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Review

A comprehensive review of hybrid photovoltaic-battery systems: Evaluating progress, identifying key issues, and exploring future prospects in sustainable energy integration

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Abstract: The depletion of fossil fuel reserves and growing environmental concerns have led to a growing interest in photovoltaic (PV) generation systems and battery storage systems (BSS). Sunlight is harnessed directly by PV technology to generate clean and eco-friendly energy. Conversely, the appeal of BSS lies in its cost-effectiveness, reliable performance, quick response times, and extended lifespan. A comprehensive review of hybrid PV-BSS systems is conducted in this article to determine their practical applications for power systems and to identify possible improvements. In conclusion, the paper offers valuable insights into potential future developments for advancing hybrid PV-BSS systems. The objective of this review paper is to provide an overview of the latest research on PV-BSS hybrid systems. Providing a critical assessment of this field's research efforts, the study sheds light on their strengths, weaknesses, barriers, limitations, and prospects for the future. Several domains are investigated related to hybrid PV-BSS systems, including methods to extend their lifespan, analyses of cost reductions, optimal sizing, solutions for mitigating power quality issues, and efficient control of power systems.

Keywords: photovoltaics; energy storage; hybrid energy systems; grid integration; microgrid

1. Introduction

The global population's continual growth has necessitated an increase in electricity generation to meet the surging demand. However, this escalating power generation is heavily reliant on the ongoing utilization of fossil fuels like coal, natural gas, and oil [1]. This dependency on fossil fuels brings about a host of challenges, including the excessive emission of greenhouse gases, environmental concerns, depletion of fossil fuel reserves, rising fuel costs, and geopolitical tensions. The problems stemming from the reliance on fossil fuels can lead to an unsustainable situation, posing potential threats to human well-being and livelihoods [2]. As a result of their eco-friendly and abundant properties, renewable energy resources are not only the ideal solution but also the preferred alternative for addressing these challenges. The share of renewable energy in total electrical energy production continues to grow steadily, with approximately one-quarter of the total output derived from these sources [3]. Modern power systems benefit from various RE resources, such as solar energy, wind energy, and geo-thermal energy, among others. As a cost-effective and highly efficient source of clean energy, photovoltaics (PV) stand out as one of the most promising sources of renewable energy in the world [4]. Photovoltaic technology is used in a variety of applications, such as battery charging for cars, lighting systems for homes, space exploration, and communication schemes. Due to their cost-effectiveness and efficiency, crystalline silicon modules dominate the PV market among the different types of modules available [5].

By 2023, PV systems will generate about 800 GW of electricity, which is double what it was in 2017 [6]. Moreover, this capacity is on a trajectory of continuous expansion [7]. What makes PV systems particularly versatile is their inherent scalability, spanning from small-scale household setups (in the kilowatt range) to large-scale systems generating gigawatts of power. In numerous regions, PV systems hold the potential to serve as distributed generation units, claiming a significant share of the PV market. The consistent drop in the cost of PV systems has opened up diverse applications across various sectors. In particular, PV systems offer a practical solution for off-grid power systems that operate independently from the main electrical grid. These PV systems present distinct advantages, such as reduced operating and maintenance costs, making them an attractive option for such scenarios [8].

In addition to its location, natural factors also greatly influence the power generated by a PV system. The inherent unpredictability of PV generation can lead to supply-demand imbalances, voltage fluctuations, and system frequency deviations, among other challenges for the PV power generation industry. In order to overcome these constraints and ensure a consistent and uninterrupted power supply, ESS and PV technology must be combined.

Many types of energy storage systems are utilized in modern power systems, including compressed air energy storage (CAES), pumped hydro energy storage (PHS), flywheel energy storage (FS), and battery energy storage systems (BSS). In spite of their capability to store substantial amounts of energy, CAES and PHS are economically less attractive due to their high installation costs. Moreover, these storage solutions require meticulous maintenance to ensure optimal efficiency. In contrast, flywheel technology, while compact, tends to be expensive for large-scale energy management applications [9].

