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A Review of Grid Connected Solar Photovoltaic Systems with Battery Energy Storage for Reliable Power Supply

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Abstract:—*The global energy landscape is witnessing a marked acceleration in solar photovoltaic (PV) deployment, driven largely by the pressing need for energy sources that are both clean and dependable. Yet, the inherent variability of solar irradiance poses nontrivial obstacles to maintaining grid stability and ensuring uninterrupted power delivery. To mitigate these issues, Battery Energy Storage Systems (BESS) are now routinely paired with grid-connected PV installations capturing surplus generation during peak insolation and discharging it when solar input drops or when the network experiences disturbances. In this review, we offer a broad yet detailed examination of such integrated PVplus storage systems, with a particular emphasis on their ability to deliver reliable supply. The discussion covers system level architectures, the spectrum of available battery chemistries, prevailing energy management frameworks, and the control methodologies that underpin effective operation. Specific attention is given to voltage regulation (VR), power quality (PQ) enhancement, and measures that boost overall system reliability. Recent progress in distributed control paradigms, optimal sizing of storage assets, and scheduling strategies for cost efficient operation is also surveyed. Beyond cataloguing the technical, economic, and operational dividends, we identify open challenges and promising avenues for future inquiry particularly those that could further strengthen modern power distribution networks (DN) against emerging demands.*

Keywords:— *Solar PV, Grid connected PV, Battery energy storage, Renewable energy, Voltage regulation, Energy management, Reliable power supply*

1. INTRODUCTION

The world needs more electricity, and it needs it with fewer emissions. Renewable energy has expanded accordingly. Among the available options, grid connected solar PV stands outmodular, widely available, and increasingly affordable (Anjali and Sharma, 2017). These systems run in parallel with the utility grid. When sunlight is strong, they feed surplus power into the network, typically under net metering or feed in arrangements. When clouds roll in or night falls, they draw electricity back from the grid to keep the lights on (Bagalini et al., 2019). That much is straightforward. The catch, however, is that sunlight is inherently variable. This intermittency provokes voltage excursions, degrades power quality, and undermines system dependability (Von Appen et al., 2014). Enter battery energy storage. BESS offers a practical remedy: it soaks up excess PV generation during sunny hours and releases that stored energy later, whether for peak shaving, grid fault ride through, or simply raising self-consumption (Bagalini et al., 2019). The academic literature reflects growing engagement with these integrated systems. Riffonneau et al. (2011), for instance, devised optimal power flow scheduling to improve operational efficiency. Sun et al. (2011) took a different tack, proposing distributed control architectures that let modular PV BESS units coordinate without a central overseer. Stecca et al. (2020) stepped back to survey the broader landscape of BESS integration into distribution networks, emphasising its role as a critical enabler of high renewable penetration. Meanwhile, the sheer density of distributed PV has sharpened anxieties over voltage regulation and power quality prompting a flurry of studies on advanced control techniques that can suppress fluctuations and preserve stability (Von Appen et al., 2014; Wang et al., 2014; Zeraati et al., 2018). Storage sizing and energy management are equally decisive. Recent co optimisation frameworks have attacked both problems simultaneously, coupling battery capacity selection with dispatch policies to maximise network performance and reliability (Saez De Ibarra et al., 2016; Das et al., 2019; Barzegkar Ntovom et al., 2020).

All of this depends on hardware. The PV modules themselves are the front line mostly crystalline silicon, favoured for its efficiency and long service life, though their output fluctuates with irradiance, temperature, shading, and cell type (Anjali and Sharma, 2017). The inverter follows, converting DC into AC and synchronising it to grid voltage, frequency, and phase; advanced versions go further, supplying reactive power compensation and cleaning up harmonic distortions (Von Appen et al., 2014). Batteries add the storage dimension. Li ion chemistries currently lead the pack, prized for high energy density, extended cycle life, and relentlessly falling prices (Hesse et al., 2017). Charge controllers sit between the battery and the rest of the system, guarding against over charge and deep discharge. Above them sits the Energy Management System the brain that orchestrates power flows among the PV array, the battery, local loads, and the utility, all in pursuit of maximum efficiency and economic gain (Saez De Ibarra et al., 2016). The grid itself plays a dual role: backup when solar is scarce, sink when solar is abundant. Contemporary installations also incorporate monitoring and communications layers that enable real time performance tracking, fault detection, and remote operation (Stecca et al., 2020). These elements come together in a typical architecture, depicted in Figure 1. The figure shows the main components and the possible power routes.

