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Sustainable solar/biomass/energy storage hybridization for enhanced renewable energy integration in multi-generation systems: A comprehensive review

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ABSTRACT

This review provides a comprehensive analysis of the critical challenges and recent advancements related to photovoltaic (PV), biomass gasification (BG), and energy storage (ES) technologies, beginning with technology-specific developments and progressing to their integration in hybrid configurations for power generation and multigeneration systems. Major challenges identified include PV intermittency and limited forecasting accuracy, short ES lifespan and scalability constraints, and persistent BG issues such as tar formation, feedstock variability, and high operational costs. Further difficulties arise during hybridization, including poor control synchronization, high capital costs, and the lack of robust, context-specific sustainability assessments. To address these barriers, this review synthesizes insights into three strategic pillars: (1) technological integration, including modular system design and advanced storage solutions, (2) advanced control strategies featuring AI-enabled energy management and demand-side optimization, and (3) comprehensive sustainability assessment frameworks grounded in life cycle analysis and socio-economic metrics. Original contributions include the development of three structured conceptual frameworks: one for guiding system-level hybridization, another for step-by-step implementation in multigeneration settings, and a third for enhancing sustainability, policy integration, and innovation pathways. The review concludes with a roadmap connecting theory to practice through smart grids, circular economy principles, and region-specific deployment strategies to support resilient, cost-effective, and environmentally sustainable energy systems.

1. Introduction

With the increasing global energy demand, limited fossil fuel resources, and pressing environmental challenges, developing sustainable energy systems is more critical than ever [1]. Multigeneration systems offer a promising approach, efficiently producing multiple forms of energy, such as electricity, heat, and cooling, from the same primary energy source, compared to conventional systems that typically generate only a single form of energy [2]. These systems are associated with higher energy efficiency, better performance, lower costs, and fewer emissions [2]. Research in sustainability highlights the potential of integrating renewable energy sources, solar, wind, biomass, geothermal into multigeneration systems [3]. Renewable energy sources, such as solar, biomass, wind, geothermal, and other clean technologies, are characterized by their ability to produce energy with minimal or zero pollutant emissions. Integrating these resources into multigeneration systems has gained significant attention due to their potential to improve energy efficiency by optimizing resource utilization [4], lower greenhouse gas emissions by replacing fossil fuels with cleaner alternatives [5], and promote resource diversification to improve system reliability and resilience [6]. However, the intermittency of solar and wind energy presents challenges for consistent energy delivery. A common solution involves hybridizing multiple renewables, which balances variability and enhances reliability. For example, Lian et al. [7] demonstrated that hybridizing renewable sources such as solar, wind, and hydropower enhances system reliability and promotes environmental sustainability. The complementary nature of these resources mitigates the intermittency inherent in single-source energy systems. Similarly, Guo et al. [8], in a comprehensive review of hybrid renewable energy (HRE) systems, found that combining solar, wind, biomass, and

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geothermal energy improves energy conversion efficiency while addressing resource intermittency. Their analysis also highlighted the importance of hybrid storage solutions for enhancing grid stability. Likewise, Hassan et al. [9] reviewed solar and wind hybrid systems, emphasizing their effectiveness in reducing intermittency and improving grid reliability. Hybridization facilitates consistent year-round energy generation by compensating for seasonal wind and solar output variations. Additionally, recent techno-economic evaluations confirm that hybrid systems, especially in rural applications, can optimize energy cost, improve system reliability, and deliver socio-environmental benefits. Ahmad et al. [10] and Patil et al. [11] conducted detailed techno-economic analyses of hybrid systems in rural Indian contexts, emphasizing configurations that optimize cost, reliability, and socio-environmental benefits. Ahmad et al. [10] identified the PV/WT/DG/Lead-Acid Flow system as optimal for achieving a high renewable energy share (93.3 %) and low levelized cost of energy (LCOE) ($0.192/kWh), highlighting how integrating renewable resources with storage can deliver both economic and social value, such as local job creation and infrastructure development. Complementing this, Patil et al. [11] evaluated multiple hybrid scenarios and confirmed the feasibility of using underutilized biomass in tandem with solar and wind, achieving competitive Cost of Electricity (COE) and substantial emissions reduction. Their comparative use of HOMER simulations underscores the growing relevance of software-based optimization tools in rural electrification strategies. Moreover, a broader climatic perspective was offered by Ref. [12], who evaluated hybrid system performance across nine Spanish cities. Their analysis highlighted how site-specific factors, such as wind availability, directly impact economic feasibility; for example, A Coruña achieved the lowest net present cost (NPC) and COE ($1.39M and $0.199/kWh), whereas Madrid exhibited the highest values due to lower renewable resource availability.

A range of hybrid configurations for multigeneration systems has been investigated in recent research. For example, solar-wind combinations enhance reliability through complementary resource profiles [5]; solar-geothermal systems leverage geothermal energy for stability [13]; and solar-biomass setups improve efficiency by utilizing biomass for storage [14]. Wind-biomass systems address intermittency [15], while more complex configurations, such as solar-wind-biomass or solar-wind-geothermal, provide a balanced approach to resource utilization [16,17]. The selection of hybrid configurations in real-world applications depends on local resource availability, economic feasibility, and site-specific conditions. While wind, tidal, and geothermal energy are regionally limited, solar and biomass are more broadly accessible and adaptable to various geographical settings [8,18].

Among the various hybrid options, the combination of solar and biomass stands out for its availability, complementarity, and potential for clean and reliable power generation. Solar energy harnesses solar radiation, while biomass derives energy from organic materials such as agricultural residues, animal waste, and urban organic matter [19]. This combination is widely studied and applied due to the complementary nature and broad availability of both resources. Sahoo et al. [20] conducted a detailed analysis of a solar-biomass polygeneration system that integrates parabolic trough collectors (PTCs) and a biomass boiler to produce power, cooling, and desalinated water. Their findings demonstrated that hybridizing PTCs with biomass effectively addresses intermittency, achieving high efficiency and economic feasibility. In another study, Sahoo et al. [21] explored the influence of biomass availability and solar direct normal irradiance (DNI) on the viability of solar-biomass polygeneration systems. They concluded that such systems are especially advantageous in industries where biomass is more economical than coal, highlighting their potential for reducing operational costs. Expanding on the thermoeconomic performance of solar-biomass hybrids, Khalid et al. [22] examined a multigeneration system designed for community applications. The study found that hybridizing solar and biomass provides a sustainable and economical solution by overcoming the limitations of individual energy sources. Future work on scalability, optimization, and integration with additional renewables to enhance the practicality of such systems is recommended from their work.

Another recurring theme in the literature is the critical role of energy storage systems in enhancing the performance and sustainability of hybrid systems, particularly in addressing the intermittent nature of renewable energy sources. Akinte et al. [23] emphasized the critical role of energy storage (ES) in improving the performance and reliability of hybrid solar-biomass systems. Their study demonstrated that integrating advanced storage technologies, such as lithium, sodium-sulfur, and flywheel batteries, allowed a photovoltaic-biomass hybrid system to achieve 93.9 % renewable energy penetration. This enabled stable operation in grid-connected, island-able, and off-grid modes, ensuring continuous power availability. Sharifishourabi et al. [24] also emphasized the importance of storage, particularly thermal energy storage, in ensuring consistent system performance and hydrogen production. Within this evolving landscape, advancements in energy storage technologies play a pivotal role in enabling efficient hybrid systems. Arévalo et al. [25] thoroughly reviewed of thermal energy storage advancements, emphasizing phase change materials (PCMs), sensible storage, and hybrid systems, with practical applications in stabilizing solar and wind generation. This work maps technological developments and identifies integration challenges that remain underexplored in operational contexts. Building on this, Zhang et al. [26] introduced biomass-based composite PCMs, reinforcing the potential of bio-derived materials in sustainable hybrid energy systems, especially in solar-biomass pairings where thermal management is critical. Together, these studies signify a shift towards material-level innovations that could unlock higher performance and sustainability in future hybrid configurations. Mohammadi et al. [27] reviewed solar-only and hybrid solar-driven multigeneration systems, emphasizing the potential of solar-biomass integration to enhance system reliability. The study highlighted biomass as a complementary or primary energy source to support solar energy, particularly in regions with abundant biomass resources. The authors called for more work on ES, optimization of hybrid photovoltaic (PV) configurations, and experimental assessments to improve system scalability and feasibility.

Hussain et al. [28] focused on the feasibility of integrating various solar technologies, including parabolic troughs, solar towers, linear Fresnel, and PV systems, with biomass in Europe. They highlighted the role of biomass in compensating for solar energy's seasonal variability, especially during winter.

Kasaeian et al. [29] examined solar-driven polygeneration systems that produce multiple outputs, including electricity, cooling, hydrogen, and fresh water. Their review highlighted the high energy and exergy efficiencies of concentrating solar technologies, such as parabolic troughs and solar towers, particularly when integrated with advanced systems like electrolyzers and gasifiers. They recommended future experimental studies to better understand real-world performance and cost reduction strategies.

Exploring alternative hybrid configurations, Pramanik and Ravikrishna [30] evaluated the integration of concentrated solar power (CSP) with other renewables, including biomass, wind, and geothermal. The review emphasized the environmental benefits of CSP-biomass hybrids, which offer low CO_2 emissions but identified challenges related to efficiency, cost, and resource availability. Future research should focus on enhancing efficiency, reducing costs, and improving energy storage solutions for these configurations. At the small scale, Figaj [31] demonstrated over 70 % energy savings in a hybrid trigeneration system, though economic viability remains sensitive to competing technology performance and policy factors. Kallio and Siroux [32] investigated HRE system combining photovoltaic-thermal (PVT) systems with biomass-fueled Stirling engines for micro-cogeneration. Their study proposed a system that meets residential electricity, heating, and hot water needs.

Based on the presented literature review, it is evident that there are several key trends and gaps in hybrid solar-biomass multigeneration systems. Many studies focusing on hybrid solar-biomass multigeneration systems have aimed at solar thermal technologies. In contrast, PV-based systems remain less studied. Regarding biomass technologies, most research has centered on using boilers and combustion systems, while only a few studies explore biomass gasification as a viable alternative. Catalytic gasification can increase hydrogen output and reduce tar formation, though catalyst cost and degradation are challenges. Faizan and Song [33] underscored the potential of catalytic gasification to improve efficiency and hydrogen yield, while minimizing tar formation, though they also noted persistent technical hurdles such as catalyst degradation and cost limitations. Complementing this [34], highlighted the promise of hydrothermal gasification as a cleaner, more effective option for wet biomass feedstocks, aligning well with low-emission multigeneration goals. These advancements indicate a paradigm shift toward cleaner, more efficient biomass processing pathways that are better suited for integration in hybrid systems, particularly when aligned with modern energy storage solutions.

Also, most studies have primarily concentrated on the theoretical aspects of energy storage systems, with limited attention given to their implementation's practical and operational challenges. Thus, while a substantial body of literature explores hybrid solar-biomass multigeneration systems, it often remains fragmented and narrowly focused on specific combinations or technologies of renewables. A comprehensive and integrative review that synthesizes this work, identifies systemic gaps, and proposes actionable frameworks is lacking.

This review responds to that gap by analyzing the sustainable integration of solar PV, biomass gasification (BG), and ES in multigeneration systems, and presenting strategies to address key challenges and promote scalable implementation. The original contributions of this review are: (i) Identification and categorization of technological, operational, and sustainability challenges in PV-BG-ES systems, (ii) Introduction of three new conceptual frameworks for integration, modeling, and optimization, and (iii) A step-by-step roadmap for real-world implementation and long-term deployment. This review paper addresses the following objectives to establish these roadmaps.

- To provide an overview of PV, biomass gasification, and energy storage systems, including key challenges and solution strategies.
- To investigate technical, control, and sustainability aspects of hybrid PV-BG-ES integration.
- To assess the contribution of renewable technologies to the technical performance (including reliability and resilience) and socio-political dimensions (including policy, regulation, and public acceptance) of multigeneration systems
- To examine modeling approaches and configurations, with emphasis on integration, microgrid applications, and advanced control strategies.
- To analyze real-world implementations to connect theory with practical outcomes.
- To propose comprehensive frameworks and incremental steps for reliable, efficient, and sustainable hybrid multigeneration systems.

At the end of this section, we briefly outline the methodology adopted for this comprehensive review. The study involved a structured literature search aimed at identifying and analyzing relevant research on the hybridization of PV, BG, and ES systems, with a particular focus on their sustainable integration into multigeneration systems. The primary search engine used was Google Scholar, supplemented by results from major academic databases such as ScienceDirect, IEEE Xplore, and Scopus, to ensure the inclusion of high-quality, peer-reviewed publications. Rather than limiting the search to "multi-generation" systems alone, the scope was expanded to include related system configurations, such as power generation, cogeneration (CHP), trigeneration (CCHP), and polygeneration systems. Search queries combined relevant keywords using Boolean logic (e.g., PV + biomass gasification + energy storage, sustainable hybridization + renewable energy, techno-economic + life cycle assessment + policy, etc.) to capture literature on both the technical and sustainability dimensions of hybrid renewable systems. Although no strict filter was applied regarding publication year, the majority of the reviewed works are recent, reflecting the rapid development of this research field in recent years. Studies were analyzed and classified based on whether they addressed theoretical, practical, or comparative aspects of hybrid PV-BG-ES systems, and were further evaluated according to three core themes: technological integration, advanced control strategies, and sustainability assessment (Sections 3 and 6). The organization of this paper reflects this classification and continues through an exploration of renewable integration in multigeneration systems (Section 4), modeling approaches (Section 5), case studies (Section 6), proposed frameworks for sustainable implementation (Section 7) and a Comparative evaluation of this review with existing literature (Section 8). A graphical abstract has also been included to provide a visual summary of the review's structure and content.

2. Renewable energy technologies

Solar and biomass energy are abundant, widely accessible renewable resources with significant potential to support global energy systems. Solar energy, captured from sunlight, is virtually unlimited and can be harnessed across most regions. Biomass, sourced from materials like agricultural residues, wood waste, and energy crops, can depend on regional conditions [19,35]. These resources are crucial for reducing fossil fuel dependence, mitigating climate change, and fostering sustainable development [36,37]. Various advanced technologies have been developed to harness these resources efficiently, each offering unique advantages and applications. The following subsections explore these technologies in detail, including PV systems, biomass gasification, and energy storage systems, which are essential for advancing sustainable and reliable energy solutions.

2.1. Solar energy technologies: photovoltaic systems

Table 1 presents an overview of solar energy technologies, including their advantages, disadvantages, and applications. These technologies vary in efficiency, cost, and application suitability. PV systems are widely used for electricity generation, offering moderate efficiencies (15 %–22 %, [38,39,40]) and scalability for both residential and commercial use. However, they require large areas and suffer efficiency losses in high temperatures. Concentrated solar power is ideal for large-scale power generation in sunny regions. It works by concentrating sunlight to generate heat, which can be stored for use during periods without sun. While highly efficient, CSP's high initial cost and land requirements limit its applicability to utility-scale plants in arid areas. Solar thermal energy (STE) is the most effective for heating applications, such as water and space heating. It is cost-effective for residential and commercial use but less efficient for electricity generation than PV and CSP. Solar thermoelectric systems convert heat directly into electricity but are less efficient and more expensive, making them suitable only for niche applications that require maintenance-free operation. Solar cooling systems efficiently reduce cooling needs in hot climates but have high initial costs. These systems are ideal for commercial and industrial cooling in regions with high demand. In summary, PV and CSP are most suitable for electricity generation, STE for heating, and thermoelectric and cooling systems for specialized applications.

For this study, PV technology was selected for further investigation due to its scalability, cost-effectiveness, and suitability for a wide range of applications. PV panels directly convert sunlight into electricity using semiconductor materials like silicon. Advances in materials, manufacturing processes, falling costs, and policy support over the past decade have significantly advanced PV technology, rendering it a viable option for most regions [44]. Nonetheless, challenges persist, including

Table 1
Overview of solar energy technologies: advantages, disadvantages, and application [38–43].

Technology	Description	Advantages/Disadvantages/ Application
Photovoltaic (PV)	PV panels convert sunlight directly into electricity using semiconductor materials like silicon.	- Efficiently converts sunlight into electricity, with commercial efficiencies from 15 % to 22 %. - Falling costs and scalability make PV systems economically attractive for both small and large installations. - Requires large areas for significant power generation, and efficiency decreases with high temperatures. **Best for:** General electricity generation, residential and commercial applications.
Concentrated solar power (CSP)	CSPs concentrate sunlight onto a small area to generate heat, which is then used to produce electricity.	- Highly efficient for large-scale power generation and capable of storing thermal energy for use during non-sunny periods. - High initial costs and land requirements can be barriers, but it's cost-effective in areas with abundant direct sunlight. **Best for:** Utility-scale power plants in sunny, arid areas.
Solar thermal energy (STE)	STEs use sunlight to heat fluids directly/indirectly for hot water, space heating, and electricity.	- Highly efficient for direct heating applications, such as water and space heating. - Cost-effective for heating purposes, but less so for electricity generation compared to PV and CSP. **Best for:** Residential and commercial heating, especially in colder climates.
Solar thermoelectric systems	These technologies convert heat directly into electricity using thermoelectric materials.	- Solid-state technology with no moving parts, but generally less efficient than other solar technologies. - High costs and lower efficiency limit its appeal for large-scale power generation. **Best for:** Niche uses requiring maintenance-free operation.
Cooling and refrigeration systems	These systems use solar energy for cooling without grid electricity.	- Highly efficient in hot, sunny climates, reducing cooling electricity needs. - High initial costs and complexity can be a barrier, but it's economically attractive in regions with high cooling demands. **Best for:** Commercial and industrial cooling in hot climates.

intermittency, reducing costs, ensuring sustainability, and overcoming grid integration and regulatory hurdles. Various solutions have been proposed in the literature. To manage intermittency and grid integration, several studies have suggested integrating complementary technologies and renewable energy sources. For example, Traube et al. [45] explored the integration of electric vehicle charging with PV systems. They found that adding small energy storage (0.05 kWh/kW) could significantly reduce ramp rates by 90 %, improving grid stability. Their experimental validation with a 10-kW charger demonstrated how this solution could mitigate solar intermittency and enhance the grid integration of PV systems. Similarly, Badwawi et al. [46] examined hybrid systems that combine solar PV and wind energy, addressing both intermittency and power fluctuations in weak grids. Their findings suggested that combining these resources can improve reliability and reduce operational costs. They concluded that forecasting and optimization are essential for ensuring efficient integration, making hybrid systems a viable solution for renewable energy adoption. In the residential sector, Mehmood et al. [47] studied the integration of solar PV systems, emphasizing the importance of energy sustainability from both a technical and economic perspective. They found that while grid-connected systems provided greater overall energy impact, systems with battery storage performed more competitively. The study highlighted the economic and environmental benefits of incorporating poly-Si energy devices and lead-acid storage systems, contributing to enhanced sustainability in residential energy solutions.