In recent years, BSS has gained popularity as an ESS due to its reliable performance and reasonable capital investment [10]. After analyzing the pros and cons of the BSS, it emerged as the most promising energy storage system for integrating with PV systems to mitigate power fluctuations and address issues related to power [11]. Several applications of the hybrid PV-BSS system have been studied in the literature, covering six domains: lifetime enhancement, system cost reduction analysis, sizing optimally, mitigating power quality issues, controlling the power system optimally, and shifting and minimizing peak loads. We do not include studies that only use PV, solely BSS, or other distributed energy resources (DER) units coupled with PV-BSS in this review.

This review paper’s objectives are to identify the hybrid PV-BSS system’s appealing applications and enhance the methods for making the most use of this coupled unit. This paper provides an overview of microgrids, PVs, and BSSs, as well as essential information about each technology. A comprehensive review of hybrid PV-BSS systems is provided, discussing both their advantages and limitations. Moreover, potential avenues for future research and recommendations regarding hybrid PV-BSS systems are outlined. Finally, this review concludes by underscoring the significance of the research findings.

2. A brief description of the PV, BSS, and microgrid systems

This section provides a basic description of the numerous types of battery storage, photovoltaic, and microgrid systems. In the development of PV systems, battery storage, and microgrids, great attention has been paid to the details.

2.1. Microgrid system

There are a variety of microgrid configurations available, from those that operate independently to those that are interconnected with the main grid, based on physical and economic conditions [12]. Traditional power systems are likely to be replaced by alternative systems due to many reasons, including rising fuel prices, bad power quality, lack of availability, natural disasters, and deterioration of infrastructure. In order to address these issues, microgrids are a modern innovation in the electric industry that can help [13]. **Figure 1** shows how microgrids are categorized based on the way they operate, connected power sources, applications, structures, and connections to dispersed resources.

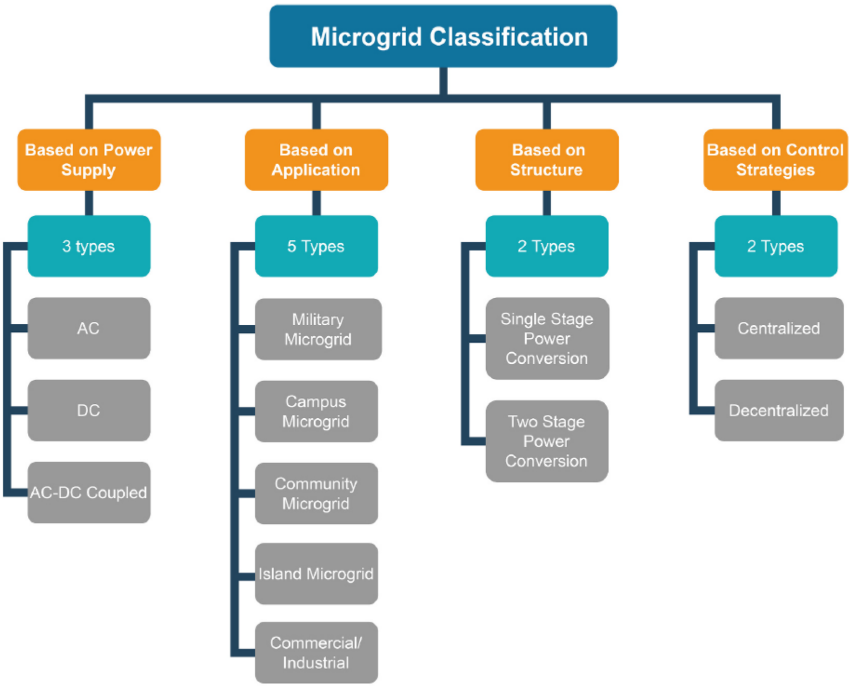

Figure 1. Classification of microgrid systems.

