---|---|---|
| Standalone PV microgrid | Combination of PV, Battery and SC | Data-based, model-free I/O control with SoC or voltage constraints | Simulations with real irradiance/load data: Evaluated DC-bus voltage deviation, settling time, battery current peak/rms reduction, SoC fluctuation dampening. | Stable DC-bus regulation and effective fluctuation smoothing; reduced battery stress vs. baseline control. |
| Grid-connected PV–Battery–SC HESS | Combination of PV, Battery and SC | Power Limiting Control (PLC), Power Ramp-Rate Control (PRRC), and Power Reserve Control (PRC) used to regulate DC-link voltage and active/reactive power in PV–battery–supercapacitor hybrid systems. | MATLAB/Simulink under dynamic irradiance: Voltage stability (±<1 %) battery stress reduction by 20 %, Total Harmonic Distortion (THD) < 5 % | SC integration enhanced DC-link stability, reduced battery degradation, and improved power quality. |
| Hybrid PV–Battery–SC with Fuzzy Logic Control | Combination of PV, Battery and SC via bidirectional DC–DC converter | Fuzzy Logic Controller for voltage control | Simulated under irradiance transients: voltage settling time - 33 ms overshoot - 19 % battery life extension and continuous supply efficiency qualitatively highlighted. | Rapid transient response, acceptable overshoot, improved system stability and battery safety. |

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|---|---|---|---|---|
| Urban-cycle HESS for Electric Vehicles | Combination of PV, Battery and SC (HESS) | Rule-based EMS with GA sizing | MATLAB/Simulink: Peak battery current reduced by around 55 %, battery capacity loss over 30 days: HESS –0.85 % vs BESS –2.91 % | Demonstrated significant battery stress reduction and ~2 % slower capacity fade |
| Economic evaluation of HESS for frequency response | Combination of Li-ion Battery and SC | HESS providing frequency regulation services | Market and technical data: Utility factor 4.33, increased lifetime to 8.4 years, lifecycle economic benefit ≈ 36.55 M | HESS ranked top in utility and returned higher economic benefit over its lifecycle. |
| HESS role in battery life extension | Combination of Battery and SC in remote systems | Semi-empirical modeling and experimental validation | Predicted current distribution and voltage response under arbitrary cycling, experimental confirmation of improved battery lifetime and reduced cost. | Validated battery protection from high-frequency cycling and confirmed cost-benefit of hybrid approach. |

## V. DESIGN PATTERNS AND AI-BASED EMS

Across studies, a consistent pattern emerges:

- The battery attends to energy needs at low frequencies.
- The SC transients buffers stabilize the DC link.
- The EMS self-protects based on the energy State (SoC), current, and voltage.

By applying SoC-based power split coefficients, it’s easy to make senior EMS rule followers with frequency separation. Without a model, a ‘rule-free’ controller defined to the practiced levels, certainly flow control. With AI control, self-protection is practiced to the extreme with shallow RL and model predictive control from the top of the rule set.

While battery size meets minutes to hours needs, ensure fast transients absorption SC limit power. Protection logic cutting SC voltage, battery current, and SoC windows of a held control, idle for discharge balanced with, must comply. Fast control at converter levels of the EMS and SC master to idle over EMS and DC-link control.

Implementation, especially in resource-constrained off-grid deployments, Order rule based EMS plus frequency separation and SoC limits and telemetry based data-driven adaptation (e.g. model-free tuning of thresholds will allow cross the EMS control odd balance. AI control must have settled safety limit to cross.

The recommended reference architecture suggests an off-grid PV–battery–supercapacitor (SC) system with AI for energy management. An energy storage tier consists of a Li-ion battery and a SC bank, connected with bidirectional DC–DC converters, to address high-power demands. The generation stage consists of a PV array with maximum power point tracking (MPPT). A controlled DC bus provides direct DC load supply and an inverter (when needed) for AC loads. An energy management system (EMS) has predictive dispatch at the AI layer, advanced with techniques such as model predictive control (MPC) and reinforcement learning (RL). A supervisory rule-based coordinator that controls frequency splitting, alongside other SoC, current, and voltage constraints, manages the EMS's supervisory layer. Stability is ensured with fast converter control loops.

## VI. CONCLUSION

Off-grid microgrids have specific pros through hybrid PV-battery-supercapacitor systems with advanced Energy Management Systems (EMS). Moved battery currents get routed with supercapacitors (SC), which dampens rapid power shifts, and energy demands are managed with batteries, which makes energy shifts and demand less hard to tame. Between configurations that solely use batteries, hybrid systems have achieved over published benchmarks a nearly 50% reduction in peak battery currents and ti battery savings of 2x slower. Furthermore, SC systems are buffered 5-20% buffered battery systems cycle SC systems, which improves overall transient voltage and SC life limits, with SC systems gated and buffered cycle SC systems are voltage gated. High SC life limits translate to less voltage fluctuations in less controlled systems. Extensive field observations show that SC systems buffered 5-20% improve voltage transient SC life and SC voltage limits. Decreasing expensive battery replacements is a direct result of dampened controlled CL DC links despite rapid load shifts. Furthermore, learned power limit compliance SC systems automating advanced control improves systems and maintains stringent battery replacements.

For practitioners, the main point is the benefits of merging a basic SC bank with a complex EMS. A basic controller that splits power between the PV and the load according to SoC-adjusted low-pass and high-pass filters will limit the battery’s stress. More advanced AI-powered layers can be added later to optimize the system. In the end, HESS with AI-aware EMS have proven to sharply enhance off-grid reliability. They increase effective uptime, help power quality, and save long-term battery costs, which helps battery longevity. These systems will likely become the key features of reliable and efficient renewable microgrids as practical deployments start to appear.

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