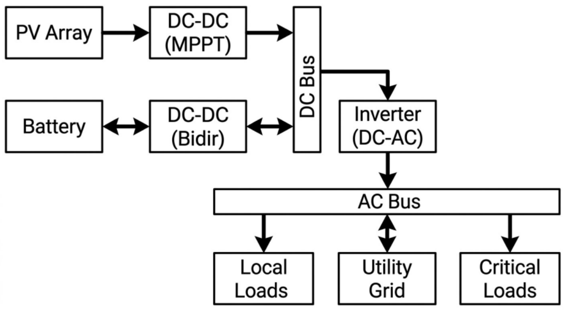

Figure. 1: Overall Structure of GridConnected PVBattery System

As illustrated, the battery can take charge from either the PV array or directly from the grid; it can also discharge toward local loads or export back to the utility. Crucially, during a grid outage, the inverter disconnects from the utility and forms a local microgrid, keeping only the critical loads energised while the rest of the system remains isolated.

The benefits are not merely technical. Raising self-consumption cuts reliance on fossil fired generation and lowers greenhouse gas outputs (Bagalini et al., 2019). The same storage asset can perform voltage regulation, flatten peak demand, shift loads to cheaper tariff periods, and even support frequency regulation within distribution networks all of which stabilise the grid and permit deeper renewable integration (Wang et al., 2014; Zeraati et al., 2018). Financially, optimised battery sizing and smart dispatch reduce peak demand charges and maximise the use of locally generated solar energy, enhancing the business case for PV investments (Das et al., 2019). Yet the path is not without obstacles. Intermittency the very reason storage is needed also provokes voltage swings, reverse power flows, and persistent PQ issues (Von Appen et al., 2014). Batteries degrade over time. Their capacity fades, their efficiency slips, and eventually they must be replaced, all of which adds to lifecycle costs (Hesse et al., 2017). Getting the sizing and management right for the long haul remains a stubborn challenge. And when many such systems are scattered across the distribution network, the demands on control infrastructure and communication become formidable. Grid codes, regulatory frameworks, cyber security, and interoperability all call for continued investigation (Stecca et al., 2020). With that in mind, this review sets out to examine grid connected PV BESS systems comprehensively across their architectures, storage choices, control strategies, EMS designs, voltage regulation measures, reliability enhancements, and future trajectories. The objective is to equip researchers, engineers, and policymakers with a cohesive reference for building robust systems in tomorrow's power networks.

Battery Storage Technologies and Integration Architectures

Solar output fluctuates. Storage addresses that directly. But selecting the right battery chemistry and deciding how to wire it into the system are two distinct design problems, both equally decisive for overall performance. The fundamental role of BESS in PV applications is straightforward: capture surplus generation during high irradiance, then release that energy when the sun fades or demand spikes. This basic function improves self-consumption, shaves peaks, shifts loads, provides frequency response, and backs up critical circuits during outages (Riffonneau et al., 2011; Bagalini et al., 2019). At the grid level, distributed storage mitigates voltage excursions, counters reverse power flows, and supplies ancillary services all of which permit deeper renewable penetration without destabilising the network (Wang et al., 2014; Stecca et al., 2020).