2.1.1. Microgrid system corresponding to its application

Microgrid systems fall into various categories when it comes to applications. The following is an overview of the primary five categories [14]:

a) Military microgrid

A military base camp’s small-scale, mostly autonomously operated power system is referred to as a military microgrid. Despite renewable energy sources being integrated into diesel generation systems, power is typically supplied by diesel generators.

b) Campus microgrid

Corporate, university, and college campuses could be included in this microgrid system. They are frequently introduced by electricity and heat together.

c) Community microgrid

Community microgrids can be utilized to electrify areas that have never been electrified before in developing nations. They are frequently employed in the developed world to assist towns in meeting their renewable energy goals.

d) Island microgrid

This little microgrid produces electricity on its own and is completely cut off from the larger grids. In order to operate this kind of microgrid visibly and inexpensively, renewable energy sources are being introduced.

e) Commercial and industrial microgrid

In the modern world, factories, industries, hospitals, and other establishments are able to generate and provide power for the loads that are linked on their own. Additionally, independent, this kind of power system is detachable from the major power grids. Occasionally, they might also be linked to the primary grids.

2.1.2. Power supplies-based microgrid

Based on the connected power supply, microgrid systems can be divided into three categories, which are briefly discussed below [15]:

a) AC microgrid

An AC (alternating current) microgrid is an independent, small-scale electrical distribution system that primarily operates with alternating current electricity. It typically consists of interconnected sources, loads, and control systems, all utilizing AC power.

b) DC microgrid

A DC (direct current) microgrid is a self-contained, small-scale electrical grid that primarily uses direct current electricity for its sources, loads, and distribution. DC power can be generated by renewable energy sources and stored in energy storage devices.

c) AC-DC coupled microgrid

Microgrids which integrate both AC and DC components are called AC-DC coupled microgrids. The system can distribute and manage energy more efficiently and effectively by using AC and DC power sources, loads, and storage systems simultaneously.

2.1.3. Control strategy-based microgrid system

The controlling strategies for the microgrid system can be broadly divided into two sorts, which are outlined below:

a) Centralized control microgrid

A microgrid with centralized control is one in which a single control center or system handles all aspects of managing and controlling the microgrid’s resources and components. Optimizing energy production, distribution, and consumption, this central control body makes decisions on the operation of power sources, energy storage systems, loads, and other devices inside the microgrid.

b) Decentralized control microgrid

A decentralized control microgrid is a type of microgrid where the management and control of the microgrid's components and resources are distributed across multiple control points or devices, rather than being centralized in a single control center. Distributed energy resources (DERs), loads, and energy storage systems are typically located near decentralized control microgrid controllers. In a microgrid, decisions and control are distributed among various local controllers.

2.2. PV system

This section provides an overview of various photovoltaic system types based on their uses and modes of operation, as well as various PV cell types depending on their raw materials. This section also discusses electricity export from PV systems based on various power system contexts. A photovoltaic cell is composed of several semi-conductive materials, including silicon, cadmium, gallium, germanium, titanium, and so forth. It is capable of directly producing solar energy from sunshine [16]. Many PV cells take their name from the semi conductive materials used in their construction. Metals can be classified by their useful characteristics, traits, and applications. Solar cells can be divided into three types based on their semiconductive metals and features: 1st generation, 2nd generation, and 3rd generation [17]. PV cells can be categorized into several different types as shown in **Table 1**.

Table 1. An overview of the various kinds of PV cells.

Aspect	First-generation solar cells	Second-generation solar cells	Third-generation solar cells
Material	Silicon	Thin-film technologies (CIGS, CdTe, a-Si)	Multilayer technologies, organic and hybrid solar cells
Efficiency	Moderate (typically 15%–22%)	Improved efficiency (ranges from 10%–18%)	Potentially higher efficiency (still under development, aiming for higher than 30%)
Cost	Relatively high cost due to silicon and manufacturing	Moderate cost due to thinner materials and less manufacturing complexity	Varied costs; some may be cost-effective due to new materials, while others may be pricier
Flexibility	Rigid, inflexible due to silicon wafers	More flexible due to the use of lightweight and thin-film materials	Offer greater flexibility due to the use of flexible substrates and new materials
Production scale	High-volume production but limited in design flexibility	Increasing production at larger scales with some design flexibility	Still in development stages, but advancements are being made for larger-scale production
Stability	Relatively stable and durable	Stability varies depending on the material used	Improved stability through new materials and designs, but still under scrutiny for long-term durability
Environmental impact	Manufacturing processes may have a moderate environmental impact	Reduced environmental impact due to the use of less material	Aimed at reducing environmental impact through the use of eco-friendly materials and production processes

Table 2 provides examples for the three generations of PV systems along with corresponding examples:

Table 2. Examples of different generations of solar cells.

