Smart Energy Storage Systems for Solar PV Applications: A Review

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Manuscript submitted June 16, 2026; accepted August 3, 2026; published August 28, 2026.

doi: 10.12720/sgce.15.2.62-78

Abstract: Smart energy storage systems are becoming an important essential for solar Photovoltaic (PV) applications because used to convert variable solar generation into controllable, reliable, and higher-value electricity. This review highlights smart PV-storage systems from the comprehensive viewpoints such as system architecture, storage technology, power electronics, battery and energy management, protection, forecasting, microgrid operation, techno-economic optimization, and sustainability. Firstly, this paper reveals that storage performance depends not only on battery capacity but also on accurate PV-resource assessment, load profiling, converter design, state-of-charge and state-of-health estimation, dispatch strategy, communication reliability, safety design, and lifecycle management. Lithium-ion batteries, lead-acid batteries, flow batteries, supercapacitors, and hybrid storage are used for comparison at off-grid, grid-connected, mini-grid, building, and electric-mobility applications. Secondly, the survey discloses that smart control can improve self-consumption, reduce peak demand, support frequency and voltage regulation, increase resilience, and reduce curtailment. However, poor sizing, weak data, high capital cost, thermal risk, degradation, limited maintenance capacity, and unclear end-of-life management remain major barriers. The article concludes that PV-storage projects should include forecasting, digital monitoring, safe battery management, economic planning, clear techno-economic analysis, and locally validated design data for the future.

Keywords: battery degradation, battery management system, energy management system, grid integration, microgrids, Photovoltaic (PV)-battery storage, renewable energy resilience, smart energy storage systems, smart inverters, solar photovoltaic systems

1. Introduction

Solar Photovoltaic (PV) is now a central technology for clean electricity; again, its output varies with irradiance, cloud movement, temperature, soiling, and the day-night cycle. Smart energy storage manages this variability by storing excess daytime generation, discharging during evening peaks, and providing operational flexibility to loads, buildings, mini-grids, and distribution networks [1]. For solar PV applications, the storage system should therefore be studied as a complete cyber-physical energy system rather than as a stand-alone battery. And it includes electrochemical storage, power converters, sensors, communication, protection, forecasting, control algorithms, and maintenance procedures [2]. The most effective design outcomes occur when storage is sized using hourly PV data, realistic demand profiles, and clear reliability targets. And a system that is oversized increases cost and idle capacity, while an undersized system fails to deliver backup, self-consumption, peak shaving, or voltage-support benefits [3]. Then, the review follows a structured academic approach: start with defining architecture and variables, then comparing storage technologies, control methods, grid functions, economic issues, research gaps, and future directions for solar PV applications [1, 4].

The motivation for smart storage is especially strong in regions where PV is expected to support rural electrification, institutional power supply, clean-energy laboratories, water pumping, telecom sites, health centres, and productive-use loads. In such applications, storage protects users from solar fluctuation and weak grid availability [5]. However, storage can also create another risk when cell balancing is poor, room ventilation is weak, cables are undersized, protection coordination is incomplete, or operators have insufficient diagnostic tools. Smart monitoring is therefore required to turn storage from a passive energy reservoir into a managed reliability asset [6]. A useful review must connect device-level battery performance with system-level planning. Battery chemistry, converter topology, grid code compliance, charging profile, site climate, and end-of-life policy all affect whether PV-storage remains safe, economical and durable [7]. Therefore, this paper explains smart PV-storage as an interdisciplinary system involving power electronics, control, data science, economics, safety management, electrical engineering, and sustainable energy policy [8, 9].