To tackle the challenge of cost reduction, Gervais et al. [48] analyzed sustainability gaps within the PV industry. They highlighted issues such as resource use, waste management, and hazardous substances in the PV lifecycle. Their proposed solutions emphasized the importance of context-based sustainability assessments to measure PV's progress toward planetary boundaries. This approach could guide future PV industry practices and improve cost-efficiency through enhanced life-cycle management. Regarding cost reduction and efficiency improvements, Kavlak et al. [49] provided an in-depth analysis of the cost decline in PV modules. Their research indicated that improvements in module efficiency and material costs were crucial drivers of cost reduction, with economies of scale and research and development (R&D) playing significant roles. They noted that larger plant size offer considerable potential for future cost reductions. They also argued that public R&D should complement market policies to overcome the limitations of current PV technology and explore alternatives like new materials to ensure further cost reduction in the future. Finally, the regulatory and policy challenges related to PV integration were addressed by Zsiboracs et al. [50], who focused on regulatory frameworks and policy measures in the European electricity market. Their study highlighted that improved forecasting, especially intraday forecasting, could significantly reduce the need for grid balancing in PV systems. They also found that integrating energy storage technologies, such as lithium-ion and vanadium redox flow batteries, could help stabilize the grid and reduce regulatory burdens. They called for stronger policies supporting forecasting and energy storage solutions, arguing that regulatory frameworks must evolve to facilitate the growth of renewable energy sources like PV while ensuring grid stability and energy security.

In conclusion, the reviewed studies emphasize the critical role of energy storage in addressing PV systems, particularly intermittency and grid integration. Technologies such as lithium-ion and vanadium redox flow batteries essential for stabilizing the grid, enhancing forecasting accuracy, and reducing regulatory burdens. These advancements are key to enabling a more sustainable and cost-effective renewable energy future.

2.2. Energy storage technologies

Energy storage technologies are crucial for ensuring grid stability, particularly with the growing integration of intermittent renewable energy sources such as solar and wind. These technologies store excess energy generated during periods of high production or low demand and release it when generation is low, or demand is high. By balancing supply and demand, ES supports grid reliability and facilitates the widespread adoption of renewable energy [51]. Different ES technologies vary in capacity, response time, and application. Table 2 presents an overview of these technologies, including their description, advantages, disadvantages, and applications.

Electrochemical energy storage, such as batteries, offers high

Table 2
Overview of energy storage technologies: advantages, disadvantages, and application [51–53].

Technology	Description	Advantages/Disadvantages/ Application
Electrochemical	Electrochemical energy storage systems store and release energy through reversible chemical reactions or electrostatic processes. Classification: classical rechargeable batteries (lead-acid, lithium-ion, lithium polymer, metal-air, nickel based, sodium-ion), flow batteries (redox flow and hybrid flow), and electrochemical capacitors (hybrid capacitors and pseudocapacitors).	- High efficiency and rapid energy delivery, scalable for diverse applications, integrates well with renewables. - Expensive with limited material availability, Degrades over time with use **Best for:** Renewable energy storage, electric vehicles, portable electronics, and grid stabilization.
Mechanical	Stores energy through physical mechanisms like compression, tension, or motion. Classification: pumped hydroelectric (PHES), compressed air (CAES and ACAES), liquid air (LAES), flywheels (FES), and gravity (GES).	- Long lifespan, high reliability, low operational costs, environmentally friendly with no chemical waste - Requires large space and infrastructure, Limited energy density compared to other technologies **Best for:** Grid-scale storage, peak load management, and renewable energy integration
Thermal	Stores energy as heat or cold for later use, using materials like water, molten salts, or phase-change substances. Classification: sensible heat (liquid, solid, gas), latent heat (Phase Change Materials (PCMs), and thermochemical (chemical reactions and sorption systems).	- Cost-effective, scalable, long storage, supports renewables, and heating/ cooling. - Low energy density, design-dependent efficiency, limited portability and application flexibility. **Best for:** Heating and cooling systems, industrial processes, and renewable energy storage.
Chemical	Stores energy in chemical bonds, often through hydrogen, synthetic fuels, or other chemical processes, for later conversion to energy. Classification: hydrogen, ammonia, methanol, alternative fuels, and synthetic fuels.	- High energy density, long-term storage, supports energy transport. - Inefficient conversion, high costs, safety concerns. **Best for:** Long-term energy storage, industrial applications, and renewable energy transportation.
Electric & Magnetic	Stores energy in electrical form, typically using capacitors or supercapacitors, for quick release of energy when needed. Classification: superconducting magnets (SMES), capacitors and supercapacitors.	- High power density and rapid charge/discharge rates, long cycle life with minimal degradation, simple and efficient for short-term storage. **Best for:** applications requiring quick bursts of power, like in electric vehicles and grid stabilization.
Hybrid	Combines multiple energy storage methods (e.g., electrical, chemical, and mechanical) to optimize performance, efficiency, and versatility.	- High energy density, efficient, flexible, supports renewables, balances storage needs - Complex, costly, integration challenges, limited commercial availability. **Best for:** large-scale renewable energy systems, grid storage, and electric vehicles requiring high performance.

efficiency, rapid power delivery, and scalability, but can be costly and degrade over time. Specifically, lithium-ion batteries are associated with high energy density and fast response, however also with large costs and limited operational lifespan. Mechanical storage (e.g., flywheels, compressed air) provides a long lifespan and low operational costs but lacks high energy density and requires significant space. Pumped hydroelectric energy storage (PHES) systems are scalable and provide large capacity, although their environmental impact is high and are restricted to specific geographic regions. Thermal energy storage (TES) is cost-effective for long-term energy retention but has low energy density and limited flexibility. While its lower energy density and flexibility pose challenges compared to electrochemical or mechanical storage, recent advancements in materials and system integration have improved its responsiveness and viability in multi-generation systems. Prior work, such as Arévalo et al. [25], provides foundational insight into these advancements, which continue to evolve through innovations in latent and thermochemical storage mechanisms, complementing solar-biomass hybrid configurations. Chemical storage, like hydrogen, offers high energy density for multiple applications but, faces conversion inefficiencies, high costs and safety concerns. Electric and magnetical storage in capacitors excels at fast charge/discharge, power density, and life cycle but has low energy capacity. Hybrid technologies combine multiple methods for improved efficiency, though they are still complex and expensive.

Regarding energy capacity, mechanical storage together with chemical and molten salts sensible thermal systems provide the largest figures in the order of GWh [54]. Concerning the discharge times at rated power, high-power supercapacitors and superconducting magnets (SMES) can respond in seconds; most electrochemical systems except for flow batteries and high-energy supercapacitors in minutes; and mechanical and chemical systems in hours. Fuel cells can supply high energy densities (about 103 Wh/kg [55]) and capacitors, pretty large power densities (almost 104 W/kg [55]). Lithium-ion batteries, SMES and flywheels (FES) are the most efficient ES systems. The lowest capital costs (CAPEX) are found for electrochemical systems such as Pb, NaS, and lithium-ion batteries and the lowest Levelized Cost of Storage (LCOS) corresponds to pumped hydro energy storage.

For PV systems, electrochemical energy storage is commonly used due to its scalability, flexibility, and rapid response to solar generation fluctuations [56]. Depending on system size and needs, pumped hydro and thermal energy storage can also be effective options. Recent research on ES technologies for PV systems focuses on enhancing efficiency, reducing costs, improving reliability, and addressing environmental concerns. For instance, Akbari et al. [57] reviewed ES solutions to address PV intermittency and improving grid stability. Their findings emphasize the crucial role of ES in supporting grid stability and facilitating the adoption of electric vehicles (EVs). They also highlighted solutions like Vehicle-to-Grid systems, which help address grid congestion and contribute to decarbonization. Advanced storage integration and demand management were identified as essential for creating efficient and resilient energy systems. Similarly, Hannan et al. [58] focused on battery energy storage systems (BESS), tackling challenges such as cost, power quality, aging, and environmental impact. Their findings stress the importance of optimization techniques and the development of advanced battery technologies. Key solutions included better integration with renewable energy sources and novel optimization approaches to enhance system reliability, sustainability, and affordability. Addressing the intricacies of battery management systems (BMS), Nyamathulla and Dhanamjayulu [59] identified critical challenges, including fast-charging degradation, thermal management, and environmental concerns. They emphasized the need for accurate estimation methods for the State of Charge and State of Health while advocating for improved recycling and Life Cycle Assessment (LCA) strategies. Proposed solutions included hybrid algorithms, advanced thermal controls, and universal BMS designs platforms to improve the performance and safety of lithium-ion batteries, which are vital for EVs and PV integration. The environmental implications of battery storage systems were explored by Simpa et al. [60], who underscored the importance of conducting LCAs to assess the full lifecycle impact, from raw material extraction to disposal. Addressing issues such as thermal runaway, resource depletion, and pollution, the authors called for responsible material sourcing, recycling initiatives, and second-life applications. Strong policy frameworks, technological innovation, and multi-stakeholder collaboration were identified as key enablers of sustainable energy storage systems.

In contrast, Parzen et al. [61] critiqued traditional cost-reduction approaches for evaluating ES technologies. They introduced the "market potential method," which assesses storage technologies based on their overall system value rather than focusing solely on cost. Their findings suggest that high-cost technologies, such as hydrogen storage, can deliver significant long-term benefits by enhancing system performance and aligning with future energy market needs. In the context of hybrid multigeneration systems, thermal energy storage technologies are gaining prominence due to their ability to improve dispatchability and system flexibility. Barrasso et al. [62] demonstrated that TES enhances the economic and energetic performance of solar-assisted multigeneration systems, particularly when integrated with concentrating solar technologies and gasifiers. Ma et al. [63] further proposed a dynamic packed-bed TES model suitable for biomass-supported hybrid configurations, providing improved thermal response for long-duration storage needs. Finally, challenges such as grid integration, scalability, and safety are being addressed through advanced control algorithms, system design improvements, and safety protocols [64].

Overall, these studies collectively illustrate that advancements in ES technologies is addressing key challenges like grid integration, scalability, safety, and environmental impact. Solutions such as advanced optimization techniques, improved BMS designs, and comprehensive lifecycle assessments are paving the way for more efficient, sustainable, and reliable energy storage in PV systems. By focusing on system-level performance and long-term benefits, these efforts contribute to a cleaner and more resilient energy future.

2.3. Biomass energy conversion: gasification technology

Table 3 compares various biomass technologies, highlighting their processes, applications, and energy outputs. Direct combustion is the most basic method, used to generate heat, steam, or electricity in both domestic and industrial settings. In contrast, thermochemical processes like gasification, pyrolysis, and liquefaction offer greater versatility. They cover biomass into syngas, bio-oils, biochar, and hydrogen, which can be used for power generation, biofuel production, and industrial chemicals. Biochemical processes such as fermentation and anaerobic digestion focus on producing ethanol and biogas from organic materials. These methods are especially for waste management and small-scale applications. Physicochemical processes, like extraction, primarily produce biodiesel and are used in specific industries like bioenergy. In this context, Kostyrin and Machina [65] proposed a mathematical framework to optimize biofuel production from timber industry waste, highlighting the importance of factors such as moisture content and transport distance. Their model demonstrated that thermal biofuel energy yields remain favorable when transport is under 80 km and feedstock moisture is below 60 %, providing insights into practical waste-to-bioenergy logistics. Additionally, Koestoer et al. [66] explored the downstream application of green ammonia, potentially derived from renewable hydrogen or biomass sources, for localized fertilizer production. While not focused on thermochemical conversion directly, their work highlights a complementary pathway where renewable or biomass-linked nitrogen compounds can support low-carbon agricultural systems, especially in rural contexts facing fertilizer supply constraints.

Although direct combustion is relatively simple and effective for heat production, thermochemical methods, particularly BG, demonstrate

Table 3
Overview of biomass technologies: processes, application and energy output [67–69].

Technology	Processes	Application	Produced energy
Direct combustion	Domestic scale	In wood-rich rural areas	Heat for cooking or residential spaces
	Industrial scale	1) Drying, heating buildings, or powering industrial boilers, 2) Large-scale biomass power plants	Process heat, steam, electricity
Thermochemical	Gasification	- Biomass power plants: using syngas in gas turbines, engines, or fuel cells - Industries needing high-temperature heat: using syngas for industrial processes, heating, or water heating. - Multigeneration systems: Biomass gasification integrated into multigeneration systems	Electricity, heat
		- Biofuels synthesis: syngas can produce liquid biofuels like bioethanol, biodiesel, or synthetic hydrocarbons. - Biochemical conversion: syngas can be used in biochemical processes to produce bio-based chemicals. - Hydrogen production: syngas can be processed to produce a hydrogen-rich gas mixture.	Hydrocarbons, methanol, H_2
	Pyrolysis	1) Biofuels Production, 2) Chemical Feedstock	Bio-oils
		1) Agricultural soil amendment, 2) Environmental remediation, 3) Carbon sequestration	Biochar
	Liquefaction	Transforming biomass into liquid fuels and chemicals for use in transportation, industry, and agriculture.	Bio-oils
	Torrefaction	Converting biomass into solid fuels and products for energy and industry.	Dry, energy-dense solid fuel
	Plasma treatment	Subjecting biomass to high-temperature plasma.	H_2, liquid biofuels
Biochemical	Fermentation	Biofuels, food and beverage, pharmaceuticals, biotech, chemical synthesis, and environmental remediation.	Ethanol
	Anaerobic digestion	Breaks down organic materials without oxygen, producing biogas and digestate.	Biogas
Physicochemical	Extraction	Biochemical, pharmaceutical, food, beverage, bioenergy, industrial, and environmental sectors.	Biodiesel

significant versatility in producing electricity, biofuels, and value-added chemicals. This paper focuses on the potential of BG as a cornerstone technology in renewable energy systems. Recent studies emphasize the integration of BG into hybrid renewable systems, such as solar-biomass cogeneration and multigeneration plants, where its flexible output and waste-to-energy benefits complement intermittent energy sources [70].

Biomass gasification represents a promising pathway for sustainable energy production, offering benefits such as fuel flexibility, emissions reduction, and potential for carbon neutrality [71]. This technology converts organic materials into energy products like syngas, biofuels, and electricity by heating them in a controlled environment. Biomass, mainly wood, agricultural residues, and others, undergoes preprocessing before being converted into syngas through three main technologies: Fixed-bed, Fluidized-bed, and Entrained-flow [72]. The resulting syngas, containing CO, H_2, CH_4, and CO_2, is cleaned and conditioned before being used in applications including power generation, heating, biofuels, and chemicals [71].

Recent advancements in gasifier designs, feedstock preprocessing, and integration with complementary processes have significantly improved the technology's efficiency, reliability, and environmental performance [73]. For example, Sikarwar et al. [74] explored innovations to enhance BG efficiency by addressing critical challenges like tar formation, operating parameters, and reliability. Their proposed solutions, multi-stage and plasma gasification, coupled with advanced modeling techniques like Computational Fluid Dynamics (CFD) and Artificial Neural Networks (ANN)—demonstrate pathways for process optimization and efficiency gains. Plasma gasification, by utilizing extremely high temperatures generated by plasma torches, significantly reduces tar production and can handle a wide range of heterogeneous feedstocks [75]. Although plasma gasification offers high syngas quality and environmental benefits, it currently operates at a Technology Readiness Level (TRL) of 6–7, indicating pilot-scale demonstration with further work required for commercialization [76].

Further, research by Tezer et al. [77] highlights BG's potential for hydrogen-rich syngas production. By examining diverse biomass feedstocks and operational conditions, they emphasized the need to optimize syngas yields while minimizing carbon footprints. Solutions such as improved gasifier designs, enhanced syngas cleaning methods, and reduced tar formation were identified as key steps toward large-scale implementation. Dual-bed gasification systems, comprising separate reactors for combustion and gasification, allow better control over reaction conditions, leading to higher hydrogen yields and lower tar contents. This configuration enhances syngas quality by decoupling the combustion and gasification zones. Dual-bed gasifiers are relatively mature, with TRLs ranging from 7 to 8, reflecting advanced pilot plants and early-stage commercial systems [78].

Additionally, Sutton et al. [79] focused on catalysts development to enhance BG's economic feasibility. Their study evaluated dolomite, alkali metals, and nickel catalysts, noting that while dolomite effectively removes heavy hydrocarbons, it cannot reform methane. Nickel catalysts excel in syngas production but suffer from carbon deactivation. The authors suggested combining dolomite and nickel catalysts as a practical approach to balancing cost-effectiveness and performance. Catalytic reforming has also emerged as a promising solution for tar reduction and syngas upgrading. Catalytic reforming shows high effectiveness in tar cracking, although catalyst deactivation and cost remain challenges. Depending on the type of catalyst and system integration, catalytic reforming technologies for biomass gasification currently demonstrate TRLs between 5 and 7 [80].

Ruiz et al. [81] reviewed the barriers to BG for electricity generation, highlighting challenges such as selecting appropriate gasifiers, biomass moisture content, and tar formation in syngas. They noted that high moisture levels reduce efficiency and cause syngas instability. To improve fuel stability, the authors recommended pre-treatment methods like pyrolysis or torrefaction. To address tar issues, they suggested optimizing gasifier designs, adjusting operating parameters, and employing catalysts or additives. The paper also discussed the complexities of syngas cleaning and the instability caused by variations in biomass composition. The study concluded that while BG shows promise, significant technological and operational challenges remain.