Generation	Examples	Citation
1st	Monocrystalline	[18]
	Polycrystalline	[19]
	Amorphous silicon	[20]

Table 2. (*Continued*).

Generation	Examples	Citation
1st	Multi crystalline	[20]
	III-V single junctions	[20]
2nd	Cadmium telluride (CdTe)	[21]
	Gallium arsenide (GaAs)	[21]
	Cadmium sulfide (CdS)	[21]
	Microcrystalline silicon	[21]
	Copper indium gallium selenide	[21]
3rd	Dye sensitized solar cell	[22]
	Quantum dot solar cell	[22]
	Organic solar cell	[22]
	Perovskite solar cell	[22]
	Concentrated solar cell	[22]

A PV system can run independently or as part of a utility grid. Energy storage systems and other alternative energy resources can be combined with PV systems to provide alternating current (AC) and direct current (DC) power [23]. Solar panels are becoming more widely deployed, from residential homes to large-scale utility networks, as the cost of PV has decreased significantly. It has become increasingly popular to install PV systems in grid-connected power systems such as microgrids, residential homes, commercial buildings, and industrial buildings to generate electricity that can be used to increase self-consumption, lower electricity bills, or export excess electricity to the main grid [24].

2.3. Battery storage system (BSS)

Batteries storage systems (BSS) store electrical energy for later use in systems [25]. The BSS's popularity in the power system can be attributed to its quick reaction, ease of operation, multi-operation, and sensitivity [26]. Energy can be stored by pressing air into an underground hole and releasing it when it is needed to generate power during low load conditions [27]. This device's advantage is its long lifespan, but its downside is its low efficiency. In addition to having a long-life expectancy, pumped storage has a large capacity and can store energy for an extended period of time. Since pumped storage takes 4-6 years to build, its use has been limited [28]. A comparison of several energy storage devices is shown in **Figure 2** in terms of their energy density and power density.

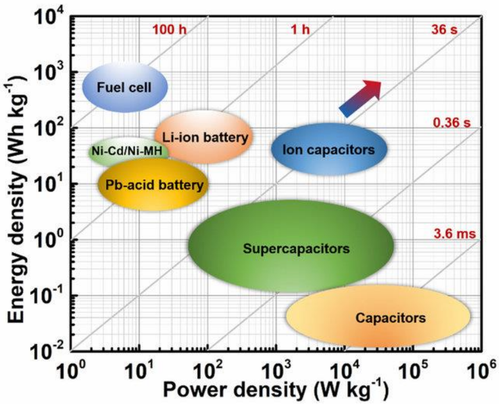

Figure 2. A comparison between the energy density and power density of different energy storage devices.

A wide variety of battery energy storage methods are available in the energy market, including sodium sulfur (NaS) batteries, lead-acid batteries, lithium batteries, and flow batteries. Among the most advanced and modern technologies for storing electrical energy are lithium-ion batteries as their energy density is high and they can be charged quickly. This battery's efficiency (80%–90%) is higher than that of other batteries [29]. It is possible for these batteries to perform differently due to their high operating temperatures. As these batteries have a high capital cost in comparison to other batteries, their prices are constantly falling. Currently, these batteries cost $175/kWh, but by 2030 they will cost $62/kWh [30].

Sodium sulfur batteries have a high and satisfactory storage efficiency, and they are flexible enough to be used in practical situations. Their versatility and light weight make them ideal for a wide range of applications [31]. These batteries have a number of drawbacks, primarily their high costs associated with the preparation and implementation of sodium solutions. Electrochemical flow batteries store energy by using ions distributed in liquid electrolytes. In addition to having a longer life cycle, these batteries are also more adaptable [32]. Some of the key disadvantages of these batteries include their implementation cost, energy density, and conversion efficiency.