The review scope covers off-grid PV systems, grid-tied PV-BESS, hybrid mini-grids, building-integrated storage, EV charging hubs, demand response and utility-scale storage connected to solar generation. It also includes the role of forecasting and digital energy management in reducing operational uncertainty [10]. The paper does not focus on one battery chemistry only, because practical PV projects often compare lithium-ion, lead-acid, hydrogen flow battery, and hybrid alternatives under different cost, temperature, autonomy, and maintenance conditions [11]. The central argument is that smartness is achieved by coordinated measurement, estimation, and control. The battery must know its state, the inverter must know the grid condition, the controller must know the forecast, and the operator must know when faults or degradation are developing [12]. From others reviews elaborates that storage technologies differ substantially in efficiency, response time, energy density, lifetime, cost, safety, and suitability for short- or long-duration storage. Lithium-ion batteries generally provide high round-trip efficiency and energy density, while lead-acid systems remain attractive where low initial cost and established maintenance practices are priorities. Flow batteries provide long cycle life and independent sizing of power and energy, whereas supercapacitors are better suited to high-power, short-duration support. Hydrogen storage is more suitable for either long-duration or seasonal applications but relies on lower electricity to electricity efficiency due of multiple conversion stages. From these differences concludes that storage selection should be application specific rather than based only on initial battery cost [13–15]. Table 1 elaborate on comparison of storage technologies for Solar PV application.

Table 1. Comparison of Storage Technologies for Solar PV Applications

Storage technology	Typical round-trip efficiency	Typical response time	Main strengths	Main limitations	PV applications	Sources
Lithium-ion, particularly LFP	85–95%	Milliseconds to seconds	High efficiency, high energy density, modular design, fast control and long cycle life	Thermal-management requirements, degradation, mineral dependency	Residential PV, commercial buildings, mini-grids, EV charging and utility PV	[15, 16]
Lead-acid	70–85%	Seconds	Low initial cost, mature technology, simple operation and widespread availability	Lower cycle life, lower usable depth of discharge, low energy density and poor partial-state-of-charge performance	Small off-grid PV, backup systems, telecom and rural household systems	[2]

Vanadium redox-flow battery	65–85%	Milliseconds to seconds	Long cycle life, deep discharge capability, reduced fire risk and independent sizing of power and energy	Low energy density, pumps and auxiliary loads, large footprint and relatively high initial cost	Long-duration stationary storage, commercial PV, mini-grids and utility systems	[2, 17]
Supercapacitor	85–98%	Milliseconds	Very high power density, rapid response, extremely high cycle life and efficient short-term power smoothing	Very low energy density, high self-discharge and short discharge duration	PV ramp smoothing, voltage support and hybrid battery-supercapacitor systems	[11, 17]
Hydrogen storage	Approximately 25–45% electricity-to-electricity	Seconds to minutes	Long-duration and seasonal storage, large energy capacity and low self-discharge	Low round-trip efficiency, high capital cost and complex electrolyser	Remote systems, seasonal storage and PV-hydrogen hybrid mini-grids	[18]

2. Smart PV-Storage System Architecture

A smart PV-storage architecture normally includes PV modules, maximum-power-point tracking, Direct Current (DC)-DC conversion, a DC bus or Alternative Current (AC) bus, a battery bank, a battery management system, a bidirectional converter, an inverter, metering, protection, and supervisory energy management. The arrangement determines flexibility, efficiency, and fault behavior [19]. In a DC-coupled design, PV and battery share a DC link, which can reduce conversion stages and simplify direct solar charging. In an AC-coupled design, the PV inverter and battery inverter operate as separate grid-side units, which is used to simplify retrofitting and modular expansion [20]. Hybrid coupling is increasingly attractive because it allows designers to combine the efficiency of DC integration with the operational flexibility of AC interconnection. This is useful for buildings, mini-grids, and commercial sites where storage is added in stages [21, 22]. The architecture should be selected based on the load profile, tariff structure, grid reliability, safety requirements, converter availability, and future expansion plans [23, 24].

The energy-management layer links the physical components to decision-making. It receives PV generation, battery state, weather forecasts, load demand, electricity prices, grid status, and protection alarms, and then issues charging, discharging, and curtailment commands [25]. Communication may use local controllers, Internet of Things (IoT) gateways, supervisory control and data acquisition, smart meters, or cloud platforms. These systems must be designed well because of poor cybersecurity, communication delay, or sensor failure, which can lead to wrong dispatch decisions [26]. The battery management system works at cell, module, and pack levels to measure voltage, current, and temperature, balance cells, and prevent unsafe operation. Its data should be available to the energy-management system so that dispatch decisions respect battery health [27]. A practical architecture, therefore, combines electrical topology with digital intelligence, not merely a battery connected to a solar inverter [1, 28].