Not all batteries are equal. The three principal chemistrieslead acid, Li ion, and flow batteriespresent radically different trade-offs across cost, energy density, cycle life, efficiency, and maintenance burden. Lead acid is the oldest and cheapest option. Its electrochemistry (lead dioxide, sponge lead, and sulphuric acid) is well understood, and its charging requirements are simple (Hesse et al., 2017). For small scale, budget constrained installations, it remains a pragmatic choice. Yet the drawbacks are severe: low energy density (30–50 Wh/kg), limited cycle life (500–1,000 cycles at 80% DoD), slow response, and high upkeep specially if deep discharges are frequent, which drastically shortens service life (Hesse et al., 2017). Li ion, by contrast, has become the market leader. Lithium iron phosphate variants, in particular, deliver 90–95% round trip efficiency, 4,000–10,000 cycles, energy density of 150–200 Wh/kg, and accept 90–100% depth of discharge. They respond in 10 –50 milliseconds, charge quickly, and require minimal routine maintenance (Barzegkar Ntovom et al., 2020). Falling costs have pushed them into residential, commercial, and utility scale systems alike. Their fast response also makes them ideal for frequency regulation, voltage control, and demand response programs (Stecca et al., 2020). That said, Li ion is not a panacea. Upfront costs remain higher than lead acid. A sophisticated Battery Management System (BMS) is non-negotiable to prevent over charge, deep discharge, and thermal runaway. And material availabilitylithium, cobalt, nickelcoupled with end of life recycling, poses sustainability questions (Hesse et al., 2017). Flow batteries, particularly vanadium redox types, occupy a different niche entirely. They store energy in liquid electrolytes held in external tanks and pumped through electrochemical cells. Power and energy capacities are decoupled system designers can independently scale tank size for longer duration without altering the cell stack (Stecca et al., 2020). This yields exceptional cycle life (>10,000 cycles), 100% depth of discharge, minimal degradation, and improved safety. For utility scale, long duration storage where reliability is paramount, flow batteries are highly attractive. The catch: energy density is poor (15–30 Wh/kg), installation costs are high, and the pumping system adds parasitic losses and moderate maintenance overhead. Table 1 crystallises these trade-offs. It compares the three technologies across cycle life, response time, round trip efficiency, energy density, allowable DoD, maintenance needs, and suitability for reliability critical applications.

Table 1 : Summarizes the main Technologies

Parameter	LeadAcid	LithiumvIon ($LiFePO_4$)	Flow Battery
Cycle life (80% DoD)	500–1,000	4,000–10,000	>10,000
Response time	100–200 ms	10–50 ms	100–500 ms
Roundtrip efficiency	70–85%	90–95%	75–85%
Energy density	Low (30–50 Wh/kg)	High (150–200 Wh/kg)	Low (15–30 Wh/kg)
Depth of discharge	50% (max)	90–100%	100%
Mainte-nance	High (watering, equalizing)	Low (BMS required)	Moderate (pumps, electrolyte)
Suitable for reliability	Limited (short life)	Excellent	Good for longdura-tion backup

Li-ion clearly dominates the mainstream market, balancing performance, efficiency, and lifecycle cost. Flow batteries are gaining traction for large, duration sensitive projects, while lead acid persists where initial capital is the overriding constraint (Bagalini et al., 2019; Hesse et al., 2017).Chemistry, however, is only half the story. The physical arrangement how the PV array, battery, inverter, and grid interconnect dictates conversion losses, retrofit feasibility, fault tolerance, and control complexity. Figure 2 illustrates the three primary architectural archetypes: DCcoupled, ACcoupled, and hybrid configurations.

Each has a distinct operational logic. In a DC coupled system, the PV array and battery share a common DC bus upstream of a single, grid tied inverter. Power from the panels can flow directly to the load, into the battery, or through the inverter to the grid (Riffonneau et al., 2011). This topology minimises conversion stagesPV to battery storage occurs without intermediate AC DC hopsso round-trip efficiency is high. Fewer power electronic components reduce installation cost and simplify design. Moreover, a single controller can centrally coordinate charging and discharging, making DC coupled architectures particularly well suited for new, purpose-built installations where PV and storage are planned together from the outset (Sun et al., 2011). The downside? Retrofits are difficult adding storage later means replacing or re-