3. Exploring cost reduction in a hybrid PV-BSS system

PV systems depend heavily on batteries to store electrical energy, so it is important to reduce the life expectancy of batteries to reduce costs [33]. It is possible to receive financial benefits as well as reliability from a battery storage with a long lifespan. A study of several HSS configurations for an island mode power system was conducted by Jing [33]. Researchers found that the HSS actively reduces battery storage's health costs. The cost-benefit analysis of BSS was conducted by Kuleshov et al. [34]. The hybrid PV-BSS system is advantageous for residential households according to his DC model of BSS and PV generation. Several technological advantages of PV-BSS hybrid systems have been examined by Sharma et al. [35]. There has been research on Building Integrated PV (BIPV) systems with or without batteries. In the study, the BIPV system with BSS proved useful to end users. Sepúlveda-Mora et al. [36] created a time of use (TOU) fee for three commercial buildings in the United States on the basis of a current flat rate. The purpose of this study is to investigate the impact of energy arbitrage on building efficiency and cost-effectiveness. Cost differences for the buildings will not be significant due to the proposed technique. In grid-connected configurations, R.H. Byrne invented a method for optimizing PV and ESS revenue [37]. The net revenue from energy exporting was calculated based on historical data and a national solar plant model. The system income is lower because fewer limits are ignored. In an attempt to reduce the cost of a grid-connected microgrid system, Teo et al. [38] proposed utilizing nondominated sorting genetic algorithms (NSGA) and fuzzy logic-based energy management systems (FEMS). PV-ESSs have been demonstrated to be highly cost-effective in microgrid systems through a few case studies in this research. Power generation costs can be reduced with the recommended solution. It is generally thought of as a distributed energy resource to use PV or BSS. Dispersed resource units can reduce power generation costs and system operation costs.

4. Hybrid PV-BSS system sizing for energy efficient power sources

There is also a significant factor to consider when designing a power system. Power systems should be sized based on the number of users and the potential linked loads. Small isolated microgrids (IMGs) have a number of characteristics that are important, but they have little impact on large-scale power systems [39]. LUU Ngoc proposed a sizing approach for integrating PV and BSS in microgrid systems. A technique has been developed for iteratively sizing microgrid power systems. Microgrid systems can be sized using this technique, resulting in lower operating costs and a smaller footprint [40]. Akram et al. have developed several methods for determining the appropriate size of PV-BSS hybrid power systems. Initially, he presented an iterative technique for grid-connected microgrids based on two restrictions [41]. Next, he performed the same procedure as before, but with only one constraint for a single power source [39]. In economics, the environment, and technology, all of the presented methodologies can be used to determine the ideal scale of the power system. A centralized, decentralized, and distributed control system was presented by Worthmann et al. [42] to reduce supply and demand imbalances. In addition, he focuses on protecting the power system against overvoltage by maintaining voltage frequency stability. The strategy protects the power system from defective conditions by calculating the right size without revealing any communication [42]. An optimal size for a hybrid PV-BSS power system was determined using a bi-level model developed by Zhou et al. It is possible to reduce electricity costs using this method [43].

5. Framework for energy management

Managing energy for the operation of a power system involves planning, coordinating, and controlling electricity generation, transmission, distribution, and consumption in a way that ensures efficient and reliable operation. It also involves minimizing the cost of electricity and reducing its environmental impact. Effective energy management is essential for a reliable, efficient, and sustainable electric grid. A suitable energy conversion system is essential for optimal power system operation. Large energy losses result from faulty conversion systems, which can negatively affect power system efficiency [44]. The transmission and distribution of power must be managed properly in order to maintain quality and efficiency. Energy management systems (EMS) that are suitable for power systems are discussed in this section. For smooth power transfer, voltage quality, and operational stability, Hu et al. introduced Model Predicted Power and Voltage Control (MPPVC). With this approach, AC/DC buses can meet expectations and maintain stable voltages [45]. An EM method for bidirectional power transmission has been proposed by Aktas et al. [46]. This study investigates PV-BSS's Unit Commitment (UC), and proposes a method to ensure the system's enhanced performance [46]. The voltage regulation scheduling technique presented by Tina et al. is a revolutionary one. Due to its ability to alleviate an overvoltage problem, the strategy is advantageous for the system [47]. Jayachandran et al. suggested a distributed secondary control technique for managing the load frequency and recovering deviated frequency in a freestanding AC-microgrid based on MPC. The proposed methodologies take into account RE generating units and BSS units. Voltage frequency can be returned to its initial value using the proposed technique [48]. A PV-BSS connected power system connected to an EMS is centrally managed by Li et al.'s aggregator service. By using this method, the load can be transferred during peak demand, saving electricity costs [49].