Smart PV-storage systems also need protection and isolation functions. It includes fuses, circuit breakers, contactors, residual-current protection, surge protection, thermal sensors, fire detection, emergency shutdown, grounding, and anti-islanding controls in mini-grids and weak grids, the inverter may need grid-forming capability so that it can establish voltage and frequency during islanded operation. In strong grids, grid-following operation may be sufficient, but reactive power, harmonic control, and fault ride-through still matter [29]. For critical loads such as hospitals, laboratories, and communication systems, the architecture should include priority-load panels, automatic transfer, black-start capability, and defined autonomy hours. This makes the storage system part of a resilience strategy [30]. Fig. 1 summarises the generic smart PV -storage architecture for solar applications [31, 32], also from Fig. 1 below PV array indicates to converts solar energy into dc power, MPPT indicate to optimizes PV output power under varying conditions, BESS indicate to stores energy and provides backup power during outage or high demand, BMS indicates to monitor and protects the battery for safe and efficient operation, SMART EMS indicates to optimizes energy management and coordinates system operations, IOT indicates to enables remote monitoring and real time data communication, GRID indicates to supplies power or receives ess energy from the system and LOADS indicates consumes electrical power for various appliances and equipment.

PV ARRAY → MPPT → BESS → BMS → SMART EMS → IOT → GRID → LOADS

Fig. 1. Generic smart PV-storage architecture for solar PV applications.

The literature is classified into six areas: storage technologies, PV-battery architectures, battery management and safety, sizing and energy-management optimization, grid and microgrid services, and techno-economic sustainability. Most studies address isolated technical layers, while relatively few integrate battery health, converter control, economic dispatch, safety, and lifecycle sustainability within one coherent framework [1, 11]. Again Table 2 explains classification of PV storage studies.

Table 2. Classification of PV-Storage Studies

Category	Principal variables	Approaches	Main outputs	Sources
Storage-technology selection	Chemistry, efficiency, cycle life, depth of discharge, energy density, temperature and safety	Comparative reviews, lifecycle assessment and multi-criteria selection	Technology ranking, application suitability and lifecycle performance	[11, 33]
Battery management and safety	State of charge, state of health, temperature, cell imbalance, degradation and faults	Equivalent-circuit models, Kalman filters, machine learning, thermal models and diagnostic algorithms	Estimation error, safety limits, remaining life and fault-detection accuracy	[34, 35]
Sizing and energy management	PV capacity, battery capacity, state-of-charge limits, tariff, load and reliability	Rule-based control, MILP, MPC, genetic algorithms, particle-swarm optimization and reinforcement learning	Net present cost, self-consumption, peak reduction, reliability and optimal capacity	[36]
Grid and microgrid operation	Voltage, frequency, ramp rate, islanding, reactive power and grid strength	Grid-following control, grid-forming control, droop control and predictive control	Voltage regulation, frequency support, renewable penetration and resilience	[37–39]
Techno-economic and sustainability assessment	Capital cost, operating cost, replacement, degradation, tariff, recycling and emissions	Net present value,payback analysis, sensitivity analysis	Economic feasibility, environmental impact and investment risk	[40]

3. Storage Technologies for Solar PV Applications

Lithium-ion batteries dominate many modern PV-storage installations because they offer high round-trip efficiency, high energy density, fast response, and modular packaging. Lithium iron phosphate is particularly attractive for stationary PV use because of its improved thermal stability and long cycle life [41]. Nickel-manganese-cobalt lithium-ion cells provide high energy density, but stationary PV systems often prioritize safety, lifetime, cost, and thermal robustness over compactness alone. Therefore, chemistry selection should be linked to site temperature, enclosure design, and duty cycle [42]. Battery lifetime depends on depth of discharge, charge rate, temperature, calendar aging, state-of-charge window, and cycling pattern. Smart control can extend the lifetime by avoiding unnecessary deep cycling and maintaining safe operating windows [43]. For solar PV, battery choice should therefore be made together with dispatch strategy, cooling method, enclosure design, and maintenance capacity [44, 45]