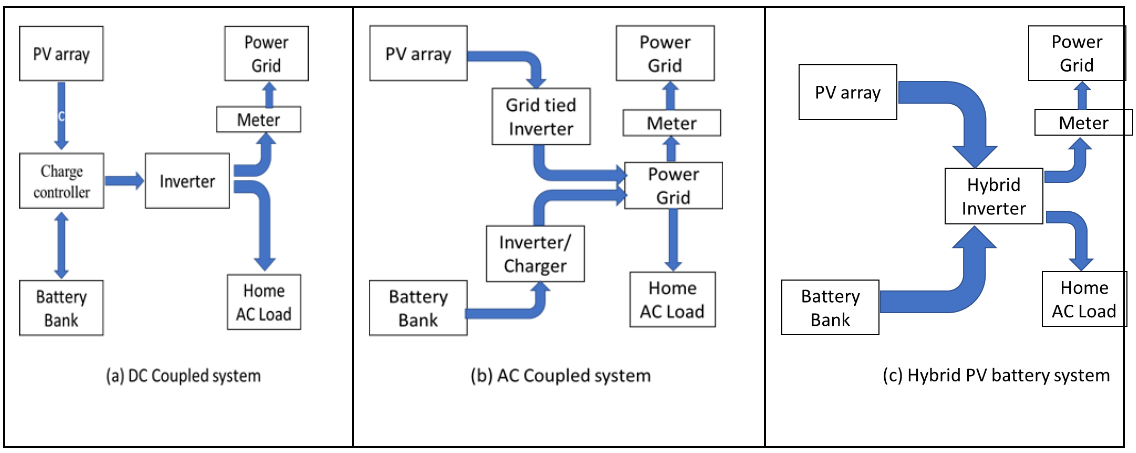

Figure 2. Types of PVBattery Architectures

engineering the existing inverter. The shared inverter also becomes a single point of failure, and operational flexibility is somewhat constrained, particularly when the inverter must handle both PV variability and battery dispatch simultaneously (Sun et al., 2011). AC coupled systems take a different approach. The PV array connects through its own dedicated grid tied inverter, while the battery interfaces via a separate bidirectional inverter; both sit on a common AC bus (Bagalini et al., 2019). This modularity offers enormous practical advantages. Existing grid connected PV installations can be upgraded with battery storage without touching the original invertera major factor driving AC coupling in residential and commercial retrofits (Bagalini et al., 2019). PV and battery inverters operate independently, which simplifies maintenance and enhances fault tolerance: if one converter trips, the other can continue working. Researchers have shown that AC coupled storage effectively supports voltage regulation, frequency control, and ancillary services in high penetration distribution networks (Wang et al., 2014). The principal penalty is conversion loss. Energy stored in the battery must undergo AC DC (during charging) and DC AC (during discharging) conversions, adding extra stages compared to the DC coupled case (Stecca et al., 2020). Still, for most retrofit scenarios, the flexibility and scalability advantages outweigh the efficiency hit. Hybrid architectures, as the name implies, merge both philosophies. They employ advanced power electronic converters and an intelligent Energy Management System (EMS) that dynamically routes power among PV, battery, loads, and the grid (Barzegkar Ntovom et al., 2020). Operating modes shift based on generation levels, battery state of charge, real time tariffs, and grid conditions. The result is a unified platform capable of islanding during outages, peak shaving, load shifting, demand response, and voltage regulation (Zeraati et al., 2018). Recent EMS developments incorporate optimisation algorithms that compute optimal charge schedules, minimise energy costs, and maximise renewable utilisation while respecting battery degradation constraints (Das et al., 2019). Hybrid systems are arguably the most promising for future smart gridsthey integrate generation, storage, and grid support functions into a single, adaptive platform. As battery costs continue to decline and control technologies mature, these hybrid topologies are positioned to become a primary enabler of reliable, flexible, and sustainable power networks (Stecca et al., 2020).

Energy Management and Control Paradigms for PVBESS Integration

Effective operation hinges on two tightly interwoven pillars: energy management and real-time control. The EMS orchestrates power flows among the PV array, battery, loads, and grid to maximise renewable utilisation, reduce electricity costs, and preserve system stability (SaezDeIbarra et al., 2016; Stecca et al., 2020). Yet coordination alone cannot succeed without robust control logic capable of executing these decisions under volatile irradiance and fluctuating demand. The basic hierarchy of power dispatch is straightforward. During high insolation, local loads take priority; surplus either charges the battery or exports to the grid. In deficits, storage discharge or grid import covers the shortfall (Bagalini et al., 2019). Modern EMS, however, moves far beyond this simple rule set. It integrates electricity pricing, battery state of charge, load forecasts, weather predictions, and grid conditions into a dynamic optimisation framework (Riffonneau et al., 2011). This predictive capability directly benefits voltage stability and power quality in high penetration networks (Wang et al., 2014).