A distributed energy management system (EMS) based on multi-agent systems (MAS) is presented for regulating energy flow in hybrid energy systems. The battery unit is guided by fuzzy logic principles **(Figure 3)**. A hybrid microgrid system incorporating a solar array, a fuel cell, a battery, and a supercapacitor minimizes the drawbacks of fuel cells while providing sufficient and reliable power. Fuel cells are slow to respond during rapid changes in load power, so the battery and supercapacitor are employed to solve these problems. Power can be distributed across the dispersed generator components of a hybrid microgrid system, even when difficult conditions exist. The proposed energy management system provides high performance related to the existing energy management system [50].

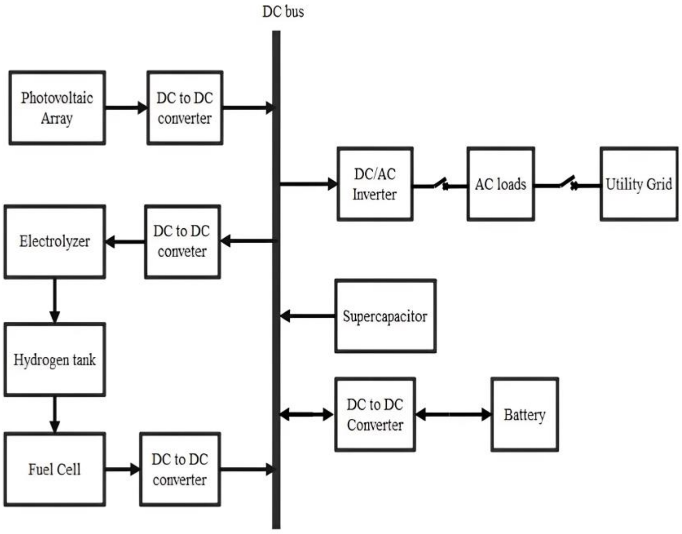

Figure 3. A distributed energy management system (EMS) based on multi-agent systems (MAS).

To meet the challenges of the 21st century, power system operators are developing and implementing new energy management strategies. In order to ensure a reliable, efficient, and sustainable electric grid, power system operators must manage energy efficiently. **Figure 4** shows a prototype for a stand-alone power system's energy management method [51]. The ultimate decisions of the strategy control the actions of multiple interconnected switches. A trio of electrical switches work in unison to oversee the transmission of power from power generation systems to distribution networks. As a result of this system's management, an optimal power flow is maintained in accordance with the connected loads and the power supply's capacity. Within the outlined process, PPV signifies the instantaneous power supply of the photovoltaic (PV) system, P_{Load} represents the electrical demand, and PAV indicates the surplus power available from the PV system after meeting the load requirements. Excess generated power (PAV) is reduced to zero when the electricity demand exceeds the PV system's power output. Alternatively, when the PV system's instantaneous power is equal to or greater than the demand, PAV registers as zero or higher. Switches

2 and 3 are activated if PPV is zero, while switch 1 is deactivated if PPV is zero. A switch 3 is switched on instead of a switch 1, and a switch 2 is switched off if the PPV exceeds zero. Switch 2 is triggered if the State of Charge (SOC) is below SOC_{max}, leading to switches 1 and 3 being turned off. Conversely, if the SOC surpasses SOC_{max}, switches 1 and 2 are engaged, while switch 3 is deactivated. These established criteria dictate the function of switches responsible for managing the electricity flow. This method, coupled with power generation systems, oversees the storage and distribution of power from storage units.