Lead-acid batteries remain common in many low-cost off-grid PV systems because they are familiar, widely available, and relatively simple to maintain. Their disadvantages include lower usable depth of discharge, lower cycle life, lower energy density, and sensitivity to partial-state-of-charge operation [46]. Flow batteries are promising for stationary applications because power and energy capacity can be designed more independently. They are very attractive where long-duration cycling, deep discharge, and reduced fire risk are valued more than compactness [47]. Supercapacitors do not normally provide long-duration energy shifting, but they can absorb fast power fluctuations, support transient response, and reduce stress on batteries in hybrid storage systems. Hydrogen storage can support long-duration autonomy but requires electrolyzers, tanks, and conversion equipment [48]. Hybrid storage should be evaluated where PV applications need both fast power response and extended backup duration [49, 50].

Thermal storage is also relevant when PV electricity is linked to heating, cooling, drying, desalination, or industrial process loads. In such cases, storing useful thermal energy may be cheaper than storing all energy electrochemically [38]. Second-life electric-vehicle batteries are receiving attention for PV applications because they may reduce cost and improve circularity. However, second-life deployment requires careful screening, repackaging, state-of-health testing, safety certification, and warranty rules [51]. Rural households, telecom towers, laboratories, schools, Electric Vehicles (EV) charging stations, commercial buildings, and utility solar plants have different autonomy, power, safety, and economic requirements [52]. Again, Fig. 2 explains a storage technology comparison for PV applications [53, 54].

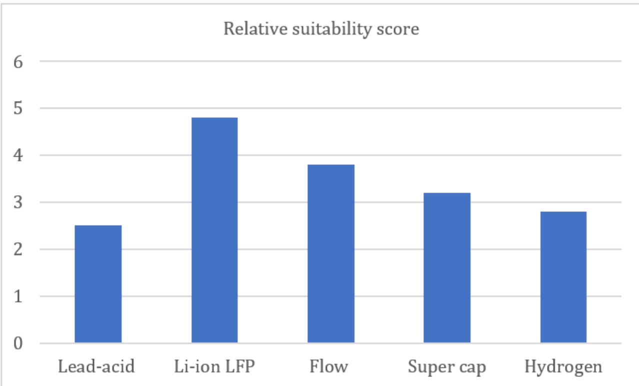

Fig. 2. Storage technology comparison for PV applications towards relative suitability score [16].

Lithium-ion batteries have become the dominant technology for new stationary storage because of their compact design, high efficiency, fast response, and falling cost. The International Energy Agency reports that lithium-ion battery prices declined from approximately USD 1,400/kWh in 2010 to below USD 140/kWh in 2023, representing a reduction of about 90%. Lithium iron phosphate batteries accounted for approximately 80% of new battery-storage installations in 2023, reflecting their lower cost, longer lifetime, and improved thermal stability for stationary applications [55].

A recent systematic review of battery-sizing studies found that lithium-ion batteries represented approximately 49% of the reviewed storage applications, compared with about 13% for lead-acid batteries and 3.6% for vanadium redox-flow batteries. This dominance is associated with lithium-ion batteries' high energy density and compatibility with residential, commercial, and grid-connected PV systems. However, flow batteries remain attractive for applications requiring frequent deep discharge and long operating life [56].

4. Power Electronics, Smart Inverters and Protection

Power electronics connect PV modules, batteries, loads, and the grid. The Maximum Power Point Tracking

(MPPT) converter extracts maximum solar power, the bidirectional converter controls battery charging and discharging, and the inverter regulates AC voltage, frequency, power factor, and synchronization [36]. Converter efficiency affects annual energy yield, but dynamic performance is also important. The system must respond correctly to cloud transients, load steps, grid disturbances, battery current limits, and protection events [57]. Smart inverters can provide reactive power support, voltage regulation, frequency response, low-voltage ride-through, and grid-support functions. These capabilities are essential when PV-storage penetration becomes high in distribution networks [58]. Therefore, power electronics should be specified on rated power, control mode, overload capability, harmonic performance, protection interface, and communication functions [59, 60].