At the hardware interface, the BMS enforces strict operational boundaries overcharge, deep discharge, thermal limits to prolong battery life (Hesse et al., 2017; Sun et al., 2011). Advanced strategies now employ predictive and distributed control to coordinate frequency support and energy arbitrage while actively minimising degradation (Lee et al., 2016; Zeraati et al., 2018). Among the most economically impactful applications are peak shaving and load shifting. Peak shaving deploys stored energy to cap grid draw during expensive high demand intervals, lowering bills and easing infrastructure strain (Dongol et al., 2018). Load shifting, similarly, arbitrages time of use tariffs by storing cheap off-peak PV for expensive peak periods (Das et al., 2019). These techniques facilitate demand side management and smooth the generation load mismatch (Luthander et al., 2017). Self-consumption optimisation has gained acute urgency as feed in tariffs decline. Without storage, daytime surplus is exported while night time demand draws grid power; optimal battery dispatch retains that energy locally, elevating the SC ratio and cutting overall electricity costs (Barzegkar Ntovom et al., 2020; Azuatalam et al., 2019).

Translating these EMS schedules into hardware action requires a suitable control architecture. Centralised control gathers system wide data to execute global optimisation effective for large scale plants and micro grids where coordinated resource dispatch is paramount (Riffonneau et al., 2011; Saez DeIbarra et al., 2016). The approach, however, creates a single point of failure, incurs heavy communication overhead, and scales poorly as system size grows (Stecca et al., 2020). Distributed control offers a compelling alternative. Local controllers operate on neighbour limited information, which enhances scalability, fault tolerance, and flexibility (Sun et al., 2011). Voltage regulation and power balancing have been successfully demonstrated using such distributed schemes without requiring ubiquitous communication infrastructure (Zeraati et al., 2018; Worthmann et al., 2015).

Voltage regulation is critical. Intermittent PV injection can push feeder voltages beyond acceptable limits, damaging equipment and violating PQ standards (Von Appen et al., 2014). BESS counters this through active power curtailment, reactive power injection, VoltVAR droops, and coordinated battery dispatch techniques that consistently improve voltage profiles in distribution grids (Wang et al., 2014; Ariyaratna et al., 2018). Frequency stability presents a different, equally pressing challenge. Conventional grids rely on synchronous inertia; PV inverters provide none. Batteries, however, can emulate virtual inertia or apply droop control to inject or absorb power within milliseconds, effectively arresting frequency deviations (Lee et al., 2016). As inverter-based resources proliferate, this fast frequency response will become indispensable for system security (Stecca et al., 2020). Ultimately, the combination of centralised and distributed control strategies, together with advanced VR and frequency support mechanisms, enables efficient RE utilisation while maintaining the stability and reliability of the modern power network.

Power Quality and Reliability Enhancement

PV inverters lack rotating mass. They are not inherently grid friendly. This creates power quality headaches voltage excursions, frequency drift, and harmonic injection that intensify as penetration rises (Stecca et al., 2020). BESS provides the counterweight. By absorbing or injecting both real and reactive power, storage stabilises the very phenomena that PV alone exacerbates. Voltage stability is the most immediate concern. Cloud passage can swing feeder voltages beyond statutory limits within seconds; overvoltage during low load, high irradiance periods damages equipment, while sudden dips threaten PQ compliance (Von Appen et al., 2014). Battery dispatch directly counters this: active power curtailment, reactive power compensation, VoltVAR droops, and coordinated distributed strategies flatten these excursions (Ariyaratna et al., 2018; Zeraati et al., 2018). The effect is a measurable improvement in voltage profiles across high penetration distribution networks.

Frequency stability presents a different but equally pressing problem. Conventional grids rely on the rotational inertia of synchronous generators. PV inverters provide none (Lee et al., 2016). As renewables displace thermal plant, the system loses its natural damping against generation load mismatches. BESS fills this gap with millisecond class response. Droop control, virtual inertia emulation, and model predictive dispatch allow batteries to inject or absorb active power faster than any turbine can ramp (Stecca et al., 2020). Lee et al. (2016) demonstrated that coordinated battery control substantially reduces frequency deviations, even under high PV variability. Harmonics, meanwhile, emerge from the power electronic interfaces themselves. Advanced pulse width modulation and passive filtering mitigate the worst, but smart inverters can go further operating as active power filters that inject compensating currents to cancel integer order distortions (Wang et al., 2014). Beyond these corrective functions, BESS participates directly in ancillary service markets. Voltage support, frequency regulation, reactive power compensation, spinning reserve, load following, and even black start capability are all technically feasible (Steccaet al., 2020). For system owners, these services offer revenue streams; for grid operators, they provide flexible, fast acting stability reserves that conventional plants cannot match.