Meanwhile, Sansaniwal et al. [82] examined both technical and non-technical barriers to BG's sustainable development, including biomass supply chain management, pretreatment, and high syngas cleaning costs. Their analysis highlighted strategies such as improved logistics, hybrid machinery for biomass collection, and waste-heat utilization to overcome these hurdles. Non-technical challenges, such as workforce development and supportive policy frameworks, were also emphasized as critical for successful commercialization. Emerging economic assessments also point to the competitiveness of BG in distributed energy systems. Chattopadhyay and Ghosh [83] conducted a techno-economic analysis of a hybrid tri-generation system that integrates biomass gasification and solar energy. The economic analysis revealed an effective price of electricity (EPOE) of 0.068 USD/kWh without subsidies, which drops to 0.04 USD/kWh with a 50 % capital subsidy. The discounted payback period is 10.8 years without subsidy and 5 years with a 50 % subsidy. The study emphasizes that for high discount rates (above 8 %), a minimum of 25 % subsidy is necessary for the system to remain economically viable. This tri-generation system shows promise for rural or remote applications where both biomass and solar resources are available, offering a cost-effective solution with potential for broader deployment in hybrid renewable energy systems.

In summary, advancements in BG technologies—including gasifier design, catalyst development, and preprocessing techniques, have significantly improved syngas quality, efficiency, and environmental performance. However, persistent challenges, such as tar formation, biomass variability, and high operational costs, continue to limit large-scale adoption. Addressing these issues requires ongoing research into advanced gasification methods, durable catalysts, and integrated pretreatment processes. Emerging solutions such as plasma gasification, dual-bed reactors, and catalytic reforming offer promising pathways to overcome these technical barriers, with TRLs indicating progressive movement from pilot to early commercial stages. Moreover, recent research underscores the importance of integrating BG into hybrid multigeneration and decentralized systems, where its firm output helps balance variability from other renewables [27]. Coupled with hydrogen production and thermal storage, BG can support cogeneration, desalination, and district heating applications. Solutions to non-technical barriers, including improved supply chain logistics and supportive policies, are essential to drive commercialization. With these efforts, biomass gasification holds immense potential to contribute to global energy sustainability, reducing dependence on fossil fuels and advancing renewable energy systems.

3. Hybridization strategies for PV, BG, and ES in power production

Hybridization in renewable energy integrates diverse sources and storage to overcome limitations like intermittency and variability, ensuring reliable and sustainable power generation [7,8]. Recent research has focused on strategies to improve hybridization by enhancing efficiency, reliability, and sustainability. One key approach is **complementary pairing**, which integrates energy sources with different generation profiles, availability, or geographical characteristics that complement each other. This strategy enhances energy output, minimizes resource wastage, and improves overall system reliability [84]. Another widely adopted strategy is **system design and optimization**, which applies multi-criteria decision analysis to select the optimal renewable combination. Factors such as cost, efficiency, and environmental impact are considered using advanced software tools like HOMER (Hybrid Optimization Model for Electric Renewables) for simulation and optimization [85]. Similarly, **techno-economic optimization approaches** utilize mathematical models to determine cost-effective configurations and operational strategies. By evaluating resource availability, energy demand, and economic feasibility, this approach provides actionable insights for designing hybrid systems for both grid-connected and off-grid applications [86,87]. In this context, the economic dimension of hybridization plays a central role in determining its practical applicability. The cost-effectiveness and return on investment (ROI) of renewable hybrid systems vary significantly depending on scale, local resources, and market factors. For instance, a study in Spain reported the LCOE for these hybrid systems ranging from $0.199 to $0.374/kWh across different cities, highlighting the influence of regional factors on cost-effectiveness [12]. In Ghana, a PV-assisted biomass gasification system achieved an LCOE of $0.287/kWh, demonstrating economic viability in rural electrification contexts [88]. The costs of PV modules, biomass processing units, and energy storage systems influence capital expenditures. Operational expenditures (OPEX) depend on factors like biomass feedstock availability and maintenance requirements. For example, a study in Iran designed an optimized hybrid system with a biogas generator, PV panels, wind turbine, and batteries, achieving a cost of energy of $0.201/kWh, showcasing the potential for cost-effective solutions in remote areas [89]. Financial viability is assessed through ROI and payback period analyses. In the Ghanaian case, the hybrid system recovered the initial investment within approximately 7 years, indicating a favorable ROI [88]. Similarly, in Switzerland, PV-battery systems showed varying payback periods depending on customer profiles and policy scenarios, emphasizing the importance of context-specific analyses [90]. Economic feasibility is closely linked with energy policy frameworks. Government subsidies, feed-in tariffs, and carbon pricing mechanisms significantly influence investment attractiveness. For instance, feed-in tariffs have been successfully implemented in countries like Germany and Japan, providing long-term contracts and fixed prices to renewable energy producers, thereby reducing investment risks and promoting the adoption of hybrid systems [91].

To ensure long-term sustainability, **life cycle assessment** has become an integral tool for evaluating the environmental impact of hybrid systems, providing insights into their carbon footprint, emissions reduction potential, and overall sustainability. LCA offers a comprehensive framework to assess environmental performance across all life cycle stages, from raw material extraction, manufacturing, transportation, system operation, and maintenance, to end-of-life disposal or recycling, commonly referred to as a cradle-to-grave approach [92]. Among the various environmental impact categories, greenhouse gas (GHG) emissions are the most extensively assessed and consistently show substantial reductions in hybrid systems compared to conventional energy options [93–95]. The mitigation of GHG emissions remains a key driver for the deployment of renewable energy systems, with hybrid configurations significantly lowering the carbon footprint by displacing fossil fuel-based generation. This reduction is particularly notable when renewable technologies such as solar PV, wind, and biomass are integrated into hybrid systems, resulting in lower net GHG emissions [93]. Land use and water use impacts, while less frequently evaluated in existing LCA studies, are recognized as critical considerations, particularly for biomass-integrated and large-scale PV-based hybrids [94,96]. These impacts, especially land use related to biomass cultivation and PV array installation, are influenced by spatial and ecological trade-offs. Water use, particularly in biomass-based systems, is also an important factor to consider, particularly in regions where water resources are scarce [96]. Beyond land use and water use, several other impact categories are relevant to the environmental performance of hybrid systems. Global Warming Potential (GWP) remains the most evaluated category, particularly for GHG emissions, and is consistently prioritized in LCA studies of renewable energy [94]. Additionally, Acidification Potential and Eutrophication Potential are important considerations, particularly for systems that involve large-scale biomass cultivation or material production, as these can be influenced by upstream emissions [95]. Although less frequently considered, impacts such as Photochemical Ozone Creation Potential and Particulate Matter Formation are relevant for assessing air quality and human health [95]. Moreover, the depletion of fossil fuels and Ozone Depletion Potential are occasionally evaluated in hybrid systems, especially when assessing the production phases of components like PV panels and batteries. In hybrid systems incorporating energy storage, particularly battery technologies, additional environmental impact categories gain importance. Studies have shown that battery storage systems significantly contribute to Human Toxicity Potential, Freshwater Ecotoxicity Potential, and Marine Ecotoxicity Potential [95]. These impacts are primarily associated with the extraction of raw materials (e.g., lithium, cobalt, nickel) and the manufacturing processes of batteries. Consequently, while energy storage enhances system reliability and renewable integration, it also introduces critical environmental burdens that must be considered when evaluating the full sustainability profile of hybrid energy systems. While not always included in every LCA study, the consideration of these broader impact categories provides critical insights into the comprehensive environmental performance of hybrid systems and should be prioritized in future assessments.

In addition, the integration of smart grid has emerged as a critical focus area within hybrid renewable energy systems. Technologies such as real-time monitoring, demand response mechanisms, and energy flow optimization, help smart grids balance supply and demand, enhance grid stability, and support the seamless integration of hybrid systems into existing infrastructure. These technologies are essential for facilitating the transition to more resilient and sustainable energy systems [97]. The **community-based approach** to hybridization emphasizes the active involvement of local stakeholders in the development, ownership, and operation of renewable energy projects. By aligning system design with local needs, resources, and priorities, this model fosters social acceptance, empower communities, and promotes equitable energy solutions. As a result, community-driven hybrid systems enhance resilience while maximizing social and economic benefits [98]. In conclusion, this study broadly categorizes hybridization strategies into three interconnected areas.

- Technological integration: The integration of renewable energy sources, energy storage systems, and microgrid applications to optimize efficiency and enhance system performance.
- Advanced control strategies: Employing real-time monitoring, demand-side management (DSM), and predictive algorithms to manage energy flows and grid interactions, enhancing system stability and dynamic performance.
- Sustainability assessment: Evaluating the environmental, social, and economic impacts of hybrid systems to ensure long-term viability and alignment with sustainability goals.

These categories highlight the diverse and complex nature of hybrid renewable energy systems. Considering the objectives of this paper, focusing on the hybridization of PV, BG, and ES technologies for multigeneration systems, the subsequent analysis examines the literature on PV-ES, PV-BG, and PV-BG-ES hybrid systems. This review aims to identify applied methodologies, highlight challenges encountered during their development and implementation, and present innovative solutions for enhancing performance, cost-efficiency, and sustainability.

3.1. PV and ES hybrid systems

3.1.1. Theoretical considerations: challenges and proposed solutions

The integration of ES with PV systems for power production has been extensively studied, with various strategies tailored for grid-connected, off-grid, and microgrid configurations. Rana et al. [99] investigated strategies to integrate PV systems with BESS in microgrids, aiming to enhance energy performance, balance supply and demand, improve power quality, and achieve cost-effective operation. These strategies include dynamic energy management, which optimizes PV-BESS operations but is challenged by inaccurate PV forecasts and inadequate battery health monitoring. Hybrid energy storage systems (HESS) were also explored, combining BESS with devices like supercapacitors to extend system lifespan and support rapid response and peak load shaving through efficient charge-discharge control. Cost optimization approaches focus on determining the optimal size and configuration of PV-BESS systems to minimize costs while ensuring sufficient energy supply. Challenges in hybridization include the need for accurate system modeling, limited research on standalone systems, and the complexity of optimizing system size and controls. Suggested solutions involve advanced forecasting models, refined control algorithms, and hybrid storage solutions to enhance performance and cost-efficiency, thereby unlocking the full potential of hybrid PV-BESS systems as sustainable energy solutions. Vega-Garita et al. [100] examined methodologies for integrating PV generation with energy storage systems into a single device, categorizing research into low-power (<10 W) and high-power (>10 W) applications. For low-power applications, the integration of PV systems with supercapacitors or batteries was emphasized, highlighting the crucial role of power electronics in enhancing efficiency and safety. For high-power applications, thermal stress on system lifespan was identified as a major challenge. The study also revealed research gaps, such as the absence of standardized long-term reliability tests and limited studies on thermal stress effects. To address these issues, the authors stressed the importance of conducting long-term testing to validate integration concepts and improve device reliability. Khezri et al. [101] reviewed optimal planning methodologies for PV and BESSs in grid-connected residential sectors, emphasizing economic data, optimization algorithms, and electricity pricing models, Challenges identified include the underuse of real-time pricing and time-of-use tariffs. It proposed guidelines for PV and BESS sizing that take rooftop areas, daily energy consumption, and grid constraints into account. The authors advocated for robust optimization methods to manage uncertainties in solar generation and consumption. Recommended strategies include incorporating demand response strategies, integrating EVs, and enhancing grid dependency and system resilience. The review highlighted the need for further research to deliver practical solutions for residential consumers. Lamnatou et al. [102] reviewed the integrating of smart grids, PV systems, energy storage, and smart buildings, focusing on addressing environmental challenges. Key issues identified include using transparent building-integrated PV modules, the impact of energy tariffs, and the limited scope of existing LCA studies. The review emphasized the need for further research into the economic, technical, and environmental dimensions of these integrated technologies to enhance their sustainability and efficiency. Adeyemo and Amusan [103] investigated optimization strategies for a PV-battery-hydrogen hybrid system designed for off-grid net-zero energy buildings. Employing a multi-objective optimization approach via the Non-dominated Sorting Genetic Algorithm (NSGA-II), the study focused on minimizing annualized cost (ACS), loss of power supply probability (LPSP), and the probability of energy waste. It evaluated three battery technologies, lithium iron phosphate (LFP), retired electric vehicle batteries (REVB), and OPzV lead-acid batteries, while considering degradation due to cycling and aging to improve cost estimation and system performance. The findings revealed that LFP and REVB offered superior economic performance, with battery-only systems being optimal for LPSP above 1 %, while hybrid systems performed better at lower LPSP levels. Challenges included accounting for battery degradation's impact on costs and performance. Proposed solutions involved a simplified degradation model for cost assessments, exploring cooling strategies for REVB packs to reduce costs, and designing HRES to achieve minimal LPSP across their lifespan. The authors also called for improved metrics to better evaluate energy waste in future studies. Raugei et al. [104] applied LCA methodology to evaluate the energy and environmental impacts of integrating lithium-ion battery storage with PV systems. They analyzed various storage duration scenarios to determine their effects on energy payback time (EPT), GWP, and overall environmental performance. The study revealed that adding energy storage increased EPT and GWP by 7–30 %, depending on the storage duration, primarily due to the additional energy and resources required for battery production, maintenance, and disposal. A key challenge was the marginal increase in environmental impacts from energy storage, which, while not negating the benefits of PV, slightly reduced its sustainability. The authors suggested further research on regional electricity profiles to optimize storage use, improve the efficiency of hybrid PV-storage systems, and minimize environmental costs and unnecessary battery storage. They also emphasized the importance of optimizing the sizing and performance of hybrid systems to enhance system viability. Jacob et al. [105] proposed a methodology for sizing hybrid energy storage in PV-based microgrids using pinch analysis and design space approaches. Their optimization strategies aimed to balance supply and demand while minimizing lifecycle costs. The study highlighted the need for future work on uncertainty analysis and advanced energy management to further improve system performance. In a complementary study, Guentri et al. [106] assessed hybrid battery-supercapacitor storage systems for PV applications, identifying Particle Swarm Optimization as an effective technique for enhancing grid flexibility and mitigating the solar intermittency. The research suggests that these optimization techniques can improve the reliability and efficiency of hybrid energy storage systems in PV applications.

In summary, the reviewed theoretical studies have identified several key challenges in integrating energy storage with PV systems. These include inaccurate PV forecasting, battery degradation, system sizing, and thermal stress effects. Future research should prioritize enhancing forecasting models, refining control algorithms, and developing hybrid storage solutions. Environmental concerns such as global warming potential and energy payback time also require further exploration. Additionally, optimizing storage sizing, incorporating demand response strategies, and exploring advanced optimization techniques like Particle Swarm Optimization are critical for overcoming these challenges and improving system efficiency. By addressing these gaps and challenges, further development in PV-energy storage systems can significantly contribute significantly to sustainable energy production and grid resilience.

3.1.2. Practical applications: barriers and proposed solutions

To complement the studies on ES and PV hybridization, Table 4 provides a detailed overview of case studies in this field, highlighting key challenges, applied methodology, and obtained results. Additionally, some case studies on PV-ES hybridization for electricity production are selected for comparison with other kinds of hybrid systems and are gathered in Table 5, where key performance metrics are presented. The goal is to deepen our understanding of the challenges associated with hybridizing these systems by examining real-world case studies alongside theoretical research.

A study on the hybridization of a single-phase PV system with $LiFePO_4$ batteries, focusing on an on-grid application in Australia, identified high capital costs as a key challenge hindering the widespread adoption of residential battery energy storage systems [107]. To overcome these challenges, the paper employed methodologies such as Mixed-Integer Linear Programming (MILP)-based energy management, ROI for economic analysis, and cost minimization strategies. The findings revealed that optimizing energy storage improves ROI, reduces PV curtailment and emissions, and increases the cost-effectiveness of battery storage, particularly when supported by government rebates. In the hybridization of PV and ES in Burkina Faso, the study focused on both urban (on-grid) and rural (off-grid) settings, using mono-crystalline PV combined with pumped hydro storage (PHS) and Li-ion batteries [108]. The primary challenge identified was the sustainable integration of PV, due to high capital costs and the limited lifespan and high cost of battery storage systems. The applied methodologies included evaluating the techno-economic feasibility by calculating the NPC and COE for various combinations of PV, battery, and PHS using HOMER software. The

Table 4
Case studies on the hybridization of PV/ES technologies for electricity production.

Ref.	PV and ES type/On-grid or Off-grid/ Country	Challenges	Applied Methods	Results
[107]	- Single-phase PV system - $LiFePO_4$ batteries - On-grid - Australia	High costs restrict the adoption of residential battery energy storage systems.	- MILP-based energy management. - ROI for economic analysis. - Cost minimization and BESS vs. self-consumption comparison	Optimizing energy storage improves ROI, reduces PV curtailment and emissions, and makes battery storage more cost-effective with government rebates.
[108]	- Mono-crystalline - PHS, and Li-ion batteries - On-grid (urban) and off-grid (rural) - Burkina Faso	Sustainable PV integration.	Evaluating techno-economic feasibility by calculating NPC and cost of electricity (COE) for different PV, battery, and PHS combinations using HOMER.	- Solar PV with PHS is optimal for both rural and urban areas. - Battery storage remains costly due to short lifespan and high capital expenses, even with PHS costs. - PV capital costs are the main factor in both settings.
[109]	- Single-Si, multi-Si, ribbon-Si, CIS, a-Si - Nickel-metal hydride, sodium chloride, Li-ion - Off-grid - Bangladesh	Maximizing distributed energy use in a solar-PV islanded microgrid.	- Proposing an NPC simulation for optimal microgrid sizing. - Creating a new life-cycle inventory (LCI) to assess microgrid impacts. - Performing the sensitivity analysis	- Three PV panels with community storage cut microgrid costs. - Batteries heavily impact LCA indicators. - Longer storage lifespan and larger solar capacity reduce costs; CIS-PV and Li-Ion batteries are more eco-friendly.
[110]	- PV - BESS - On-grid - Italy	Insufficient cross-analysis of economic and environmental optimal designs across different contexts.	Proposing a methodology combining MILP optimization, life cycle assessment and life cycle costing	- Reducing technology costs and adjusting tariffs can reduce environmental impacts, but major reductions in battery and PV costs are necessary for significant gains. - Environmental designs are costly due to batteries, while economic designs are less impactful. Lowering battery and PV costs will enhance the environmental benefits of economic designs.
[111]	- Solar photovoltaic panels - Lead-acid batteries bank - Micro-grid - Morocco	Meet load demand, reduce energy costs, boost renewables, and prevent losses and overloads.	Developing a new P-GA-PSO to tackle both sizing and energy management issues in microgrids.	P-GA-PSO outperforms standard algorithms in both convergence and solution quality. The proposed microgrid effectively meets load demand, cuts costs, and reduces emissions.

results showed that a solar PV system combined with PHS is optimal for both rural and urban areas. However, battery storage remained costly despite the inclusion of PHS due to its short lifespan and high capital expenses, with PV capital costs being the most significant factor in both settings.