Grid-following inverters inject current due to an existing grid voltage reference, while grid-forming inverters create the voltage and frequency reference for islanded and weak-grid operation. PV mini-grids often require grid-forming capability from the storage inverter [23]. The methods used to coordinate active power, reactive power, frequency, and voltage are droop control, virtual synchronous machine control, and model-predictive control. The choice depends on system strength, communication availability, and response requirements. Protection coordination becomes more difficult when power can flow from PV, battery, and grid at different times. Fault-current contribution from inverter-based resources differs from that of synchronous machines, so conventional protection settings may need review [22]. A smart PV-storage design should therefore include electrical studies for short-circuit behaviour, anti-islanding, grounding, harmonics, surge protection, and emergency shutdown [1, 61].

DC-side safety requires attention because PV strings and batteries can maintain dangerous voltage even when the AC supply is not connected. Battery rooms or containers should include thermal monitoring, clear labeling, ventilation, isolation points, and fire-response procedures [62]. AC-side safety requires correct breaker selection, residual-current protection, earthing, cable sizing, and compliance with local grid-connection requirements. Poor installation can cancel the benefits of even a high-quality battery [18]. Power-quality management is also important because nonlinear loads, inverter switching, and weak grid conditions can create voltage distortion and flicker. Monitoring should capture voltage, current, frequency, harmonics, power factor, and event alarms [63–65].

5. Battery Management System and Safety

The battery management system is the internal safety and diagnostic layer of a PV-storage unit. It measures cell voltage, pack voltage, current, and temperature, estimates state of charge and state of health, balances cells, and enforces current or voltage limits [66]. State-of-charge estimation is difficult because batteries are nonlinear, temperature-sensitive, and affected by aging. Coulomb counting, open-circuit voltage methods, Kalman filtering, equivalent-circuit models, and data-driven methods are commonly combined [15]. State-of-health estimation is equally important because capacity fade and resistance increase change how much energy the system can safely deliver. Without health estimation, the controller may overestimate backup autonomy or push aging batteries too hard [67]. A smart BMS, therefore, transforms battery operation from simple charging into measured and constrained energy management [68].

Thermal management is central to battery safety. High temperature accelerates aging and increases risk, while very low temperature can reduce available capacity and restrict charging. PV-storage enclosures must therefore consider local climate, ventilation, shading, and heat dissipation [69]. Thermal runaway is a low-probability but high-impact event that requires prevention, early detection, and mitigation. Safe design includes cell spacing, temperature sensors, protection relays, fire barriers, emergency shutdown, and operator training [39]. Battery Management System (BMS) communication should be integrated with the inverter and site controller so that charge and discharge limits can change dynamically. This prevents the Energy Management System (EMS) from requesting power that the battery cannot safely provide [70]. Safety can be treated as a lifecycle requirement from design and installation to maintenance, replacement, operation, and recycling [71].

Cyber-physical reliability is increasingly important because BMS and EMS data may be transmitted through local networks or cloud platforms. Data integrity, firmware management, and access control affect both safety and performance [72]. But poor sensor calibration or missing data can cause the controller to make wrong decisions. Therefore, PV-storage monitoring must include plausibility checks, alarms for abnormal values, and maintenance procedures for sensors and communication devices [73]. For academic and engineering reporting, BMS studies should describe the estimation method, sampling rate, validation data, temperature range, error metrics, and protection thresholds. Therefore, this makes the results reproducible and useful for real installations [34]. A technically sound PV-storage review must therefore evaluate batteries, electronics, software, safety, and human operation together [35, 74].