Reliability, however, extends beyond dynamic stability to outright outage survival. Standard gridtied PV automatically trips during utility faults to prevent unintentional islandinga safety requirement that leaves consumers powerless exactly when the grid fails (Anjali and Sharma, 2017). Add a battery with suitable control, and the inverter can intentionally island, forming a local microgrid that sustains critical loads indefinitely, subject only to stored energy and ongoing solar input (Bagalini et al., 2019). Residential systems typically prioritise lighting, refrigeration, and medical devices; commercial installations protect production lines and data centres; utilityscale units provide emergency reserve (Barzegkar Ntovom et al., 2020). The duration of backup depends on battery capacity, load magnitude, state of charge, and the availability of sunlight to recharge during the event. Quantitative reliability indices capture these benefits with hard numbers. SAIDI (System Average Interruption Duration Index), SAIFI (System Average Interruption Frequency Index), CAIDI (Customer Average Interruption Duration Index), and ENS (Energy Not Supplied) are standard metrics utility planners use. Multiple studies confirm that optimally sized and sited BESS significantly lowers all four measures, particularly in distribution systems with high renewable penetration (Das et al., 2019).

Resilience is a related but distinct attribute. Reliability addresses normal operating contingencies; resilience concerns extreme, low probability events severe storms, cyber attacks, equipment cascades, natural disasters. The rising frequency of such incidents has shifted attention toward distributed, localised resources that can function when central infrastructure fails (Zhang et al., 2019). BESS fits this role precisely. Its ability to operate autonomously, respond instantly, and coordinate with neighbouring units enhances network adaptability and recovery speed (Worthmann et al., 2015). Optimal allocation of PV and storage across the distribution footprint can dramatically improve resilience under extreme conditions without excessive investment (Zhang et al., 2019). The deployment spectrum is already broad. Residential PVBESS improves self-consumption and provides household backup; commercial systems shave peak demand charges while safeguarding business continuity; large scale storage attached to PV plants delivers grid stabilising ancillary services and reserve capacity (Bagalini et al., 2019; Stecca et al., 2020). Micro grids, perhaps, offer the most compelling demonstration operating seamlessly grid connected during normal times, yet islanding instantly during upstream faults to keep critical feeders alive (Sun et al., 2011; Zeraati et al., 2018). As renewable penetration continues its upward trajectory, the role of battery storage in securing a stable, uninterrupted electricity supply will only grow more indispensable.

Optimization, Economic Performance and Environmental Impact

Designing a grid connected PVBESS system demands deliberate optimisation at every stage. Suboptimal sizing compromises either reliability or financial returns; careless siting degrades network performance instead of improving it; and poor dispatch schedules waste the very flexibility storage is meant to provide (Riffonneau et al., 2011). The optimisation problem spans multiple interdependent layers. Battery capacity occupies the central trade-off. Under sizing curtails backup duration and peaks having capacity; over sizing inflates capital expenditure without commensurate benefit (Riffonneau et al., 2011). Pflaum et al. (2017) addressed regulatory constraints on capacity, demonstrating that correct sizing directly improves project profitability and operational reliability. Modern solvers genetic algorithms, particle swarm optimisation, mixed integer programming systematically explore this design space to determine optimal capacities under diverse operating conditions (Azuatalam et al., 2019; Das et al., 2019). Placement within the distribution network is equally decisive. Poorly sited storage yields minimal voltage improvement and may even increase system losses. Macedo et al. (2015) demonstrated that optimal location reduces network losses and bolsters voltage regulation performance. Zhang et al. (2019) extended this logic to resilience, finding that coordinated placement of PV and storage significantly accelerates post disturbance recovery during extreme events a finding with direct implications for system planners.

Financial viability is assessed through lifecycle cost frameworks rather than simple payback calculations. Net Present Value, Internal Rate of Return, and discounted payback period are standard yardsticks; they capture not only initial outlay but also replacement cycles, maintenance, and degradation (Ratnam et al., 2016). Battery degradation heavily skews these metrics capacity fade forces premature replacement, elevating lifecycle expenditure substantially unless high cycle life chemistries are selected (Hesse et al., 2017). Bagalini et al. (2019) quantified that optimal dispatch, aligned with time of use tariffs, materially improves self-consumption and reduces annual grid purchases for residential systems. Ratnam et al. (2016) compared centralised versus localised optimisation methods for residential management, finding that intelligent scheduling yields significant economic advantages by exploiting price arbitrage and demand response signals. Saez DeIbarra et al. (2016) framed a co optimisation framework that couples capacity selection with control policy; their results showed superior economic outcomes compared to sequential design approaches, effectively integrating technical performance with profitability.