In the hybridization of PV and ES in Bangladesh, the study focused on an off-grid solar-PV islanded microgrid using various PV types (single-Si, multi-Si, ribbon-Si, CIS, a-Si) and different energy storage systems (nickel-metal hydride, sodium chloride, and Li-ion batteries) [109]. The main challenge addressed was maximizing the use of distributed energy in the microgrid. The applied methodologies included proposing an NPC simulation for optimal microgrid sizing, creating a new life-cycle inventory (LCI) to assess the impacts of the microgrid, and conducting sensitivity analysis. The results indicated that using three PV panels with community storage helped cut microgrid costs. However, batteries significantly impacted LCA indicators. It was found that a longer storage lifespan and larger solar capacity helped reduce costs, with CIS-PV and Li-ion batteries proving to be more eco-friendly options. In the hybridization of PV and ES in Italy, the study focused on an on-grid application using PV and BESS [110]. The primary challenge identified was the limited comparative assessment of economic and environmental optimal designs across different contexts. To address this, the paper proposed a methodology combining MILP optimization, LCA, and life cycle costing (LCC). The results revealed that reducing technology costs and adjusting tariffs could help to reduce environmental impacts. However, significant reductions in battery and PV costs are necessary for more substantial gains. It was also found that while environmentally optimized designs tend to be more costly due to batteries expenses, economically optimized designs have lower environmental impacts. Lowering the costs of batteries and PV systems would improve the environmental benefits of the more economical designs. In the hybridization of PV and ES in Morocco, the study focused on a microgrid application using PV panels and lead-acid battery banks [111]. The primary challenges addressed were meeting load demand, reducing energy costs, boosting the use of renewables, and preventing losses and overloads. The applied methodology involved developing a new Particle-Genetic Algorithm-Particle Swarm Optimization (P-GA-PSO) to address both sizing and energy management challenges in microgrids. The results showed that P-GA-PSO outperformed standard algorithms in terms of convergence and solution quality. The proposed microgrid effectively met load demand, reduced costs, and minimized emissions.

In addition, recent literature further illustrates key operational barriers that commonly hinder hybrid PV-ES systems in deployment phases. For example, Rana et al. [99] highlight limitations such as battery degradation, poor energy sharing, and inefficiencies under fluctuating loads. Their case study on peak shaving illustrated real-world performance degradation and control system limitations. They suggest adaptive control and tailored energy management strategies as essential for reliable implementation, especially in regions with constrained technical capacity. Liu et al. [123] addressed PV module reliability in off-grid hybrid systems, proposing a fault-tolerant control strategy that adjusts system operation across three modes (normal, partial fault, full fault). Experimentation showed stable operation, improved system resilience, and reduced switching losses, solving a major barrier: unreliability during PV faults. Bhayo et al. [124] studied the integration of PHS into standalone PV-battery systems in rural contexts. Their work emphasized the challenge of excess energy and battery oversizing. By shifting the battery to a secondary role and using PHSS as the primary buffer, they achieved reductions in battery size (4.22 %), PV capacity (13.42 %), and excess energy (11.57 %). These operational improvements also led to a lower LCOE, showcasing the value of context-specific system design.

In summary, while economic feasibility, energy optimization, and control strategies are important, real-world implementation challenges,

Table 5
Selection of some case studies for hybrid PV-ES, PV-BG and PV-BG-ES configurations both for electricity production and multigeneration purposes. Comparative overview of each case, including location, system capacity, hybrid configuration, key performance metrics and references. NA = Not Available.

Hybrid configuration	Ref.	Publication year	PV type	ES type	BG type	BG source	Generation (power/co, tri, multi)	Location	LCOE (USD/kWh)	CO_2 emission associated with biomass (tones/year)	Project lifetime (years)	System capacity (MW)
PV/ES	[108]	2021	Mono-crystalline	PHS or BESS	–	–	Power	Burkina Faso	- Off-grid: 0.47 - On-grid: 0.153 (PV + PHS)	–	25	- PV: 1.6–2.2 - PHS: 1.4 - BESS: 14.9
	[109]	2019	a-Si, CIS, multi-Si, ribbon-Si or single-Si	BESS: Li-ion, NaCl or NiMH	–	–	Power	Bangladesh	0.13	–	25	NA
	[112]	2024	Poly-crystalline	BESS	–	–	Multigeneration: CHP and/or hydrogen production	Pakistan	0.1271–0.2812	–	NA (12.4 for CHP system)	- PV: 0.020–0.060 - BESS: 0.029–0.055 (MWh)
PV/BG	[113]	2024	NA	–	Biomass gasifier	Unused wheat straw	Power	Afghanistan	0.031	852.5 (saving)	25	- PV: 0.085 - BG: 0.083
	[114]	2009	NA	–	Downdraft fixed bed gasifier	Local forest (pellets or wood chips)	CCHP	Portugal	NA	NA	NA	- BG: order of kW
PV/BG/ES	[115]	2018	Mono and poly-crystalline Si	BESS: FLA, LFP or Ni-Fe	Imbert Downdraft Gasifier	Agricultural crop residues	Power	Egypt	0.084 (Ni-Fe battery) – 0.1341 (LFP battery)/ 0.0834 (cottonseed burs) – 0.0837 (wheat straw & corn cubs)	330.55 (cottonseed burs) – 481.287 (corn cobs)	25	- PV: 0.13104 - BG: 0.200 - BESS: 1.430
PV/BG/ES	[116]	2018	NA	BESS or TES: water sensible heat storage	NA	NA	Cogeneration (CHP)	California	0.1182–0.1310 [0.0123–0.2570]	NA	20	- PV: 0.130 - BG: 0.100–0.200 - BESS: 0.200 (MWh)
	[117]	2022	Mono-crystalline	BESS	Syngas power generator	Forest waste	Power	Cameroon	0.319	NA	20	- PV: 0.0818 - BG: 0.015 - BESS: 0.484 (MWh)
	[118]	2022	NA	BESS: Lead-acid	NA	Poultry animal waste	Power	Turkey	0.040–0.074 (on-grid)/ 0.125–0.405 (off-grid)	NA	20	- PV: 0.020–0.270 - BG: 0.090–0.270
	[119]	2022	NA	BESS	Small-scale downdraft fixed bed gasifier	Corn stover	Power	Egypt	0.080076–0.1321219	NA	25	NA
	[120]	2021	NA	BESS	NA	Forest pine needles	Power	India	0.185	27800 (saving)	25	- PV: 0.013 - BG: 0.013
	[121]	2021	NA	BESS and TES	NA	Agricultural residues (cotton, wheat, and corn) and animal manure (cows, pigs, and sheep)	CHP	China	0.275	NA	NA	- PV: 0.909 - Biomass CHP: 0.133 - BESS: 0.430 - TES: 1.649
	[122]	2022	NA	TES	NA	Maintenance of local forest, sawmill waste and pruning	CCHP	Italy	NA	NA	20	- PV: 4.22–5.22

such as battery degradation, fluctuating demand profiles, PV fault tolerance, cost overruns, and poor energy utilization, remain major obstacles. This highlights the need for adaptive system design, robust control, and site-specific strategies considering technical, financial, and environmental factors. Future research should continue to address these operational bottlenecks, particularly through integrated control frameworks, technology durability, and more accurate feasibility assessments that reflect field conditions.

3.1.3. Comparative analysis: bridging theoretical and practical perspectives

In this section, we present an overview of the theoretical and practical challenges and solutions in the hybridization of PV and ES, highlighting both shared and distinct perspectives. These are organized into three key hybridization strategies: technological integration, advanced control strategies, and sustainability assessment.

- **Technological integration**

Theoretical studies have extensively explored technological integration, focusing on optimizing system design and energy performance. However, practical applications revealed challenges such as high capital costs and short battery lifespan, particularly in off-grid and rural contexts (Burkina Faso, Bangladesh, Morocco). These studies highlight the need for hybrid energy storage systems that integrate technologies like pumped hydro storage, Li-ion batteries, and PV systems to optimize performance and cost-effectiveness.

- **Advanced control strategies**

Theoretical research has focused on advanced control strategies such as energy management systems, optimization algorithms, and grid integration to enhance system stability. A critical component of this effort involves DSM, which aims to align energy consumption patterns with production capabilities. For instance, Wu et al. [125] proposed an optimal control method for 24-h power flow scheduling in small-scale hybrid PV-battery systems, improving self-consumption and reducing reliance on the grid. Similarly, Yu et al. [126] analyzed the role of photovoltaic systems combined with TES to shift grid loads, highlighting DSM's effectiveness in minimizing peak demand. Arteconi et al. [127] further emphasized the value of DSM strategies for PV-ES integration, showing how load shifting enhances both system performance and grid stability in regions with intermittent solar availability. In contrast, practical studies highlighted real-world barriers such as inefficient energy management and inadequate control strategies. For example, hybrid systems in Italy revealed to the lack of integrated economic and environmental design analysis, while in Morocco, advanced algorithms like P-GA-PSO were employed to improve convergence and solution quality.

- **Sustainability assessment**

Theoretical research has centered on sustainability assessment, focusing on life cycle assessments, energy payback time, and global warming potential to evaluate environmental impacts. Practical studies revealed similar challenges, such as high capital costs, short battery lifespans, and limited studies on environmental impacts, particularly in regions like Burkina Faso and Bangladesh. These studies emphasize the need for improved regional electricity profiles and lower cost in battery and PV technologies to reduce environmental impacts and achieve greater sustainability.

Beyond these conventional indicators, several alternative assessment methodologies have emerged in broader literature. Exergy analysis offers insight into thermodynamic efficiency and system irreversibilities, presenting a second-law perspective on sustainability [128]. Emergy analysis, which accounts for both direct and indirect energy inputs, enables evaluation of the ecological footprint of renewable energy systems [129]. Additionally, multi-criteria decision analysis (MCDA) methods, such as Analytic Hierarchy Process and TOPSIS, support integrated sustainability evaluations by incorporating technical, economic, environmental, and social criteria into decision-making frameworks [130]. Although these approaches were not predominant in the studies reviewed in Section 3.1, their growing relevance suggests the value of a more diversified and holistic sustainability assessment strategy.

By bridging the theoretical and practical perspectives, this comparative analysis highlights the need for an integrated approach that combines technological, control, and sustainability strategies to address the challenges associated with hybridizing PV and ES systems. Continued research focusing on advanced control methods, cost-effective system designs, and comprehensive sustainability assessments is crucial for achieving practical and environmentally viable hybrid energy solutions.

3.2. PV, BG and ES hybrid systems

3.2.1. Theoretical considerations: challenges and proposed solutions

Integrating PV systems with BG and energy storage presents a promising approach to sustainable energy, particularly in regions with intermittent renewable resources and off-grid applications. These hybrid systems leverage PV power during the day and biomass during low solar periods, while energy storage enhance performance by addressing renewable intermittency and ensuring a reliable power supply. Batteries and thermal storage are key to reducing dependence on biomass during peak demand, enhancing energy efficiency, and supporting consistent power availability across varying supply and demand conditions. Despite challenges related to system integration, efficiency, and costs, numerous studies have explored methodologies aimed at mitigating intermittency, improving reliability, and addressing economic concerns.

Akinte et al. [23] investigated the hybridization of PV-BG systems, applying advanced energy storage technologies such as high-frequency flywheels. Using HOMER software, they developed combined dispatch, load-following, and cycle-charging strategies that enhanced system efficiency and reduced thermal losses. Their approach achieved a renewable penetration of 93.9 %, improved reliability, and significant emissions reductions. This highlights the critical role of advanced energy storage in stabilizing power output and optimizing hybrid systems. Similarly, Eteiba et al. [115] optimized an off-grid PV-BG system using meta-heuristic algorithms, Flower Pollination, Harmony Search, and Artificial Bee Colony, to reduce net present cost. The study found that the Firefly Algorithm outperformed others in efficiency, and Nickel-Iron batteries were the most suitable for off-grid applications, further demonstrating the feasibility of hybrid systems for rural electrification. Zheng et al. [116] contributed to the optimization of PV-BG microgrids by incorporating TES alongside battery storage. Their study highlighted the role of TES in balancing heat and electricity demands, using a sliding time window optimization approach to mitigate weather and demand uncertainties. This indicated that hybrid systems with both TES and battery storage provided the most cost-effective and reliable solutions.

Yimen et al. [117] optimized hybrid renewable energy systems with biomass integration in Babadam, Cameroon, comparing different storage technologies. They found that biomass integration reduced energy cost, though challenges such as feedstock availability and high transportation costs remained. Their findings underscored the importance of improving feedstock integration to enhance biomass system viability, aligning with Sustainable Development Goals (SDG 7 and SDG 13). Demirci et al. [118] focused on biomass-based hybrid systems for poultry farm electrification, integrating PV and wind with biomass gasification. They found that biomass-PV integration reduced NPC by 12 % and increased renewable energy penetration by 7 %, with energy storage further improving system efficiency. Challenges related to fluctuating energy prices and high biomass capital costs were noted, with government incentives proposed as potential solutions to enhance economic viability. Aguila-Leon et al. [131] developed an energy management model for a standalone hybrid microgrid combining photovoltaic arrays, biomass gasification, and energy storage. Utilizing particle swarm optimization with artificial neural networks, their model demonstrated strong forecasting performance, indicating the potential of advanced predictive models in optimizing hybrid systems. Kumar and Channi [132] evaluated the techno-economic and environmental viability of a hybrid PV-biomass-battery system. Their study highlighted the importance of optimizing the solar-biomass ratio and energy storage to reduce energy loss and improve the system's economic and environmental performance. The integration of such systems in rural areas with abundant solar and biomass resources was found to offer significant benefits in terms of CO_2 emissions reduction.

Together, these studies underscore the transformative potential of hybrid PV-BG systems integrated with energy storage for rural and off-grid applications. The key challenges identified include solar intermittency, storage inefficiencies, and biomass supply constraints. Proposed solutions emphasize optimizing storage technologies, enhancing biomass feedstock integration, and improving system forecasting. These findings contribute to the growing body of research on hybrid renewable energy systems, providing valuable insights for the development of sustainable energy solutions.

3.2.2. Practical applications: barriers and proposed solutions

To complement the studies on PV, biomass gasification, and energy storage hybridization, a detailed overview of case studies is provided in Table 6, highlighting the practical challenges of integrating PV, BG, and ES systems for electricity production across diverse regions. Additionally, some case studies on PV-BG-ES hybridization for electricity production are selected for comparison with other types of hybrid systems and are gathered in Table 5, where key performance metrics are presented. These studies underscore the distinct regional contexts, and the diverse challenges faced when deploying such hybrid systems. For instance, a study conducted in Spain explored the integration of PV-biomass gasification-ES systems for urban educational buildings [133]. It revealed that small-scale systems (under 500 kW) face high costs and limited feasibility, primarily due to restricted roof space and significant setup expenses. While PV systems alone were found to be cost-effective, the addition of biomass gasification was necessary to enhance renewable energy share within constrained spaces. However, achieving renewable penetration levels above 70 % was deemed financially unviable, pointing to the need for cost reductions or alternative designs to improve system feasibility in urban settings.

In contrast, rural and remote regions present promising opportunities for hybrid systems. Studies conducted in Central and South America focused on microgrid setups combining polycrystalline PV panels, batteries, and fixed downdraft gasifiers powered by rice and

Table 6
Case studies on the hybridization of PV-BG-ES technologies for electricity production.

Ref.	PV, ES and Gasifier type/ Biomass/On-grid or Off-grid/Country	Challenges	Applied Methods	Results
[133]	- Wafer-based silicon, Trojan T-105 - Flooded Lead Acid Battery - Bubbling fluid bed reactor - Commercial pellets - On-grid - Spain	High cost and limited practicality of small-scale PV and biomass hybrid systems for urban educational buildings due to restricted roof space and high expenses for systems under 500 kW.	Evaluating different hybrid PV-biomass systems (considering real energy use, local solar data, and nearby biomass) to find a cost-effective small-scale setup.	PV systems are cost-effective alone but need biomass to increase renewable share due to roof space limits. Hybrids work well for 50 % renewables but are costly for >70 %.
[134]	- Polycrystalline PV panels, - Battery bank - Fixed downdraft gasifier - Rice and coffee husks - Microgrid - Central and South America	Delivering reliable electricity to isolated rural areas by focusing on renewable energy and efficient use of local biomass with minimal infrastructure.	Proposing a hybrid system that integrates solar PV with a biomass gasifier, utilizing local biomass and solar energy to produce electricity.	Benefits: Reduces transportation costs, uses local biomass, and is easy to operate. Disadvantages: Less efficient, struggles with control and synchronization, and has uncertain costs compared to diesel or gasoline.
[135]	- PV panels, - Lithium battery - Fixed bed gasifier - Waste rubber, wood, sawdust - Off-grid - Thailand	Ensuring a stable energy supply in rural areas with fluctuating solar resources by integrating biomass (syngas) and battery storage with the PV system for a reliable PV-biomass solution.	- The hybrid system integrates a syngas generator, solar PV array, and battery storage. - A pilot prototype tested performance. - Evaluating the system for load management and backup power.	- The hybrid system effectively integrated syngas and solar PV to ensure 24-h power, with syngas supporting PV during low availability. - Pilot testing showed promise but needs more optimization and scaling for off-grid use.
[119]	- Photovoltaic panels - Batteries - Small-scale downdraft gasifier - Corn stover - Off-grid - Egypt	Optimally sizing an off-grid hybrid power system (PV, biomass gasifier, and batteries), to ensure reliable, cost-effective energy while minimizing costs and power loss.	Applying the Quantum RUNge Kutta (QRUN) algorithm to optimally size PV, biomass, and battery units in the hybrid power system, minimizing COE and loss of power supply probability (LPSP).	- The QRUN algorithm outperformed the Aquila Optimizer (AO) and Grey Wolf Optimizer (GWO) in fitness and efficiency, showing superior accuracy in optimizing the system. - The optimized hybrid system met Alrashda village's energy needs with minimal costs and low power loss risk.
[136]	- Off-grid - India	Finding an optimal off-grid hybrid energy system for remote areas, using biomass and solar energy to reduce diesel reliance and greenhouse gas emissions.	- Simulated seven hybrid systems with and without batteries. - Calculated LCOE, total NPC, and energy shares from biomass and PV. - Comparing GHG emissions to diesel. - Analyzed factors like solar radiation, biomass price, and system life.	- It has an LCOE of $0.185/kWh and a TNPC of $76,080. - Energy is 59 % biomass and 41 % solar, totaling 38.3 MWh/year. - It cuts GHG emissions by 90.1 %, saving 27.8 Mt CO2 annually. - Performance is influenced by solar radiation, biomass price, interest rate, gasifier life, and capacity shortage.

coffee husks [134]. These systems were designed to supply electricity to isolated areas using local biomass resources, offering benefits like reduced transportation costs and ease of operation. However, challenges such as lower system efficiency, control synchronization issues, and cost uncertainties remained when comparing with conventional fuel-based systems. A real-world pilot study by Macías et al. [134] evaluated a hybrid PV-biomass gasification system designed for off-grid rural areas in Latin America. The system, integrating a 30 kWe biomass gasifier, a 5 kWe PV array, and battery storage, faced operational issues including fluctuating syngas quality and a need for manual balancing between supply and demand. Syngas supplementation with 10 l/h of Liquefied Petroleum Gas was required to ensure engine stability, and system efficiency remained low (10.78 %). Despite these limitations, the system proved viable in remote areas due to its use of agricultural waste, simple maintenance, and low technological dependency, critical factors for decentralized energy access in non-interconnected regions.