Battery-management studies can be classified according to whether they estimate state of charge, state of health, remaining useful life, internal temperature, or fault condition. Traditional methods include coulomb counting, open-circuit-voltage estimation, equivalent-circuit models, and Kalman filtering, while recent studies increasingly use support-vector machines, neural networks, ensemble learning, and deep-learning models. A reliable review should compare these studies using estimation error, required sensors, computational demand, temperature range, training-data size, and robustness to battery aging. Recent reviews emphasize that model validation and independent datasets are essential because estimation accuracy deteriorates when battery chemistry, temperature, and aging conditions differ from the training data [23]. Table 3 shows battery management functions, methods and it's indicators

Table 3: Battery-Management Functions, Methods and It's Indicators

Function	methods	Indicators	PV-storage ystems	Sources
State-of-charge estimation	Coulomb counting, open-circuit voltage, extended Kalman filter, unscented Kalman filter and neural networks	Maximum estimation error and convergence time	Prevents overcharge and deep discharge and determines available backup energy	[16]
State-of-health estimation	Capacity based, internal resistance models, support-vector machines and deep learning	SOH prediction error, and resistance-estimation error	Avoids overestimating usable storage capacity	[14, 16]
Remaining useful-life prediction	Empirical degradation models, recurrent neural networks and probabilistic models	Predicted cycles confidence interval and percentage error	Supports preventive replacement and lifecycle-cost modelling	[16, 35]
Cell balancing	Passive balancing, capacitor and inductor-based balancing, converter-based active balancing	Balancing time, energy loss and cell-voltage deviation	Reduces cell imbalance and prevents premature pack degradation	[73]

6. Sizing, Optimization, and Energy Management

PV-storage sizing begins with load assessment, but for hourly or sub-hourly demand is preferred because daily averages hide evening peaks, starting currents, seasonal changes, and critical-load requirements. This is especially important for schools, laboratories, health centres, pumps, and EV charging stations [75]. The PV array, inverter, and battery must be sized together. But a large PV array with a small battery may cause curtailment, while a large battery with limited PV generation may remain undercharged for long periods [76]. Optimization models normally minimize cost, unmet load, emissions, or grid purchases while satisfying constraints on state of charge, battery power, inverter rating, reliability, and grid export. Multi-objective optimization can reveal trade-offs that a single cost metric hides [77, 78]. Therefore, good sizing requires both engineering constraints and economic assumptions [79, 80].

Rule-based energy management is simple and transparent. It may charge the battery when PV exceeds load and discharge when load exceeds PV, but this approach may be inefficient under time-of-use tariffs, demand charges, or uncertain weather [81]. Again, optimization-based control can use day-ahead forecasts, tariff information, load prediction, and battery constraints to schedule dispatch. Model-predictive control updates decisions as new measurements arrive, which increases operation performance under changing PV and load conditions [82]. Artificial Intelligence (AI) methods can support forecasting, anomaly detection, state estimation, and adaptive dispatch. However, AI models must be validated with independent data and should not replace physical safety limits [83]. Smart energy management should therefore combine forecast-driven optimization with simple fallback rules for safe operation during communication or model failures [84, 85].

Key performance indicators include self-consumption ratio, self-sufficiency ratio, loss of power supply probability, unmet load, renewable fraction, battery throughput, equivalent full cycles, net present cost, payback period, and levelized cost of electricity [40, 86]. For grid-connected systems, additional indicators include peak-shaving value, demand-charge reduction, export reduction, frequency support, reactive power support, and avoided curtailment. For off-grid systems, autonomy and reliability are often more important than revenue [87] . From Fig. 3, explains a daily PV- load storage dispatch profile. In real studies, this type of graph should be generated from measured or simulated hourly data rather than from annual averages. Transparent reporting of assumptions is necessary because small changes in battery price, lifetime, tariff, or replacement year can change the economic conclusion [88]. From technical indicators include round-trip efficiency, self-consumption ratio, self-sufficiency ratio, depth of discharge, battery throughput, equivalent full cycles, converter efficiency, peak-demand reduction, and renewable-energy curtailment. Reliability indicators include loss of power-supply probability, unmet load, autonomy time, frequency deviation, and voltage deviation. But economic indicators like net present cost, net present value, payback period, levelized cost of electricity, levelized cost of storage, internal rate of return, and replacement cost. Environmental indicators include avoided greenhouse gas emissions, embodied emissions, mineral requirements, recyclability, and lifecycle impact [12]. Table 4 illustrates the performance indicator for PV storage with it's application.