The reality, however, is that cost minimisation conflicts with reliability maximisation; pushing renewable utilisation higher accelerates battery degradation. Single-objective optimisation ignores these tensions. Multi-objective approaches Non dominated Sorting Genetic Algorithm II, differential evolution, artificial neural networks generate entire Pareto fronts of non-dominated solutions, empowering stakeholders to select configurations aligned with their specific risk/ return preferences (Azuatalam et al., 2019; Stecca et al., 2020). These frameworks explicitly trade off investment cost, operational expenditure, degradation rate, and reliability indices such as SAIDI or ENS within a single mathematical formulation.

Environmental performance provides the other compelling rationale. PV generation yields zero direct operational emissionsno CO_2, SO_x, NO_x, or particulates (Anjali and Sharma, 2017). Storage amplifies this advantage by reducing renewable curtailment: it captures otherwise wasted solar output during midday peaks and displaces fossilfired generation during evening ramps, thereby lowering the carbon intensity of every kilowatt our consumed (Barzegkar Ntovom et al., 2020). Distributed siting further cuts transmission and distribution losses, improving overall system efficiency (Das et al., 2019). Nevertheless, the upstream footprint is non-negligible. Manufacturing Liion batteries consumes lithium, cobalt, nickel, and manganese; mining and processing carry environmental and social costs. Responsible end-of-life recycling is imperative to contain the full lifecycle burden, and progress in closed loop material recovery is steadily addressing these concerns (Hesse et al., 2017). Several studies have quantified the net carbon benefit. Bagalini et al. (2019) found that residential PVBESS substantially lowers annual household emissions relative to PVonly or gas peaker alternatives. Zhang et al. (2019) confirmed that optimised, resilience -oriented deployment of PV and storage also serves long term decarbonisation goals, simultaneously cutting emissions and improving recovery capability. As Liion prices continue their downward trajectory and energy management algorithms grow more sophisticated, the economic and environmental cases converge more tightly. Multi objective optimisation frameworks that integrate technical, financial, and ecological criteria will be indispensable for steering largescale renewable deployment not as an academic exercise, but as a practical tool for investors, utilities, and regulators navigating the energy transition.

Outstanding Challenges and Future Trajectories

Despite two decades of intensive research and commercial deployment, grid connected PVBESS systems have yet to achieve their full technical and economic potential. Persistent obstacles span the technical, financial, and regulatory domains, and each exerts its own drag on adoption. Intermittency remains irreducible: cloud cover, seasonal shifts, and diurnal cycles impose output fluctuations that distribution networks must absorb or compensate (Anjali and Sharma, 2017). Battery degradation exacts a creeping toll capacity fade and efficiency loss accumulate with every cycle, accelerated by temperature extremes and deep discharges, ultimately raising lifecycle costs and undermining long term performance (Hesse et al., 2017). Weak distribution feeders, moreover, struggle to accommodate high instantaneous PV injections without violating voltage or frequency boundaries; sophisticated voltage regulation and frequency response schemes are non-negotiable under such conditions (Von Appen et al., 2014; Wang et al., 2014). The way forward demands intelligent battery management systems that anticipate degradation, forecasting tools that capture sub hourly irradiance variability, and adaptive control logic that can switch seamlessly between grid following and grid forming modes as circumstances dictate.

The economics, however, present an equally formidable barrier. Although Li-ion prices have plummeted, battery hardware still commands the largest share of total system capital outlay, particularly for residential and small commercial installations (Bagalini et al., 2019). Where retail electricity tariffs are low or feed in incentives are absent, the payback periods stretch beyond acceptable thresholds (Barzegkar Ntovom et al., 2020). Optimisation techniques that cosize storage and dispatch such as those proposed by SaezDeIbarra et al. (2016)can sharpen the business case, but they cannot compensate for fundamentally unfavourable tariff structures or the absence of value stacking opportunities. Regulatory frameworks complicate the picture further. Most existing policies were drafted for a centralised, fossil fuel era; they do not readily accommodate distributed storage as a multiservice asset capable of arbitrage, frequency response, and deferral of network upgrades simultaneously (Stecca et al., 2020). This policy rigidity curtails revenue streams and introduces investment uncertainty; two conditions that deter the very capital needed for scale up. Standardised technical guidelines and harmonised grid codes are prerequisites for reliable, large scale BESS integration, yet they remain fragmented across jurisdictions.