In Thailand, researchers developed a hybrid system combining PV panels, lithium batteries, and fixed bed gasifiers powered by waste materials such as rubber, wood, and sawdust [135]. This study emphasized the need for stable energy supplies in areas with fluctuating solar resources, using syngas and battery storage to mitigate low solar availability. While the pilot system demonstrated the potential for 24-h power supply, further scaling and optimization were necessary for successful off-grid deployment. Optimally sizing hybrid systems has also been a key focus. A study conducted in Egypt examined hybrid systems combining PV panels, batteries, and small-scale downdraft gasifiers using corn stover pieces to meet energy demands in off-grid villages [119]. By employing the Quantum RUNge Kutta (QRUN) algorithm, the study optimized system components to minimize costs and power losses. Compared to other optimization methods, QRUN showed superior accuracy and efficiency, enabling the system to meet local energy demands with reduced costs and fewer power outages. In India, efforts to reduce diesel reliance and greenhouse gas emissions in remote areas led to the design of an optimal off-grid hybrid system combining biomass and solar energy [136]. By simulating various configurations, the study identified a system with a levelized cost of energy (LCOE) of $0.185/kWh and an NPC of $76,080. The system achieved a 59 %–41 % energy split between biomass and solar, reducing GHG emissions by 90.1 % and saving 27.8 metric tons of CO_2 annually. Key determinants for system performance included solar radiation levels, biomass prices, and system lifespan, highlighting the importance of localized system design.

Kaur et al. [137] simulated an isolated microgrid combining photovoltaic, biogas generation, and lithium-ion batteries, highlighting both its emissions-free potential and economic inefficiencies. Despite achieving 100 % renewable fraction and near-zero emissions, the system showed higher LCOE ($0.156/kWh) and NPC ($467,858) than its grid-connected counterpart. These drawbacks were attributed to heavy reliance on biogas (372 tons/year), temperature-sensitive anaerobic digestion, and battery degradation. Depth-of-discharge limitations and the need for oversizing highlighted the vulnerability of islanded systems. Nevertheless, load-following dispatch helped mitigate excessive cycling, reinforcing the importance of control strategy integration and thermal regulation.

These studies collectively illustrate that although hybrid PV-BG-ES systems offer a promising pathway for sustainable energy, their implementation is deeply shaped by context-specific operational realities. Key recurring challenges include syngas variability, battery lifespan limitations, seasonal performance constraints, and the trade-off between cost and resilience. Mitigation strategies emphasized in the literature include adaptive control algorithms, improved system sizing, hybrid dispatch strategies, thermal management, and use of local feedstocks to ensure both economic and operational sustainability. Future research should focus on developing modular and fault-tolerant designs, conducting climate-sensitive planning, and enabling real-time control to enhance system adaptability and reliability across diverse geographical contexts.

3.2.3. Comparative analysis: bridging theoretical and practical perspectives

In this section, we present an overview of the theoretical and practical challenges and solutions in the hybridization of PV, BG, and ES, highlighting both shared and distinct perspectives. These challenges and solutions are organized into three key hybridization strategies: technological integration, advanced control strategies, and sustainability assessment.

- **Technological integration**

Theoretical studies emphasize the role of advanced energy storage technologies, such as batteries, thermal storage, and high-frequency flywheels, in mitigating renewable intermittency and ensuring reliable power supply. On the practical side, case studies from regions like Central and South America demonstrated the integration of local biomass resources with PV and battery storage in microgrid setups. These studies pointed to reduced transportation costs and increased feasibility in rural settings, although issues of efficiency, control synchronization, and cost uncertainties persisted.

- **Advanced control strategies**

Theoretical frameworks advocate for the use of energy management technologies to optimize system performance and reduce energy loss. Practical applications reinforce these strategies, significantly improving system efficiency and cost reduction. In practice, these frameworks have shown significant impact. For example, efforts in India to reduce diesel dependence through biomass-solar optimization achieved a 90.1 % reduction in greenhouse gas emissions, demonstrating the transformative role of intelligent control strategies in real-world contexts. Further illustrating this point, Jasim et al. [138] proposed a hybrid microgrid architecture integrating PV, biomass gasifiers, and battery storage, coordinated through an advanced energy management system. Their system was designed to align energy generation with local demand conditions, improving overall system efficiency, reducing costs, and ensuring a more sustainable energy supply. The incorporation of DSM elements within the energy management system allowed for load prioritization, peak shaving, and more efficient use of stored and generated power.

Together, these theoretical and practical developments underscore the critical importance of integrating energy demand management into control strategies, ensuring that hybrid PV-BG-ES systems operate effectively under varying environmental and consumption conditions.

- **Sustainability assessment**

The theoretical literature often focuses on integrating social, environmental, and economic strategies to ensure the long-term viability of hybrid systems. On the practical front, case studies from regions like Thailand emphasized the need for localized solutions, addressing challenges such as biomass availability and feedstock transportation costs. In rural areas, hybrid systems combining biomass and solar energy have shown significant promise in reducing emissions and improving energy access, aligning closely with sustainable development goals.

In summary, the comparative analysis reveals that while theoretical frameworks provide important insights into the hybridization of PV, BG, and ES systems, practical applications underscore the need for region-specific strategies that address local challenges such as system efficiency, cost uncertainties, and resource availability. Both perspectives reinforce the importance of technological integration, advanced control strategies, and sustainability assessments in advancing hybrid energy systems toward broader adoption and long-term viability.

4. The role of renewable integration in multi-generation systems

The integration of renewable energy into multi-generation systems has been widely studied and is increasingly recognized for its significance. Multigeneration systems, including cogeneration, trigeneration, and polygeneration configurations, provide a pathway to sustainable energy by producing multiple outputs such as electricity, heat, cooling, and byproducts. These systems outperform conventional power plants by capturing and utilizing waste heat, thereby significantly enhancing overall energy efficiency [139]. Currently, fossil fuels account for 70 % of global industrial energy, while renewables such as biomass, geothermal, and solar contribute just 30 % [140]. Transitioning multi-generation systems to renewable energy is essential for reducing emissions, enhancing energy security, and supporting sustainable development goals through clean energy innovations and economic growth.

A growing body of research explores how renewable sources, such as biomass, solar, and geothermal, can be effectively incorporated into multi-generation systems. Studies by Martinez et al. [141] and Raj et al. [142] highlight the feasibility of using biomass, biofuels, and PVT panels in cogeneration systems. Both Biomass and biofuels offer efficient off-grid solutions, while PVT panels show potential for cost-effective integration in small-scale systems. Fuel cells have emerged as a key technology in micro-CHP systems, offering high efficiency and low emissions, particularly in residential applications. The integration of renewable energy into CHP systems improves energy efficiency and provides a pathway to cleaner, more resilient energy infrastructure. However, integrating renewable energy introduces complexities, primarily due to the variability of renewable generation. Erixno et al. [143] emphasize the importance of hybrid systems—configurations combining multiple renewable sources—to improve energy reliability and flexibility. Their work suggests that combining technologies such as wind and solar can reduce dependence on fossil fuels and enhance operational flexibility. Similarly, Bagherian et al. [144] demonstrate that hybrid configurations, such as coupling CHP systems with wind farms or solar PV fields, contribute to lower CO_2 emissions and increased sustainability in multi-generation systems. These hybrid approaches improve both operational reliability and the ability to meet fluctuating energy demands. Advanced optimization techniques are essential for maximizing the performance of renewable-driven multi-generation systems. Studies by Kallio and Siroux [32], as well as Bagherian et al. [145], highlight the growing reliance on methods such as genetic algorithms (GA), PSO, and MILP. These techniques are particularly valuable for addressing the increased complexity of integrating multiple energy sources and managing interactions between supply and demand. By optimizing waste heat recovery, energy storage, and distribution, these methods enhance system efficiency and economic viability.

Research also indicates varying degrees of effectiveness among different renewable sources in multi-generation systems. Fig. 1 presents a comparative analysis of renewable energy sources, highlighting

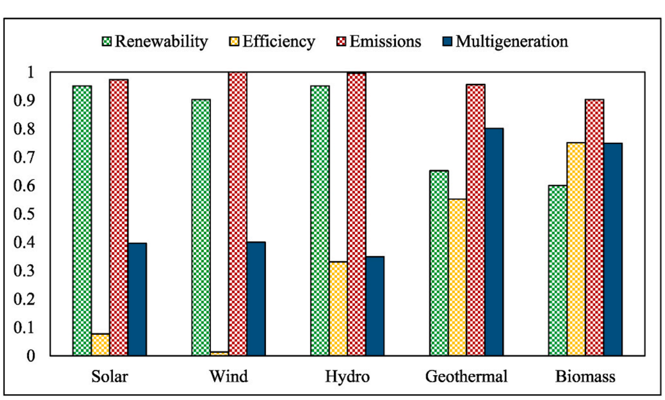

Fig. 1. Average normalized rankings (ranging from 0 to 1) of various energy sources, evaluated in terms of renewability, efficiency, emissions, and multi-generation capabilities: Adapted from Ref. [146].

normalized rankings based on renewability, efficiency, emissions, and multi-generation capabilities [146]. Geothermal and biomass exhibit the highest multi-generation capabilities, driven by their ability to provide both base-load power and useful byproducts like heat. However, their renewability rankings are lower due to location-specific constraints for geothermal energy and biomass's dependency on resource availability. In terms of emissions, geothermal and solar perform best, with rankings close to 1, indicating their low emissions during operation. Efficiency data shows that geothermal and biomass lead due to their compatibility with waste heat recovery systems. In contrast, wind, solar, and hydro rank lower in multi-generation capabilities but remain essential components of a balanced renewable energy mix.

Overall, ongoing research into renewable energy integration highlights several key themes. First, hybrid configurations combining multiple renewable sources hold significant potential for improving system efficiency, reliability, and sustainability. Second, advanced optimization techniques are essential for managing the increased complexity of these systems and ensuring their economic viability. Finally, while some renewable sources, such as biomass and geothermal, are well-suited for multi-generation applications, others, like wind and solar, need to be integrated into more comprehensive systems to maximize their contribution to a sustainable energy future.

4.1. Reliability and resilience of hybrid multi-generation systems

Operational reliability of hybrid multi-generation systems hinges on mitigating unplanned downtime, ensuring rapid fault response, and maintaining service under variable environmental conditions. Redundant architectures, such as dual-string battery banks and parallel biomass gasifier modules, have been shown to boost nominal availability above 98 %, preventing single-point failures from causing prolonged outages [103]. Real-time health monitoring of energy storage, converters, and prime movers enables predictive maintenance that can extend mean time between failures by up to 30 % and reduce repair times, thereby maintaining a low LPSP even in off-grid configurations [119]. Reliability-driven sizing criteria, including LPSP, Loss of Load Probability (LOLP), and Loss of Load Expectation (LOLE), guide component selection: for instance, hybrid battery–hydrogen systems sustain LPSP $\leq$1 % at competitive cost, while Khan et al. [112] report an LOLP of 0.21 % and a LOLE of 0.14 % (with capacity shortages below 0.3 % for electricity and heat) in an optimized rural CHP system, illustrating how stringent LOLP/LOLE targets shape system sizing. Resilience against solar intermittency and seasonal variability is further enhanced by multi-source buffering; coupling PVT arrays with biomass-fueled Stirling engines or inline electric heaters has elevated electrical reliability from 70 % to 100 % and thermal reliability from 68 % to full coverage, without incurring additional capital expenditure [32,147]. Collectively, these strategies, redundant design, predictive diagnostics, reliability-based sizing, and hybrid buffering, create robust, high-availability multi-generation plants capable of dependable energy delivery across diverse deployment scenarios.

4.2. Regulatory, policy, and public acceptance considerations for hybrid renewable systems

The successful integration of renewable energy into multi-generation systems requires not only technical advancements but also supportive regulatory frameworks, effective policy measures, and strong public acceptance. Recent studies have emphasized the critical role of regulations and policies in enabling the deployment of hybrid renewable energy systems in the energy generation systems [148,149].

- Regulatory frameworks provide legal and institutional basis for encouraging investments in hybrid renewable energy systems. Governments worldwide have implemented mechanisms such as renewable portfolio standards, feed-in tariffs (FiTs), net metering policies, and renewable energy auctions to support renewable energy integration and stimulate market growth [121,148,149]. Grid interconnection standards, frequency control, and ancillary service requirements ensure the reliable integration of hybrid systems [150]. Furthermore, national policies, such as India's Wind-Solar Hybrid Policy, provide fiscal incentives, regulatory clarity, and dedicated targets to promote hybrid renewable deployment [149]. Regulatory stability and streamlined permitting processes are critical to attract private sector investment, while poorly designed or inconsistent regulations remain major barriers in many regions [151].

- Policy instruments play a central role in shaping the financial viability and scalability of hybrid renewable systems. Incentives such as feed-in tariffs, investment tax credits, production subsidies, and carbon pricing mechanisms significantly impact the economic attractiveness of hybrid renewable projects. Moreover, adapting market structures, such as energy markets and ancillary services markets, to recognize the flexibility and reliability contributions of hybrid systems is crucial for fostering competition and innovation. In rural and off-grid areas, context-specific financing models, such as micro-financing and community ownership, support implementation and strengthen local supply chains. Nevertheless, policy gaps such as limited access to affordable financing, absence of hybrid-specific incentives, and underdeveloped local manufacturing capacities hinder the broader deployment of hybrid systems [149]. In geographically isolated or resource-limited regions, such as island archipelagos, renewable energy planning should navigate a distinct set of regulatory, environmental, and infrastructural challenges. Cruz-Pérez et al. [152] presented a detailed SWOT analysis of hydropower development across four Macaronesian archipelagos: the Azores, Madeira, Canary Islands, and Cape Verde. Their study illustrates how factors such as terrain, rainfall patterns, policy environments, and levels of public support shape the feasibility and design of renewable energy systems. Crucially, they underscore the importance of island-specific strategies and targeted policy interventions to address constraints like unstable grids, competition over water resources, and high upfront investment costs. These insights are transferable to hybrid renewable systems, where regulatory support, community involvement, and context-sensitive planning are crucial for sustainable multigeneration deployment in similarly remote or fragmented regions.
- Public acceptance is another crucial factor influencing the success of hybrid renewable energy projects. Community engagement, trust-building, and shared benefits are key determinants of stakeholder support [153]. Studies by Susskind et al. [154], Nieminen and Laitinen [155], and Beer et al. [156] highlight that opposition often arises from concerns about land use, visual and environmental impacts, perceived inequities, and lack of participation in decision-making. Effective strategies to enhance public acceptance include early and transparent stakeholder consultation, incorporation of benefit-sharing schemes (such as local revenue sharing or reduced energy tariffs), environmental mitigation efforts, and promotion of community ownership or co-development models.

5. Modeling techniques and configurations for hybrid PV-BG-ES multigeneration systems

This section explores modeling techniques and potential configurations for hybrid PV-BG-ES multigeneration systems, emphasizing key elements such as the integration of renewable energy sources, hybrid system configurations, smart grid integration, microgrid applications, and advanced control strategies. The section concludes with the presentation of a comprehensive framework for the design and integration of a hybrid PV-BG-ES multigeneration system.

- Renewable energy integration

In terms of renewable energy integration, the literature review identifies three main configurations for effective renewable energy integration: sequential, parallel, and integrated systems [149]. Sequential systems, such as solar PV, syngas, and battery setup studied by Kohsri et al. [135] in Thailand, use PV during the day and syngas as backup at night or during cloudy periods, while batteries storing excess solar energy. This configuration supports a reliable 24-h power supply but requires effective management of solar intermittency. Parallel systems, like the PV, biomass-CHP, diesel, and energy storage configuration examined by Ji et al. [121] in northwest China, operate multiple sources simultaneously to provide electricity and heat. The biomass-CHP unit serves as the primary energy source, enhancing system efficiency and reducing diesel dependence in off-grid settings. Integrated systems, as studied by Herdem et al. [157] in a study on methanol production in Crotone, combined solar PV, BG, and alkaline water electrolysis into a unified setup. Biomass compensates for solar intermittency, supplying up to 43.3 % of the electrolyzer's annual energy needs and reducing grid dependency.

Each configuration, sequential, parallel, or integrated, offers distinct advantages, with the choice depending on site-specific factors such as resource availability, demand profiles, and economic viability [149]. This adaptability ensures efficient and reliable solutions for diverse applications.