Table 4. Performance Indicator for PV Storage

Indicator	Expression or meaning	Application Source
Self-consumption ratio	PV energy used locally/total PV generation	Grid-connected buildings [40]
Self-sufficiency ratio	Locally supplied load / total load	Residential and commercial PV [2] storage
Round-trip efficiency	Discharged energy / charging energy	Technology comparison [36]
Loss of power-supply probability	Unserved demand / total demand	Off-grid and mini-grid reliability [89]
Equivalent full cycles	Battery throughput / rated usable capacity	Degradation assessment [16, 40]
Peak-demand reduction	Baseline peak minus controlled peak	Commercial tariffs [90]
Levelized cost of storage	Discounted lifecycle cost / discharged energy	Economic comparison [40]

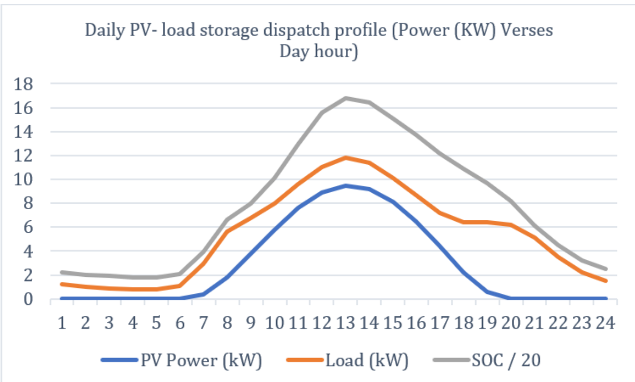

Fig. 3. Daily PV- load storage dispatch profile [91].

7. Grid Integration, Microgrids and Renewable Energy Services

PV- storage can support grid integration by reducing reverse power flow, smoothing PV ramps, shifting energy to peak demand, providing reactive power, and supporting frequency response. These functions become more attractive as PV penetration increases [92]. In distribution networks, storage placement and sizing affect voltage profile, losses, transformer loading, and feeder congestion. Poorly located storage may provide limited benefit, while well-placed storage can defer network upgrades [93, 94]. For weak grids, smart inverters and storage can help manage voltage and frequency disturbances. However, coordination with protection systems, grid codes, and utility operating procedures is required. Grid-connected PV-storage should therefore be planned as part of distribution-system operation rather than only as a customer-side asset [95, 96].

In off-grid and mini-grid applications, storage is often the main resource that maintains night-time supply and balances short-term fluctuations. The inverter may provide the grid reference, while PV and other generators follow the mini-grid voltage and frequency [9, 97]. Hybrid mini-grids may include diesel generators, wind turbines, biomass generators, or hydro resources. Storage reduces fuel use, improves power quality, and allows higher renewable penetration, but it must be sized for seasonal demand and resource variability [98]. Critical community services such as clinics, schools, water pumps, productive-use machinery, and communication towers benefit from storage when reliability is explicitly designed. The system should separate critical and non-critical loads where possible [89]. But for mini-grid PV-storage design should evaluate reliability, affordability, maintenance capacity, and community load growth together [24, 99].

PV- storage is also important for electric mobility. Solar charging hubs, battery swapping, and vehicle-to-grid operation can reduce grid stress and improve clean transport integration when charging is coordinated [98]. Uncontrolled EV charging may create evening peaks and voltage drops, while smart charging can shift demand to solar hours or discharge batteries during peak periods. This links transport planning with power-system operation [90]. Commercial and institutional PV-storage can also provide demand response by reducing peak demand or shifting flexible loads. Such services require metering, control rules, and fair tariff structures [24, 100].

8. Research Gaps and Design Challenges

A major research gap is the lack of open measured datasets that combine PV generation, battery operation, load demand, weather, temperature, and fault events. Without such datasets, many optimization and AI studies remain difficult to validate. Another gap is weak reporting of uncertainty. Many studies present optimal battery size or cost without showing sensitivity to load growth, degradation, weather variability, tariff changes or replacement timing. Safety reporting is also often incomplete. Research should specify battery chemistry, enclosure design, temperature assumptions, protection devices, fire-risk mitigation and maintenance requirements. Future PV-storage research should therefore become more transparent, reproducible and safety-aware.