Emerging technologies, nonetheless,

offer a clear route forward. Next generation chemistries solid state, sodium on, zinc air, advanced flow batteries, and lithium sulphur variants promise higher energy densities, improved safety profiles, longer calendar lives, and lower material costs than current Liion systems (Hesse et al., 2017). Machine learning and artificial intelligence are permeating forecasting, real time scheduling, and fault diagnostics; these data driven methods can outperform rule-based EMS in capturing complex, non-linear system behaviours (Azuatalam et al., 2019). The convergence of Internet of Things (IoT) infrastructure, smart metering, and high bandwidth communication networks enable coordinated control of distributed resources at unprecedented temporal resolution, laying the foundation for fully integrated smart grid operations. Electric vehicles will enter the equation as mobile, dispatchable storage units; vehicle to grid (V2G) technologies permit bidirectional energy exchange, effectively turning parked EV fleets into flexible grid assets. Grid forming inverters will grow indispensable as synchronous generators retire, they must supply virtual inertia, voltage support, and black start functionality to maintain stability in inverter dominated networks (Stecca et al., 2020). Finally, community scale micro grids, aggregating PV, storage, and controllable loads under intelligent EMS, demonstrate that resilience and self-sufficiency are not merely theoretical constructs but achievable, localised realities. Capturing these opportunities hinges on sustained, interdisciplinary efforts panning electrochemistry, power electronics, control theory, data science, and regulatory design. The technical foundation is robust; the economic incentives are aligning; the policy environment, however, must catch up. With continued innovation across these fronts, PVBESS can transition from a promising niche to the structural backbone of a low carbon, secure, and responsive power system.

2. CONCLUSION

The rising worldwide need for clean and dependable energy has resulted in the swift installation of grid connected PV systems with BESS, and although PV technology generates clean and renewable electricity, the intermittent quality of PV power presents challenges to power reliability, voltage stability, and grid operation, all of which are well met by battery energy storage by offering the capacity to store energy, balance load, backup power, and improve the grid support features. This review presented the architecture, operation and performance of grid connected PV systems coupled with battery storage technologies. Different battery technologies such as lead acid, Li-ion and flow batteries have been discussed with their advantages, limitations and suitability for PV applications. Li-ion batteries are emerging as the likely choice due to their high energy density, superior efficiency and long operational life. The review also emphasised the importance of energy management strategies, such as energy flow management, charge discharge control, peak shaving, load shifting, and SC optimisation, where effective implementation of these strategies greatly improves the use of RE, reduces electricity costs, and improves overall system performance. Advanced control techniques such as centralised and distributed control approaches are playing a vital role in maintaining voltage stability, frequency regulation, PQ improvement and reliable grid operation. Battery integrated PV systems can provide valuable ancillary services such as reactive power support, spinning reserve and VR, thereby contributing to the development of modern SG. The study found that battery storage can greatly improve the reliability and resilience of the system by providing backup power during grid outages and enabling micro grid operation. Reliability indices such as SAIDI, SAIFI, CAIDI, and ENS were significantly improved with the effective deployment of BESS. Optimisation techniques such as battery sizing optimisation, storage allocation, economic optimisation, and multi-objective optimisation approaches were discussed as necessary tools to optimise system performance and cost minimisation. Economic and environmental analyses indicated that PV battery systems provide significant long-term benefits by reducing electricity costs, increasing SC, reducing greenhouse gas emissions, and increasing energy sustainability. However, there are still several challenges such as battery degradation, high initial investment costs, regulatory barriers, and the need for advanced control and communication infrastructures. Future research should focus on next generation battery technologies, artificial intelligence-based energy management, SG integration, vehicle to grid technologies, and grid forming inverter solutions to further improve the performance and economic viability of PVbattery systems. In summary, the integration of battery energy storage with grid connected PV systems offers a promising route to a reliable, resilient and sustainable PS. Further technological advances, supportive regulatory policies and innovative optimisation techniques will be critical to accelerate the adoption of grid connected PV systems with battery energy storage and support the global transition toward a low carbon energy future.

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