- Energy storage integration

Energy storage plays a critical role in improving the efficiency and reliability of hybrid renewable multigeneration systems by balancing energy supply and demand. Section 3 emphasized the integration of storage solutions, such as batteries and thermal tanks, as essential for addressing the variability of solar and biomass resources. Recent studies illustrate various approaches and challenges in this domain. For instance, a solar-driven biomass gasification CHP system incorporates a thermal tank to recover waste heat for reuse, which enhances energy efficiency and complementing multiple energy sources. Challenges such as energy losses, cost, and supply-demand uncertainties are mitigated through optimal design and operation strategies [158]. Similarly, a CCHP system utilizing biomass gasifiers, PV arrays, and Li-ion batteries stores excess solar energy for stable power delivery. Addressing battery lifespan and reducing deep discharges are key for reliability. Solutions include regular maintenance and optimizing depth of discharge [88]. Studies also highlight hybrid and polygeneration renewable energy systems that integrate solar, wind, and biomass with thermal and electrical storage. While Li-ion batteries offer high energy density, they are costly and pose safety risks, whereas thermal storage is more affordable but less energy efficient. Advanced storage designs, hybrid solutions, and improved modeling are recommended to overcome these challenges [159]. For example, a combined cycle system with PV, biogas-fueled micro gas turbines, and thermal load controllers integrates both electrical and thermal storage, providing stability despite high initial costs [160].

Future research should focus on advancing storage technologies, refining system designs, and enhancing hybrid integration to reduce costs, improve performance, and support sustainability.

- Multigeneration systems configurations

To comprehensively explore the various configurations of hybrid PV-BG-ES multigeneration systems and the software tools employed for modeling and simulation, this literature review synthesizes key studies to highlight overarching patterns and insights. Ji et al. [121] proposed a stand-alone hybrid energy system integrating PV panels, a biomass-CHP unit, a diesel generator, a gas boiler, batteries, and thermal energy storage, with the biomass-CHP serving as the primary heat and power source. Other components provide backup and energy management. The system optimization is achieved through a MILP model, which minimizes total annualized costs by utilizing hourly profiles of representative seasonal days to account for energy demand variability. The study highlighted key challenges in modeling, including demand fluctuations, simplified input data, and limited system flexibility. To address these issues, the authors recommended incorporating ORC technologies, reducing PV capital costs, and expanding the evaluation to consider life cycle emissions and land use impacts. Li et al. [155] developed a CHP system integrating biomass gasification, solar energy, and a gas turbine for sustainable heat and power generation. In this system, solar energy supports biomass gasification, producing syngas that powers a gas turbine for electricity generation, while waste heat is recovered for heating. The system's performance was evaluated through 4E analysis (energy, exergy, economy, and emissions) using Aspen Plus and Fortran simulations. Key challenges in the modeling process included uncertainties in energy supply and demand and significant exergy losses during combustion and gasification. To address these issues, the authors suggested optimizing and scheduling the system for real-world applications and improving the stability of solar-biomass integration. Mazzola et al. [161] investigated the techno-economic feasibility of a hybrid microgrid system incorporating PV panels, lead-acid batteries, and biomass-based generators, specifically, a gasifier with an internal combustion engine (ICE) and a boiler coupled with an ORC, with diesel generators as a backup. Using MILP optimization, simulations revealed that integrating PV reduced the LCOE by 19 %, while biomass-based systems lowerred LCOE by up to 38 %, achieving a 95 % share of renewable energy. The study identified energy demand uncertainties and operational constraints as key modeling challenges, addressed through sensitivity analyses. Recommended improvements include optimizing the mix of renewable energy sources and generators, advancing PV and battery technologies, and ensuring cost-effective biomass availability. Homa et al. [159] examined hybrid and polygeneration renewable energy systems that integrate multiple sources, such as PV, wind, biomass, and heat pumps, to meet energy demands at small scales. They highlighted that system configurations are influenced by local resource availability and climate conditions. Modeling and simulation are supported by tools like TRNSYS, HOMER-Pro, IHOGA, and MATLAB, which aid in optimizing system designs, assessing performance, and addressing technical and economic challenges. Key challenges in modeling these systems include uncertainties in energy demand and operational constraints, both of which require sensitivity analyses. Advancing energy storage solutions, such as phase-change materials and compressed air storage, could further enhance the flexibility and effectiveness of these hybrid systems. Behzadi and Sadrizadeh [162] proposed a hybrid energy system combining solar PVT panels, biomass heaters, and scaled-down heat pumps to meet year-round energy demands. The system features bidirectional grid interaction, for surplus energy sales and importing electricity during low renewable generation. Modeling and simulation were performed using TRNSYS, complemented by MATLAB for multi-objective optimization through the Grey Wolf Optimizer. While TRNSYS effectively models system components, its lack of built-in optimization capabilities was addressed using MATLAB, which improved efficiency, reduced costs, and minimized CO_2 emissions. Challenges included energy demand uncertainties and biomass price fluctuations affecting economic performance. Future work should focus on enhancing energy storage and integrating AI/ML for improved system adaptability and grid interaction. Farzaneh [163] introduced an HRES integrating PVT panels, supercritical water gasification, pressure swing adsorption units, and a fuel cell for off-grid electricity, heat, hydrogen, and water supply in Japan. Modeling and simulation were performed using TRNSYS, with MATLAB applied for multi-objective optimization using the Grey Wolf Optimizer, addressing issues such as biomass variability and fluctuations in hydrogen prices. Future efforts should focus on enhancing energy storage solutions and refining control strategies to improve grid integration. Zhang et al. [164] developed a multi-generation system that integrates biomass gasification, PVT collectors, a Brayton cycle, and a ground source heat pump (GSHP) to supply electricity, heating, domestic hot water, and cooling. The PVT and GSHP were modeled using TRNSYS and MATLAB, while Aspen Plus was employed to simulate biomass gasification and the Brayton cycle. The primary challenge of solar intermittency was addressed by coupling PVT with GSHP, which improved thermal efficiency and increased DHW production. Future research should focus on further optimizing system design and reducing solar intermittency through energy storage solutions and advanced control strategies. Ray et al. [165] proposed a polygeneration system that integrates biomass gasification, solar PV, ethanol production, and a vapor absorption cooling system. The system generates syngas from biomass gasification, which powers a gas engine-generator. Waste heat is utilized for cooling. Solar PV provides additional electricity during the day, with surplus biomass allocated for ethanol production. The study employed MATLAB and linear programming to optimize system sizing, aiming to minimize the LCOE and ensure reliable operation. Key challenges related to resource constraints and fluctuating demand were effectively addressed, leading to significant reductions in CO_2 emissions compared to diesel generators.

From these reviewed studies, it is evident that the composition of hybrid multigeneration systems can vary based on specific energy requirements. In a basic CHP system, PV panels generate electricity for direct use or storage. BG produces syngas that fuels a power generation unit which can be an ICE, gas turbine, steam turbines, ORC systems, and fuel cells for generating both electricity and heat. The heat is captured by a heat recovery system for heating purposes, and excess electricity is stored in batteries or sold to the grid. The CCHP system builds on this by incorporating an absorption chiller, which utilizes waste heat for cooling, enabling simultaneous electricity, heating, and cooling production. Also, a heat pump can use the electricity produced by PV for cooling production. The multigeneration system extends this further by adding a Syngas Utilization Unit, which can generate additional by-products like H_2, SNG, biofuels and CO_2 capture. This broader functionality enables the system to meet diverse energy and material needs, making it more versatile and sustainable.

Furthermore, the reviewed studies revealed that multigeneration system configurations can be advanced through several key components such as smart grid integration, microgrid applications, and advanced control strategies, which are elaborated upon below.

- Smart grid technology

Smart grid integration is essential for improving hybrid system performance. It provides a robust control and communication network, enabling real-time optimization and seamless coordination with the main electricity grid. For example, integrating smart grids with solar and biomass systems improves resource coordination, supported by technologies such as AI, blockchain, and advanced storage solutions [166]. Waste-to-energy processes, like pyrolysis, when combined with smart energy networks, show significant improvements in efficiency and emissions reduction [167,168]. These innovations highlight the importance of regulatory frameworks and economic analysis to maximize the benefits of smart grids for a sustainable energy future.

- Microgrid applications

Microgrid integration supports localized grids to operate independently or in coordination with the main grid, enhancing system resilience and flexibility. However, integrating hybrid systems into microgrid applications presents several technical challenges, including resource intermittency, economic viability, load management, and system robustness. Recent studies offer solutions to these issues. For example, advanced optimization techniques like MILP have been used to design robust microgrid configurations that replace diesel generators, reduce costs, and cut carbon emissions, demonstrating their sustainability and reliability [169]. In rural contexts, two-stage stochastic optimization has improved system reliability by addressing uncertainties in renewable generation [170]. Additionally, frameworks like peer-to-peer (P2P) resource trading have enhanced economic outcomes and autonomy, particularly in decentralized setups [171]. For systems balancing electrical and thermal demands, a multi-energy microgrid integrating solar, wind, batteries, electric boilers, and gas boilers employed a fuzzy logic-based energy management system. This approach dynamically optimized power and temperature, reducing grid dependence and ensuring efficient operation [172]. These studies demonstrate that advanced optimization methods, distributed resource trading frameworks, and dynamic energy management systems make hybrid microgrids a viable and sustainable solution for diverse energy needs, particularly in rural and remote areas.

- Advanced control strategies

Demand response and load management systems dynamically adjust energy production to match real-time demand and grid conditions, optimizing resource use and enhancing system efficiency. Section 3 emphasized the crucial role of advanced control strategies in improving the performance, efficiency, and economic feasibility of hybrid PV, BG, and ES systems. These strategies address key challenges such as demand-side management, real-time control, and the integration of distributed energy resources (DERs) within multigeneration systems. Chicco and Mancarella [173] highlighted the importance of advanced control in managing DERs in distributed multi-generation systems, focusing on energy balance, resource allocation, power quality, and meeting regulatory requirements. Techniques like thermal storage, cooling systems, agent-based real-time control, and advanced inverters address challenges such as load transients, voltage quality, and integration, improving operational reliability and sustainability. Jana et al. [174] emphasized the use of Model Predictive Control (MPC), SCADA, and multi-objective optimization algorithms to address renewable intermittency and variable demand in polygeneration systems. These strategies, along with energy storage, enhance system efficiency and reliability. Twaha and Ramli [175] identified key optimization approaches, including Proportional Integral Controllers (PI), fuzzy logic, and MPC, to manage renewable variability and ensure stable operation. Hybrid optimization algorithms, like genetic algorithms and dynamic programming, are recommended to address system sizing challenges and improve load balancing. Overall, advanced control strategies, including MPC, RHO, and PSO, are essential for optimizing hybrid energy systems. These approaches address challenges such as renewable intermittency, system sizing, and stability while integrating energy storage and demand-side management to improve efficiency, reliability, and sustainability.

To conclude the findings in this section, Fig. 2 presents a proposed general framework illustrating the integration of key components for a hybrid PV-BG-ES multigeneration system. This framework focuses on primary outputs such as electricity, heating, and cooling, while also generating valuable byproducts including H_2, synthetic natural gas (SNG), CO_2, and biofuels, contributing to the system's overall sustainability and efficiency.

6. Case studies demonstrating successful implementations

This section presents a structured review of case studies that explore the hybrid integration of PV, biomass, and energy storage systems into multigeneration systems. The case studies highlight practical challenges, methodologies, and solutions, bridging the gap between theoretical models and real-world applications. By synthesizing insights from these studies, this section provides a comprehensive understanding of how various challenges have been addressed, offering valuable guidance for researchers, policymakers, and industry practitioners.

Wang et al. [176] examined challenges in integrating biomass and solar energy within an integrated energy system (IES). Key issues included the complexity of combining multiple renewable sources,

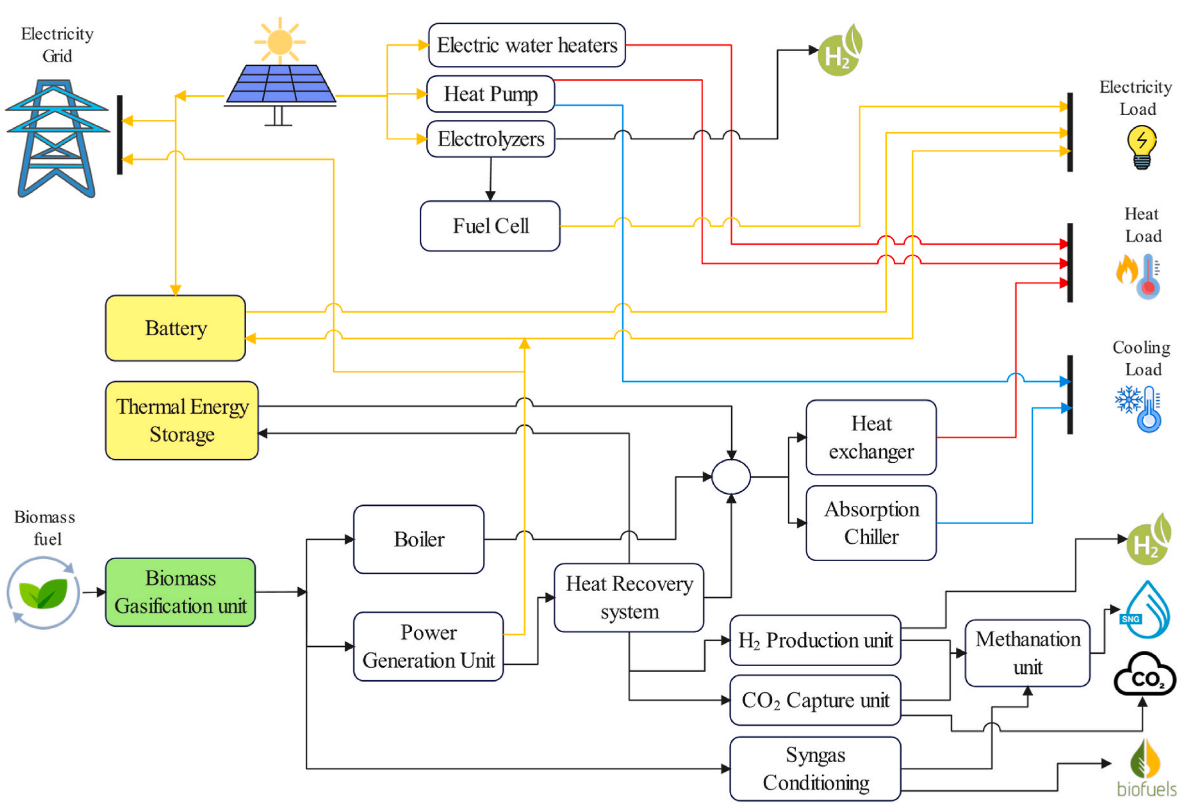

Fig. 2. Outline of general schematic configurations for integrating hybrid PV, BG, and ES technologies into CHP, CCHP, or multigeneration systems for main products and byproducts.

off-design performance of components like internal combustion engines, and trade-offs between energy efficiency, cost, and CO_2 emissions. The authors proposed a multi-objective optimization model integrating energy efficiency, economic costs, and CO_2 emissions, supported by thermodynamic modeling for off-design conditions. Pareto frontier-based decision-making and sensitivity analyses enhanced system adaptability, though further research on uncertainty quantification and advanced optimization techniques is needed. Ceglia et al. [122] focused on the performance degradation of biomass-based CHP systems due to reduced thermal loads in summer. Challenges included inefficient operation due to low thermal demand and limited utilization of waste heat. The authors proposed a smaller, optimized biomass-based CHP unit to enhance efficiency and maximize waste heat utilization. Increased penetration of distributed photovoltaic systems was suggested, achieving a 10.1 % increase in renewable electricity production under Italy's regulatory framework. Further research in energy storage, load matching, and off-design condition modeling is necessary to enhance system robustness. Zhang et al. [177] addressed the challenges of integrating biomass-based combined cooling, heating, and power systems with solar energy for a small farm in Jinan, China. Key challenges included variability in solar energy and biomass gas production, reducing system efficiency, and increasing operational costs. The authors proposed an integrated optimization model using genetic algorithms, focusing on renewable energy capacity, PGU capacity, and key operating parameters. Future research should focus on dynamic load management and design optimization under varying conditions. Kramens et al. [178] investigated integrating biomass micro-cogeneration (mCHP) systems with solar PV panels for a zero-energy family building in Latvia. Seasonal mismatches between solar energy availability and heating demand were identified as key challenges, leading to reliance on grid power during the heating season. The authors proposed a hybrid system combining Stirling engine-based mCHP units, biomass gasification boilers, and solar PV panels, which optimized energy production and consumption year-round. The study emphasized off-design performance analysis, energy storage, and renewable integration to enhance system efficiency and sustainability. Tilahun et al. [179] focused on challenges in integrating solar-biomass hybrid systems for industrial energy supply, highlighting issues like model simplifications, uncertain cost structures, and biomass resource limitations. An optimization approach combining TRNSYS/MATLAB modeling with GenOpt was proposed to minimize biomass usage and excess steam generation. A case study on a textile industry in Ethiopia demonstrated a hybrid plant efficiency of 31.5 %, with a solar gain of 23.5 % and a levelized cost of generation of 0.094 $/kWh. The authors emphasized performance analysis of solar and biomass systems, as well as optimization techniques, to address these challenges effectively.