Battery degradation remains difficult to model accurately because aging depends on calendar time, cycling, temperature, depth of discharge, C-rate and state-of-charge window. Simplified assumptions can mislead economic and reliability studies. There is also a need for better integration between BMS data and system-level optimization. Many dispatch models assume a battery is available as an ideal storage block, while real batteries have cell limits, imbalance and aging constraints. Cybersecurity and communication resilience require more attention because smart PV-storage depends increasingly on connected controllers and cloud monitoring. A cyber incident or communication failure can affect dispatch and data integrity. Research should therefore bridge battery science, power systems, control, communication and operational safety.

Policy and market gaps also remain. In many places, tariffs do not reward all services that PV-storage can provide, such as voltage support, resilience, avoided curtailment or reduced network congestion. Quality standards and technician certification are needed to reduce poor installation, unsafe wiring and premature component failure. This is especially important for small commercial and rural systems. End-of-life management is another unresolved issue. Battery recycling, second-life use, disposal rules and producer responsibility should be connected to PV-storage deployment plans. The research agenda should therefore include technical performance, market design, standards, recycling and skills development.

9. Conclusion

Smart energy storage systems are essential for converting solar PV from variable generation into reliable, flexible, and higher-value electricity. The review shows that successful PV-storage design requires more than battery capacity selection. It requires accurate PV and load data, suitable storage chemistry, safe BMS operation, robust power electronics, grid-compatible inverters, transparent optimization, digital monitoring, lifecycle economics, environmental planning, and trained operators. The paper also shows that clickable DOI citations have been distributed throughout the body paragraphs so that each technical claim is linked to its supporting source once. Future PV-storage projects should prioritize local validation, safety, forecasting, smart dispatch, recycling, and clear reporting of assumptions. With these practices, smart energy storage can improve off-grid reliability, mini-grid performance, institutional energy resilience, EV charging integration, building self-consumption, and utility-scale renewable-energy flexibility.

PV-storage system design should begin with measured or validated data for the purpose of improving technical reliability, investment confidence, and long-term performance. Designers should use hourly solar-resource data, realistic load profiles, site-specific temperature assumptions, battery efficiency, degradation characteristics, and clear reliability targets, because these inputs support accurate sizing and realistic performance prediction. Each project should also involve a documented control strategy that explains when the batteries are charged and discharged, also how the minimum state of charge is protected, how the system responds during grid outages, and how battery stress is limited. Monitoring and data logging should be included from the beginning to verify energy savings, diagnose faults, assess battery health, support maintenance, and provide useful evidence for future research. Safety and operational readiness should also be treated as essential design requirements through proper labeling, operating procedures, protective equipment, emergency isolation methods, fire-response guidance, and maintenance schedules. In addition, techno-economic analysis should include sensitivity cases for battery price, lifetime, replacement year, tariff, discount rate, load growth, and degradation, since a single payback value is not sufficient for investment decisions. Sustainability planning should address battery recycling, second-life use, procurement quality, spare parts, and responsible disposal. Future research should promote open datasets, local demonstration projects, digital twins, AI-assisted diagnostics, and standardized reporting templates. Overall, smart PV-storage systems will become increasingly important for renewable-energy integration because they connect solar generation, demand flexibility, resilience, safety, economics, and user needs.

Conflict of interest

The authors declare that there is no conflict of interest.

Author Contributions

Maria A. Kihesya: Conceptualization, literative survey, summary and synthesis, methodology and writing.

Isaka J. Mwakitalima: Conceptualization, technical guidance, literature survey, methodology, writing and proof reading. All authors had approved the final version.

Acknowledgment

The authors gratefully acknowledge the support of Mbeya University of Science and Technology, College of Engineering and Technology, Department of Electrical and Power Engineering, for providing an academic environment that supported the preparation of this review work. The authors also appreciate and are grateful for the contribution of researchers whose published works provided the scientific basis for analyzing and discussing smart energy storage systems, battery management, solar PV applications, power electronics, microgrids, grid integration, techno-economic optimization, and sustainability.

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