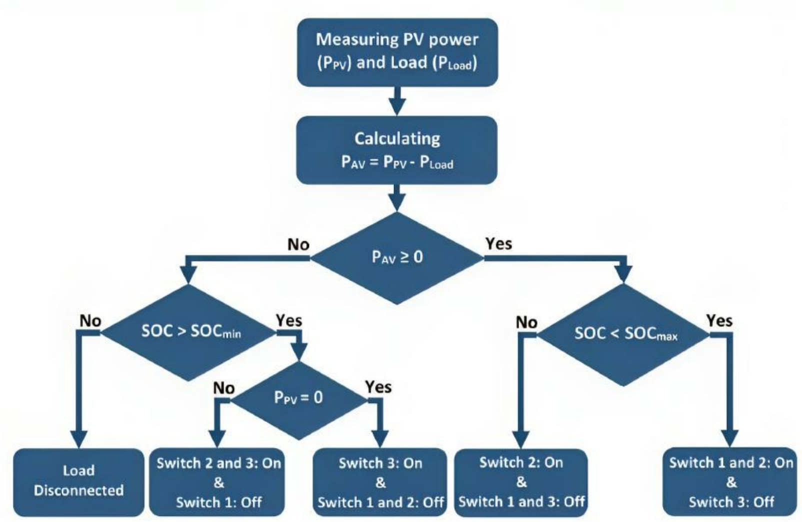

Figure 4. Mechanism for energy management in power system operation.

6. Future research directions based on existing research

Prior studies on hybrid PV-BSS systems propose viable approaches to enhance the power system's efficiency and cost-effectiveness. Due to the constraints within the current research, this section offers recommendations and insights for potential future research endeavors.

6.1. Lifetime enhancement

Research into improving the life-span of hybrid PV-BSS systems should focus on the following points:

1) Lifetime enhancement of BSS should be further investigated in PV-connected power systems, taking into account the system's real-time current and voltage profiles.
2) Most research studies focus on grid-connected power systems, however BSS lifespan improvement for isolated microgrid systems with hybrid PV-BSS units should be investigated to assure increased performance.
3) Designing an appropriate BSS model should prioritize the longevity of the energy storage system. While hybrid energy storage systems offer enhancements for aging, it's solely the BSS that can deliver superior and more economically efficient performance for a smaller power system. A small-scale power system therefore requires a BSS model that is specifically tailored to meet its needs.

4) It is possible to reduce generation uncertainty by properly forecasting PV generation and ensuring a nearly correct PV generation profile Incorrect PV generation predictions might put additional strain on the BSS unit, reducing its lifespan. The working period of BSS can be extended by taking into account the fluctuation in PV generation over time. It can also be looked into in the near future.

6.2. Reducing costs without sacrificing quality

The following factors can be taken into account in future analyses of reducing costs with a hybrid PV-BSS system:

1) IMG systems with hybrid PV-BSS units should be evaluated economically since this component is understudied in existing literature.
2) The hybrid PV-BSS system often has a high installation cost. In the future, the installation cost reduction for grid connected power systems and low investment IMG systems should be thoroughly examined.
3) Another vital factor in reducing costs involves determining the optimal capacity for the BSS. The assessment of cost reduction should consider the ideal BSS size. Furthermore, investigating a hybrid PV-BSS system with optimal capacity could significantly reduce overall system expenses. Even though the hybrid PV-BSS system has a higher initial installation cost, it proves beneficial over the long haul.
4) In future, it would be wise to contemplate reducing the replacement expenses associated with a hybrid PV-BSS system. Elevated replacement costs can contribute to an increase in the total system expenditure and may also affect the maintenance costs due to system replacements. Therefore, minimizing these replacement expenses is a sensible aspect to consider for the future.

6.3. Optimal power system control

A number of directions can be explored for optimizing power systems control, including:

1) An isolated microgrid’s optimal scheduling of power producing units can be significant. There are extremely few research studies on it in the extant literature.
2) There are several options for improving power quality and minimizing voltage drop for isolated microgrids. There is very little study done on this topic in the available research.
3) Dispersed generation units can also be controlled and positioned optimally for improved power flow operation in future research.
4) For preventing over-generation and rapid deterioration of electrical equipment, it is crucial to control renewable energy generation optimally. Over generation can cause voltage and frequency deviations in the system, lowering power quality. For the PV generation system, actual weather forecasts and seasonal effects should be considered.