In addition, Table 7 summarizes further case studies, providing detailed insights into system configurations, challenges, methodologies applied, and results obtained. Additionally, some case studies on PV, BG, and ES hybridization for multigeneration are selected for comparison with other kinds of hybrid systems and are gathered in Table 5, where key performance metrics are presented. For a remote village in Indonesia [180], a hybrid PV-biomass system was studied to address deforestation, water scarcity, and unreliable energy access. Challenges included providing affordable, reliable electricity using local resources while minimizing environmental impacts. The methodology assessed local energy needs, defined criteria for 100 % renewable energy, and modeled a hybrid system optimizing PV, gasification, and storage capacities. Scenario analysis identified daytime gasification at half-load and full PV utilization as efficient strategies, demonstrating cost-effectiveness, sustainability, and broad applicability for remote and grid-connected areas. In Italy [181], a microgrid integrating PV, batteries, thermal energy storage, hydropower, heat pumps, and a biomass gasification CHP system improved energy efficiency and reduced CO_2 emissions in industrial and office settings. Challenges included managing energy flows to maximize renewables, operational inefficiencies in biomass gasification, and fouling caused by dust and TARs. Methodologies like system integration, biomass feedstock analysis, and continuous data collection resolved these issues, enhancing output. Scenario evaluations were conducted to explore upgrading to a trigeneration system, considering environmental impacts and water usage. The hybrid system demonstrated improved energy efficiency, steady electrical output, and reduced dependency on variable renewables. In Portugal [114], a hybrid energy system combining gasifiers, PV panels, and heating/cooling systems was designed to create an eco-friendly energy model for small-scale applications, such as hotels. The main challenge was reducing energy demand, costs, and emissions while meeting efficiency and certification standards. Methodologies included energy forecasting through simulations, thermographic analysis to improve insulation, and designing a cogeneration system for power, heating, and cooling. The system met energy needs, reduced costs and emissions, achieved certification, and proved scalable for other small-scale uses like bakeries and remote homes. In Spain [182], a hybrid system integrating lead-acid batteries, PV panels, a downdraft gasifier with ICE, air-sourced heat pumps, and storage tanks addressed challenges in designing cost-optimal, solar-assisted CCHP systems. Issues included improving energy and exergy efficiency, reducing CO_2 emissions, ensuring cost-effectiveness, and managing high investment costs. A three-part modeling approach using TRNSYS and MATLAB simulated demand, supply, and economic performance. The study highlighted the sustainability and autonomy of small-scale CCHP systems, with broad applicability for global energy solutions. In China [183], a hybrid system combining gasification, PV, heat pumps, boilers, battery storage, and thermal energy storage addressed challenges in balancing solar and biomass integration, minimizing environmental impacts, and ensuring economic efficiency. Methodologies included system configuration, thermodynamic modeling, LCA for energy use and emissions, and multi-objective optimization using NSGA-II and TOPSIS. Performance was evaluated under full electricity load (FEL) and full thermal load (FTL) strategies, demonstrating improved performance, reduced emissions, and optimized PV capacity at 1000 kW. In another study from China [184], a hybrid system combining gasification, electricity, thermal, heating, and cooling subsystems utilized various biomass types, including corn straw (CS), rice straw (RS), wood pellets (WP), and wheat straw (WS). Key challenges included efficiently integrating solar thermal collectors (STC) and PV, optimizing system performance under FEL and FTL strategies, and selecting biomass types for high efficiency and low emissions. The authors configured the system with STC, PV, electric chillers, and heat storage, developing an optimization model that balanced energy, economic, and environmental factors, tested on a Beijing hotel. Performance was evaluated under FEL and FTL strategies, with sensitivity analyses assessing biomass price and gasification efficiency impacts. The solar-assisted hybrid BGCCHP system demonstrated significant improvements in energy savings, cost efficiency, and emissions, with CS proving to be the most effective biomass type. The FTL strategy consistently outperformed the FEL strategy, particularly in winter, yielding better results year-round.

Three additional case studies are presented to further illustrate practical challenges and solutions in PV-BG-ES multigeneration, each from a distinct application and climate context. In an off-grid Indian building, Sadi et al. [185] combined concentrated photovoltaic-thermal (CPVT) panels (162 kWp), a sugarcane-bagasse heater, an absorption chiller and thermal energy storage to meet year-round cooling loads up to 17.2 MWh/day and on-site power demand. Biomass logistics proved critical: securing bagasse at stable prices required local supplier contracts, while excess midday solar heat was routed to storage to avoid CPVT curtailment. A multi-objective GA optimization reduced the LCOE to 58.1 USD/MWh, cut lifecycle CO_2 to 233.6 kg/MWh, and balanced chiller Coefficient of Performance (COP) against photovoltaic sizing. In an intensive pig farm in China, Zhang et al. [186] deployed flat-plate PV, a biomass combustor, ice-based TES and a double-effect absorber to match highly variable cooling and heating loads driven by animal heat

Table 7
Case studies on multigeneration systems using hybrid PV-BG-ES: configuration, challenges, methods, and outcomes.

Ref.	Configuration/Biomass fuel/ Country	Challenges	Applied Methodology	Results
[180]	- PV plant, gasification CHP plant, battery storage. - Local biomass resources - Indonesia	**Primary challenge**: Design a sustainable energy system for a remote Indonesian village facing deforestation, water scarcity, and poor food conservation. **Specific challenges**: 1) Provide reliable, affordable electricity to meet growing demand. 2) Use local resources, like solar and biomass, for sustainability. 3) Address deforestation, water scarcity, and refrigeration needs.	**Local context analysis:** Assess village energy needs and create a load curve for demand patterns. **Criteria definition:** Setting criteria for 100 % renewable solutions, ensuring reasonable plantation size, max 5 % blackout rate, and Lowest LCOE. **Plant modelling:** Develop a hybrid plant model focused on gasification operations and technical limits. **Optimal sizing:** Use simulations to determine ideal PV, gasification, and storage capacities to meet criteria. **Scenario analysis:** Evaluate the optimal scenario with half-load gasification during the day and full PV usage for a smooth power curve and balanced energy ratio.	**Renewable integration:** Combining renewables, polygeneration, and sustainable practices ensures the village's energy is affordable, reliable, and environmentally sustainable. **Optimal configuration:** PV plant: 1600 kWpeak, Gasification plant: 450 kW, Storage: 1274 kWh. **Performance metrics:** Environmental: <50 ha for biomass plantations. Reliability: 3.51 % blackout rate. Affordability: Lowest LCOE at $141/MWh. **Comparison with other solutions:** The PV-Gasification-Battery system is more affordable and sustainable than alternatives like PV-Batteries or PV-Genset-Storage. **Broader applicability:** Gasification's synergy with PV can benefit both remote and grid-connected areas.
[181]	- Rooftop PV, batteries, thermal storage, hydropower, heat pumps (HPs), biomass gasification CHP - Wood gasifier, Fir and EN Plus A1 certified - Italy	**Primary challenge**: Developing and optimizing a microgrid with a biomass gasification CHP system. **Specific challenges**: 1) Enhancing energy efficiency and reducing CO_2 emissions in industrial and office buildings. 2) Managing energy flows to optimize renewable sources like solar PV, hydropower, and biomass. 3) Addressing operational issues with the biomass gasification system, including maintenance and fouling from dust and TARs.	**System installation and initial operation:** Installing and integrating the biomass gasification CHP system with existing renewable sources. **Data collection and monitoring:** Gathering performance data and conducting biomass feedstock analysis in the laboratory. **Maintenance and cleaning:** Performing deep maintenance and cleaning operations to address initial operational issues and improve performance. **Operational analysis:** Analyzing the preliminary results from the first months of operation to identify energy benefits and critical issues. **Scenario evaluation:** Assessing the potential upgrade to a trigeneration system, including environmental impact and water usage.	Integrating a biomass gasification CHP system into a microgrid enhances energy efficiency and sustainability. **Improved production:** Maintenance and cleaning boosted production quality and quantity, indicating the need for frequent maintenance. **Fouling issues:** Dust and TARs caused fouling, suggesting the need for a screening system before biomass enters the reactor. **Constant production:** Biomass ensured steady electrical output, reducing reliance on variable solar PV and hydropower. **Maintenance recommendations:** More frequent maintenance is necessary to maintain high productivity. **Trigeneration potential:** Upgrading to a trigeneration system requires careful assessment due to lower efficiency and high-water usage.
[114]	- Gasification system, PV panels, heating and cooling systems - Pellets or wood chips - Portugal	**Primary challenge:** Creating an efficient, eco-friendly energy model for small-scale uses like hotels, reducing demand, costs, and emissions with renewable sources. **Specific challenge**: Securing energy efficiency and certification for a small hotel with a hybrid system.	**Energy consumption forecasting:** Used simulations to predict energy needs based on building features and external conditions. **Thermographic analysis**: Identified thermal leaks and improved insulation to boost energy efficiency. **Cogeneration system design**: Installed a small cogeneration system with a gasifier and engine/generator for power.	The hybrid energy system met the building's needs for heating, cooling, and hot water, complied with regulations, and achieved certification. It reduced costs and emissions while boosting efficiency. The solution is also suitable for other small-scale applications, like bakeries and isolated houses, and serves as a model for integrating renewable energy in decentralized settings.
Ref.	Configuration/Biomass fuel/Country	Challenges	Applied Methodology	Results
[182]	- Lead-acid batteries, converter, polycrystalline PV panels, downdraft gasifier & ICE, air-sourced HPs, absorption chiller, and storage tanks & pumps. - Woodchips - Spain	**Primary challenge:** Designing and optimizing a biomass-based, solar-assisted CCHP system with a HP for various climates. **Specific challenges**: 1) Creating a cost-optimal design for CCHP-assisted HP systems in various climates. 2) Maximizing energy and exergy efficiency while ensuring economic viability. 3) Reducing CO_2 emissions and enhancing system sustainability. 4) Overcoming high investment costs and complexity to make the CCHP/HP system a feasible alternative to traditional systems.	**Modelling approach:** Developing a three-part model with demand, supply, and economic sub-models. 1) Demand: TRNSYS and TRNBuild for electric and thermal demands. 2) Supply: TRNSYS and MATLAB for performance simulation. 3) Economic: MATLAB for linking performance to economic outcomes. **Case study:** Applied to Montjuïc Castle, Barcelona, for CCHP/HP performance. **Scenario Analysis:** Assessing performance across different system sizes and climates. **Optimization and comparison:** Determining optimal system size	**Optimal system size:** Smallest biomass-based CCHP system reduced lifetime costs by 7 % vs. an HP-only system, with 60 % energy efficiency and 18 % exergy efficiency. **Economic viability:** Larger CCHP systems were unprofitable, the smallest system effectively balanced costs. **Energy efficiency:** The CCHP/HP system achieved high energy efficiency, with a 75 % reduction in CO_2 emissions. **Impact of climate change:** Climate change slightly reduced costs by up to 2.5 % with minimal impact on system sizing. **Sustainability and autonomy:** Small-scale CCHP system is ideal for sustainable, autonomous energy supply at cultural and tourism sites. **General applicability:** The model supports various buildings and regions for global sustainable energy design.

(*continued on next page*)

Table 7 (*continued*)

Ref.	Configuration/Biomass fuel/Country	Challenges	Applied Methodology	Results
			and compares CCHP/HP to HP-only.	
[183]	- Gasification cycle, power generation unit (PGU), PV, solar collector, boiler, air source heat pump, PGU recovery unit, heat exchanger, absorption chiller/heat pump, battery, thermal energy storage tank. - Cornstalk - China	1) Balancing solar and biomass integration for high efficiency and sustainability. 2) Minimizing environmental impacts, especially greenhouse gas emissions. 3) Maximizing economic benefits while maintaining high performance. 4) Using LCA to assess energy use and environmental impact. 5) Optimizing the system for varying electricity and thermal load demands.	**System configuration and modeling:** Designing hybrid systems and thermodynamic models. **LCA Integration:** Assessing energy use and emissions across all life cycle stages. **Optimization model:** Developing a multi-objective model that integrates LCA for optimal performance. **Operational analysis:** Evaluating the system's performance under FEL and FTL strategies. **Optimization process:** Using NSGA-II and TOPSIS for multi-objective optimization and Pareto solutions. **Case Study:** Applying the methodology to an industrial park to assess practical performance.	The multi-objective optimization model with LCA designs effective, sustainable CCHP systems by balancing environmental, economic, and performance factors. **Performance improvement:** FEL mode (EILRR[a] 46.03 %, RECP 92.73 %, ATCSR 35.75 %), FTL mode (EILRR 35.31 %, RECP 81.73 %, ATCSR 32.57 %). **Environmental impact:** Resource Depletion (48–49 %), Emissions (67 % CO2-eq, 58 % SO2-eq, 65 % PM2.5-eq). **System configuration:** Optimal PV capacity is 1000 kW in both strategies, enhancing system performance. **Monthly Performance:** PGU and PV cover 87.23 % of electricity demand.
[184]	- Gasification, electricity, thermal, heating and cooling subsystems. - Corn straw (CS), rice straw (RS), wood pellet (WP) and wheat straw (WS). - China	1) Solar integration: Efficiently combining STC and PV into the Biomass Gasification Combined Cooling, Heating, and Power (BGCCHP) system. 2) Operational strategies: Optimizing performance for FEL and FTL. 3) Biomass selection: Evaluating CS, RS, WP, WS for impact. 4) System configuration: Minimizing energy use, costs, CO_2 while improving performance.	**System configuration:** Configuring the SAHB system with STC, PVP, an electric chiller, and heat storage. **Optimization model:** Identifying optimal configurations balancing energy, economic, and environmental factors. **Case study:** Testing on a Beijing hotel with various biomass materials. **Strategy analysis**: Comparing FEL and FTL strategies. **Sensitivity analysis**: Assessing impact of biomass price, gasification efficiency, and other factors.	The solar-assisted hybrid BGCCHP system excels in energy savings, cost, and emissions, with key design guidelines for hybrid solar and biomass CCHP systems. **Optimal configuration:** PVP area (880.40 m^2), FTL mode is better than FEL due to higher electricity sales. **Biomass:** CS performs best with the highest CSR. **Sensitivity analysis**: Biomass price and efficiency affect performance. **Seasonal performance**: FEL has lower MPECSR and MCDERR but higher MTCSR in winter. FTL shows better MTCSR, MPECSR, and MCDERR year-round.

[a] Environmental impact load reduction rate (EILRR), renewable energy contribution proportion (RECP), following electricity load (FEL), following thermal load (FTL), solar-assisted hybrid BGCCHP (SAHB).

dissipation. Seasonal mismatches between solar generation and peak cooling were mitigated via oversized ice storage. Still, battery cycling and compressor partial loads highlighted trade-offs between capital cost and round-trip efficiency. NSGA-II tuning achieved 53.6 % energy and 19.1 % exergy efficiency, slashed CO_2 by 70.4 %, and delivered a 5.1-year payback despite high upfront TES investment. In rural Ghana, Sánchez-Lozano et al. [88] optimized a hybrid of 16.2 kWp PV, a 30 kWe peanut-shell gasifier-CCHP unit, 56 kWh battery bank and 10 kWe diesel backup for community electrification, heating and cooling. PV output dips during rainy months drove deeper battery discharge cycles, while biomass handling logistics (229 t/yr of shells) required feeder contracts and dry-storage infrastructure. The integrated HOMER design achieved 18.2 % electrical and 62.0 % CCHP efficiency, a 93.8 % CO_2 reduction, an LCOE of 0.287 USD/kWh and a 6.8-year discounted payback under conservative Weighted Average Cost of Capital (WACC). These cases demonstrate the importance of securing reliable biomass supply chains, sizing PV and storage to local climatic variability, and applying multi-objective optimization to navigate cost–performance–emission trade-offs in real-world PV-BG-ES multigeneration systems.

At the end of this section, the key challenges addressed, and corresponding solutions related to hybrid PV-BG-ES multigeneration systems discussed in the above literature review are categorized into technological, advanced control strategies, and sustainability assessment challenges.

- **Technological challenges and solutions**

Challenges such as renewable energy intermittency, seasonal mismatches, and biomass resource limitations impact system efficiency. Solutions like multi-objective optimization models, thermodynamic modeling, and genetic algorithms improve system adaptability, enhance waste heat utilization, and optimize renewable energy capacity.

- **Advanced control strategies challenges and solutions**

Demand-side management and real-time control of DERs pose challenges due to system complexity and uncertainties. Pareto frontier-based decision-making and optimization models enhance control strategies, improving energy efficiency and reducing inefficiencies caused by variable energy sources.

- **Sustainability assessment challenges and solutions**

Trade-offs between energy efficiency, economic feasibility, and CO_2 emissions remain key challenges. Multi-objective optimization models, energy storage solutions, and integrated system configurations help reduce emissions and improve sustainability while ensuring economic efficiency.

In conclusion, addressing these technological, control, and sustainability challenges through advanced modeling and optimization improves the performance, efficiency, and sustainability of hybrid PV-BG-ES multigeneration systems.

7. Frameworks for sustainable hybrid PV-BG-ES in multigeneration applications

Building on the discussions in the previous sections regarding theoretical and practical research studies on methodologies, approaches, modeling, system configurations, and the challenges associated with hybrid PV-BG-ES multigeneration systems, this section introduces the proposed pathway of frameworks. These frameworks are detailed as follows.

7.1. Framework for sustainable hybridization of PV, BG and ES

Achieving sustainable hybridization of PV, BG, and ES technologies within multigeneration systems requires a multifaceted approach. Fig. 3 outlines key elements, including effective technological integration, advanced control strategies, and comprehensive sustainability assessments. This integrated approach aims to enhance the system's efficiency, reliability, and sustainability by addressing critical aspects across technical, environmental, economic, and social dimensions.

Aligning PV, BG, and ES outputs with system demands necessitates three primary integration methods: sequential, where the systems are linked stepwise; parallel, where the systems operate independently but collaboratively address energy needs; and integrated, where all systems are interconnected for optimal performance. To enhance operational flexibility and system efficiency, thermal energy storage and hybrid storage, combining battery and thermal technologies, are employed.

In the context of microgrid applications, the framework emphasizes localized grids designed for isolated or independent operations, and systems capable of connecting to the main grid when necessary. Energy management and control strategies are crucial to ensuring operational efficiency, with demand-side management optimizing energy use patterns and real-time control enabling immediate adjustments to system conditions. Incorporating smart grid technology highlights the need for advanced digital infrastructure to facilitate intelligent energy distribution and monitoring.

On the social and policy front, community engagement is stressed as a cornerstone for building local support, alongside supportive policies that foster a conducive regulatory environment and feasibility studies that assess project viability. Environmental considerations should be pivotal to the framework, emphasizing the use of LCA to minimize ecological impact, leveraging local biomass to reduce transportation emissions, and ensuring biomass is sustainably harvested. Lastly, economic strategies ensure the financial viability of these systems, including cost optimization to minimize expenses and identifying diverse revenue streams to bolster economic returns.