7. Conclusion and future goals

An examination of hybrid PV-BSS systems was the purpose of this research. Based on the results of this study, we can identify promising applications of hybrid PV-BSS systems and enhance existing methodologies for utilizing them to achieve optimal power system performance. In order to gain a better understanding of integrated renewable energy power systems, it is necessary to explore microgrids, battery storage systems, and PV systems in detail. Using hybrid PV-BSS systems, future research prospects are outlined in order to enhance power system performance. We examine potential outcomes, limitations, and recommendations for future research on integrated power systems involving hybrid photovoltaic and battery energy storage systems. Several factors influence the practical implementation of this hybrid technology in power system applications, necessitating more in-depth research. **Table 3** below describes in-depth case studies of successful hybrid PV-battery system implementations, along with an analysis of the outcomes.

Table 3. Hybrid PV-battery system case studies.

Case study	Location	System size	Purpose	Outcomes	Lessons learned
Kauai island utility cooperative (KIUC)	Kauai, Hawaii, USA	58 MW PV, 129 MWh battery	Reduce reliance on fossil fuels, increase grid stability, provide backup power.	Increased renewable energy penetration, reduced reliance on fossil fuels, improved grid stability, provided backup power during outages.	PV and battery storage can work together to provide reliable and cost-effective renewable energy.
Hornsdale power station	Hornsdale, South Australia	150 MW battery	Provide frequency regulation, improve grid stability.	Reduced frequency regulation costs, improved grid stability.	Battery storage can provide valuable grid services.
AES alamitos energy storage	Long Beach, California, USA	350 MW battery	Provide peak shaving, load leveling, frequency regulation.	Reduced peak demand costs, improved grid stability.	Battery storage can help to reduce the need for expensive power plants.
Vermont energy storage and supply (VESS)	Ludlow, Vermont, USA	10 MW PV, 10 MW battery	Provide backup power, reduce peak demand, increase renewable energy penetration.	Provided backup power during outages, reduced peak demand, increased renewable energy penetration.	PV and battery storage can provide multiple benefits to the grid.
Tesla powerwall	Residential neighborhoods around the world	10–13.5 kWh battery	Provide backup power, reduce dependence on grid, reduce electricity costs.	Provided backup power during outages, reduced dependence on grid, reduced electricity costs.	Battery storage can provide homeowners with increased energy independence and cost savings.
Sonnen eco	Residential neighborhoods around the world	5–10 kWh battery	Provide backup power, reduce electricity costs, increase self-consumption of solar energy.	Provided backup power during outages, reduced electricity costs, increased self-consumption of solar energy.	Battery storage can help homeowners maximize the benefits of their solar PV systems.
Stem Grid	Residential neighborhoods around the world	10–15 kWh battery	Aggregate distributed energy resources to provide grid services.	Provide peak shaving, load leveling, frequency regulation.	Aggregated battery storage can provide valuable grid services.
GridX	Commercial and industrial facilities around the world	100–1000 kWh battery	Provide backup power, reduce peak demand, improve energy efficiency.	Provided backup power during outages, reduced peak demand, improved energy efficiency.	Battery storage can help businesses save money and improve their resilience.
Younicos	Commercial and industrial facilities around the world	500 kW–5 MW battery	Provide backup power, reduce peak demand, improve energy efficiency.	Provided backup power during outages, reduced peak demand, improved energy efficiency.	Battery storage can help businesses save money and improve their resilience.
EnerNOC	Commercial and industrial facilities around the world	10 MW–100 MW battery	Provide peak shaving, load leveling, frequency regulation.	Reduce peak demand costs, improve grid stability.	Battery storage can provide valuable grid services.

In power systems, achieving optimal energy distribution among different components remains a crucial responsibility. In order for this hybrid system to act effectively in power-sharing situations, it is essential to conduct a thorough analysis encompassing its overall performance, economic feasibility, system requirements, and capital investment. To optimize power sharing, a hybrid PV-BSS system will be considered in a future extension of this study.

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