Additionally, integrating Circular Economy (CE) principles can introduce an important sustainability dimension to the hybridization framework. The CE approach emphasizes transitioning from the traditional linear "take-make-dispose" model to regenerative systems where materials and energy are continuously reused, recovered, and retained within the system boundary for as long as possible [187]. Within the context of biomass-based energy systems, CE is reflected in the valorization of organic waste, such as agricultural residues, food processing by-products, and municipal solid waste, through waste-to-energy processes like anaerobic digestion and gasification. These practices enable both energy recovery and nutrient recycling, reducing dependency on landfills and mitigating greenhouse gas emissions [188,189]. Similarly, battery recycling plays a critical role in enhancing the circularity of

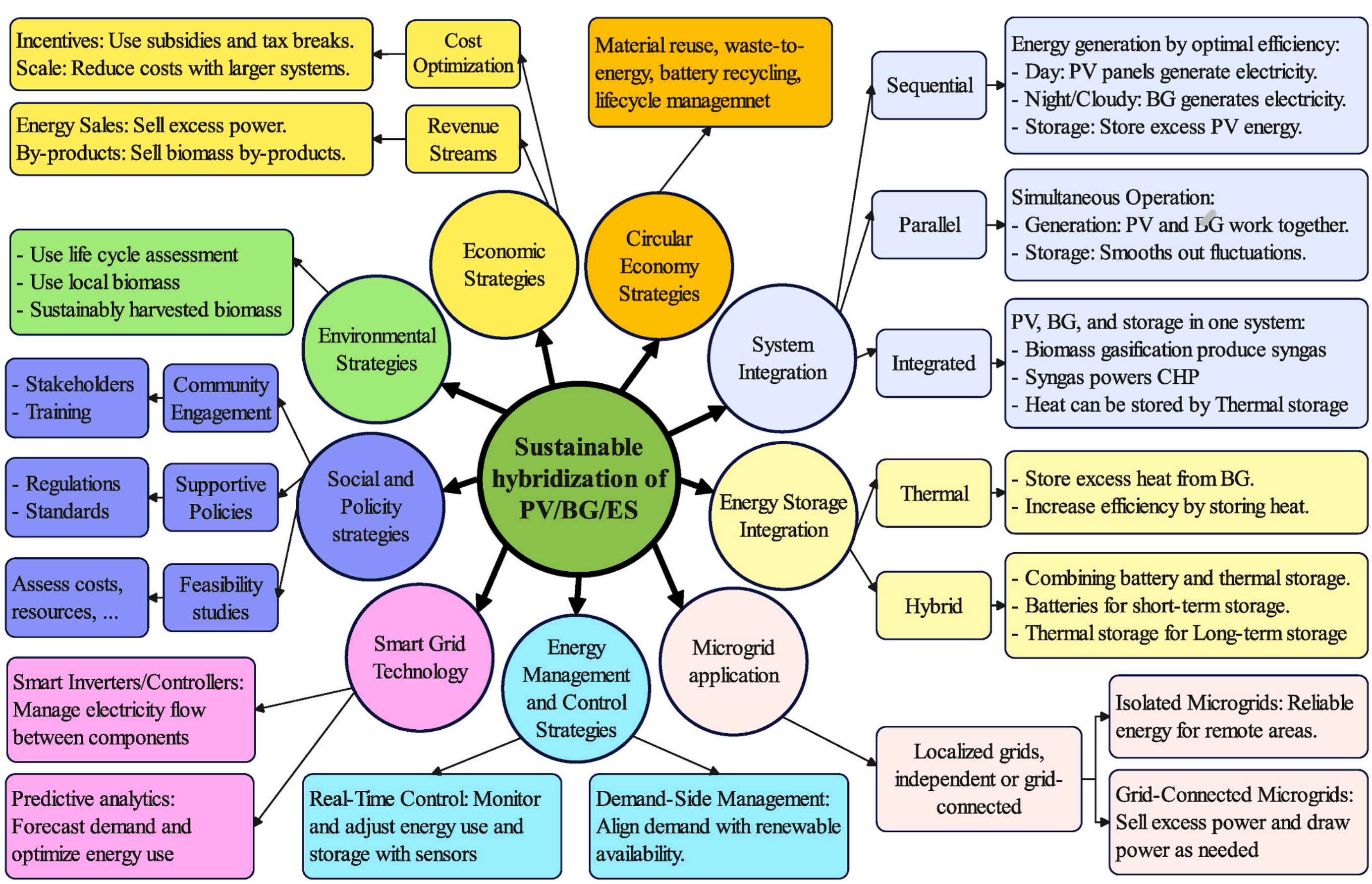

Fig. 3. Sustainable integration of PV, Biomass Gasification, and Energy Storage systems for multigeneration application.

hybrid PV-ES systems. As lithium-ion batteries reach end-of-life, advanced recycling methods, such as hydrometallurgical and direct recovery processes, can reclaim valuable materials like lithium, cobalt, and nickel, thereby reducing raw material extraction and associated environmental impacts [190,191]. These practices are increasingly seen as essential for sustainable energy storage deployment, especially given the rapid growth in demand for batteries in renewable energy and electric mobility sectors. Incorporating such CE strategies into hybrid PV-BG-ES systems has been shown to improve lifecycle performance, increase resource efficiency, and enhance the overall environmental sustainability of multigeneration energy systems.

This holistic framework provides a roadmap for stakeholders, including researchers, engineers, and policymakers, to design and implement effective hybrid energy systems that meet sustainability goals while addressing local needs and constraints.

7.2. Step-by-step framework for sustainable application of PV, BG and ES integration in multigeneration systems

To effectively transition hybrid PV-BG-ES systems from concept to real-world deployment, it is essential to adopt a structured, step-by-step implementation framework that integrates both technical workflows and decision-making checkpoints. This section complements the visual roadmap presented in Fig. 4 by elaborating on each stage with precise technical detail, best practices, and field-tested recommendations, thus addressing real-world challenges and bridging theory with practice.

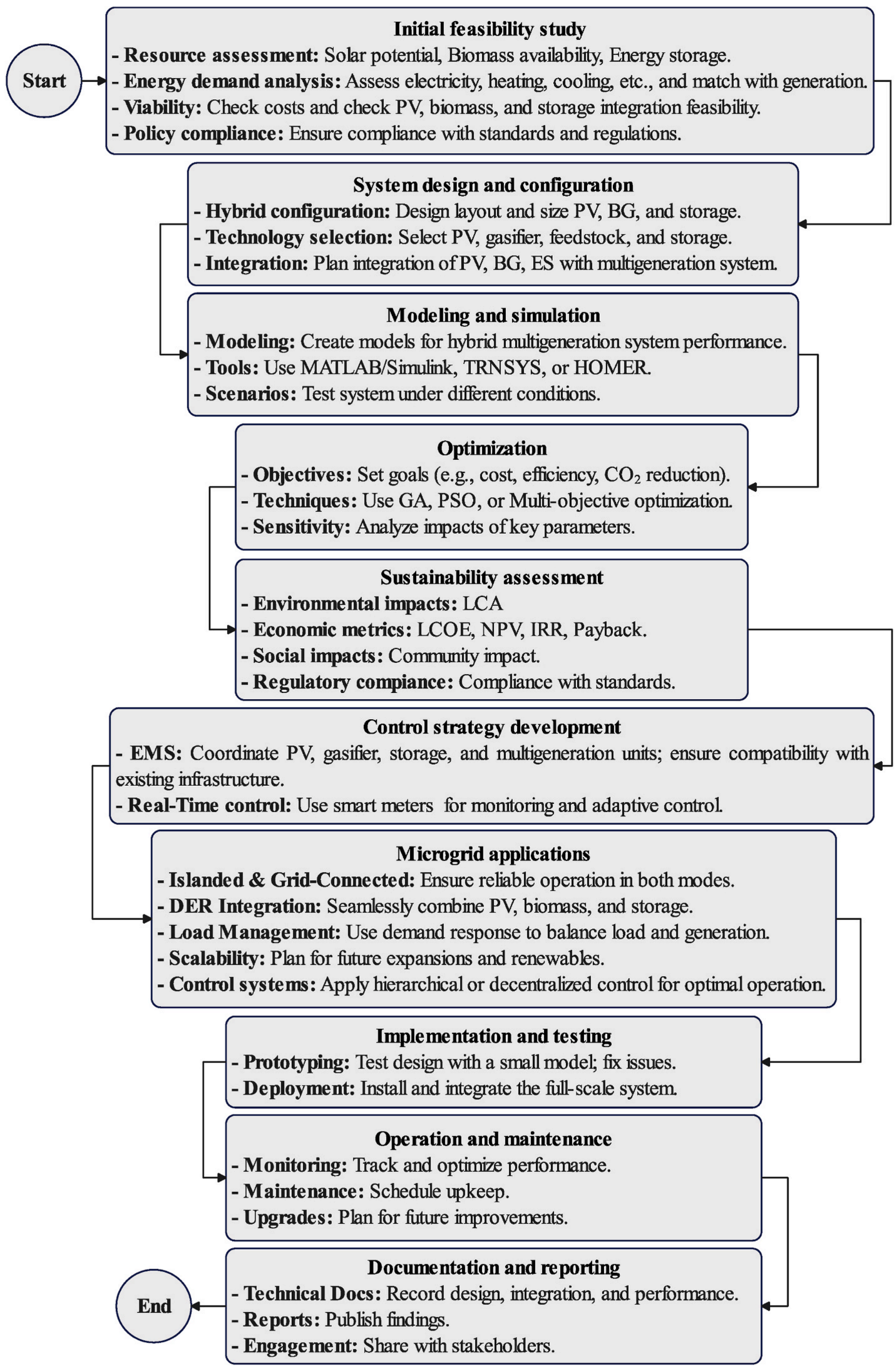

Fig. 4. Sustainable integration framework for PV, BG, and ES in multigeneration system.

1 **Initial feasibility study**: The first stage involves identifying solar potential, biomass feedstock availability (including seasonal patterns and transport logistics), and suitable energy storage technologies. An accurate demand profile, covering electricity, heating, and cooling loads, is essential for system sizing. Site selection should consider grid access, environmental constraints, and local acceptance. Regulatory assessments should screen for eligibility under incentives, subsidies, and emissions regulations.

Best practice: Utilize GIS-based tools for mapping solar and biomass potential [192], and tools like RETScreen for pre-feasibility assessments [193]. Apply biomass resource estimation protocols from IEA Bioenergy Task 40 guidelines [194]. Engage in early-stage community consultation to optimize site selection, ensure social acceptance and environmental impact regulations [195].

2 **System design and configuration:** This stage involves developing and sizing of hybrid system architecture, including layout optimization and selection of PV modules, gasifiers, appropriate biomass feedstock (e.g., agricultural residue, wood chips), and storage technology (e.g., Li-ion, flow batteries). Integration strategies should ensure compatibility with multigeneration demands and regional grid standards.

Best practice: Co-design the system with local utility partners to ensure grid compliance. Employ advanced metaheuristic optimization methods, such as the Giza Pyramids Construction (GPC) algorithm, for accurate and cost-effective component sizing, as demonstrated in recent case study for hybrid systems [196]. Include redundancy in both electrical and thermal subsystems to enhance resilience and use tools like HOMER Grid to assess optimal component configuration [197].

3 **Modeling and simulation:** In this phase, digital twins or simulation models are developed to predict system behavior under varying climatic, load, and policy scenarios. This step is especially valuable in de-risking investments decisions and identifying failure points prior to implementation.

Best practice: Use TRNSYS or HOMER Pro for energy modeling, and MATLAB/Simulink for control simulations. Include uncertainty modeling and Monte Carlo simulation for financial forecasting. Validate simulation models using data from real deployments such as the PV-hybrid mini-grids in Sub-Saharan Africa [198] to ensure modeling assumptions reflect real-world operational conditions and constraints.

4 **Optimization:** Performing multi-objective optimization using techniques like Genetic Algorithms, Particle Swarm Optimization, or Multi-Objective Evolutionary Algorithms to balance competing goals, minimizing LCOE, reducing emissions, or maximizing self-consumption. Sensitivity analyses are used to assess the impact of key uncertainties such as fuel price volatility or load variation.

Best practice: Using Python or MATLAB for implementing custom optimization algorithms. Performing sensitivity analyses to understand the impact of critical parameters (e.g., solar irradiance, fuel moisture). Apply NSGA-II and MOPSO algorithms for resolving trade-offs, as demonstrated in the optimization of a hybrid PV-wind-fuel cell-diesel system for a residential application in Iran, which simultaneously minimized LCOE, emissions, and reliability metrics under high renewable fraction constraints [199]. Evaluating robustness under various policy scenarios to ensure long-term viability.

5 **Sustainability assessment:** A holistic sustainability analysis includes environmental, economic, and social indicators. LCA evaluates emissions, resource use, and ecological impact. Economic viability is assessed via LCOE, NPV, and IRR. Social metrics include job creation, energy equity, and community benefits. Regulatory alignment, such as adherence to national clean energy targets and safety codes.

Best practice: Use SimaPro or GaBi for environmental LCA modeling. Incorporate stakeholder input when defining sustainability metrics. Apply MCDA for integrating LCA with circular economic indicators [200].

6 **Control strategy development:** In this phase, a hybrid EMS is formulated. It coordinates PV, BG, and ES units and supports real-time control using smart inverters, SCADA systems, and Internet of Things (IoT)-based sensors. The use of decentralized or hierarchical control approaches depends on the scale and complexity of the system.

Best practice: Implement hierarchical control schemes combining centralized AI algorithms with local rule-based logic. For instance, the MERLON project, funded by the EU's Horizon 2020 program, introduced an Integrated Modular Local Energy Management Framework for the holistic operational optimization of local energy systems [201].

7 **Microgrid applications:** In this phase, systems are configured to operate in both grid-connected and islanded modes, integrating DERs with demand-side management tools. Load prioritization, dynamic pricing signals, and forecasting-based control are important practices here.

Best practice: Design systems in accordance with standards like IEEE 1547, which establishes criteria for the interconnection of DERs with electric power systems [202]. Leverage frameworks such as the NREL Microgrid Interoperability Framework to enhance modularity and scalability [203].

8 **Implementation and testing:** This phase includes piloting small-scale deployments and scaling up based on observed performance. Real-world validation is essential for refining designs and identifying operational challenges.

Best practice: Adopt a Design-Build-Operate-Maintain (DBOM) model to integrate long-term operational and maintenance considerations into early project phases, thereby reducing lifecycle costs and increasing system sustainability. Begin with small-scale pilot deployments to validate system performance, identify design refinements, and inform regional scale-up strategies [204].

9 **Operation and maintenance:** Sustainable operation depends on predictive maintenance, fault detection, and periodic performance evaluation. The system should be designed for upgrades as technology evolves.

Best practice: Incorporate AI-driven predictive maintenance using machine learning and analytics, as demonstrated in rural mini-grid projects in Kenya and Nigeria, where AI was applied for fault detection, energy forecasting, and system optimization [205].

10 **Documentation and reporting:** Effective documentation and reporting are crucial for knowledge dissemination, transparency, and fostering broader acceptance of renewable energy projects.

Best practice: Prepare comprehensive technical manuals detailing system design, modeling outputs, control strategies, and performance data. Share anonymized performance data with researchers and policymakers through open-access repositories such as Zenodo and IEEE DataPort. Publish periodic reports on technical, environmental, and economic performance to keep stakeholders informed. Utilize standardized data collection and reporting methodologies, as outlined in resources like the IEA PVPS Best Practices Handbook, to ensure consistency and reliability in data reporting [206].

11 Recommendations for Stakeholders

Building on the reviewed literature and case studies, the following recommendations are proposed to support the successful implementation and scalability of hybrid PV-BG-ES multigeneration systems.

- **For Industry Stakeholders:**

Prioritize flexible system configurations that can adapt to seasonal load mismatches and renewable intermittency, as demonstrated in successful case studies across climates and building types.

Adopt advanced optimization tools (e.g., genetic algorithms, NSGA-II, Pareto front analysis) to improve performance under off-design conditions and to balance trade-offs between efficiency, cost, and emissions.

Invest in modular, scalable technologies, such as biomass micro-CHP or gasification units integrated with solar PV and energy storage, especially for decentralized or rural applications.

Strengthen local supply chains for biomass and improve pre-treatment infrastructure to reduce feedstock variability and ensure consistent system operation.

- **For Policymakers:**

Develop hybrid-specific regulatory frameworks that provide fiscal incentives (e.g., hybrid feed-in tariffs, tax credits) and clearly define grid interconnection standards, ancillary service participation, and emissions compliance for multigeneration systems.

Simplify permitting processes and ensure regulatory stability to de-risk private sector investments, particularly for SMEs or community-led initiatives.

Tailor policy instruments to local contexts, especially in remote or resource-constrained regions, drawing on insights from island-based studies that emphasize context-sensitive planning and public involvement.

Promote community ownership models and benefit-sharing mechanisms to enhance public acceptance and ensure equitable energy access in hybrid deployments.

- **For Researchers:**

Advance dynamic modeling techniques that capture real-time load variation, storage behavior, and multi-source integration under uncertainty.

Explore novel hybrid control strategies, including AI-enabled demand forecasting and real-time DER optimization, to enhance system responsiveness and reliability.

Conduct long-term field demonstrations and techno-economic-environmental assessments across diverse geographies to validate model assumptions and guide context-specific design.

Integrate social and policy dimensions into techno-economic models, enabling the co-design of systems that are not only efficient but also publicly acceptable and institutionally feasible.

7.3. Incremental framework for enhancing sustainable hybridization of PV, BG and ES in multigeneration systems

Fig. 5 presents a comprehensive framework to enhance the sustainable hybridization of PV, BG, and ES technologies within multigeneration systems. This framework highlights critical strategies across system design, efficiency optimization, policy support, environmental sustainability, and innovation to improve the overall performance and reliability of these systems.

- Enhancing system design and renewable integration: The framework emphasizes integrating advanced PV, gasifier, and storage technologies while exploring diversification through additional renewable sources, such as wind and hydro. Real-time modeling and predictive analytics are prioritized to optimize resource integration and develop hybrid configurations tailored to multigeneration needs. The incorporation of smart grid technologies ensures efficient energy distribution and monitoring.
- Improving storage efficiency: Advanced storage solutions, including batteries, thermal storage, and hydrogen, are key to addressing the diverse energy demands of multigeneration systems. The adoption of hybrid storage systems is encouraged, supported by AI-driven dynamic management algorithms to optimize real-time operations and seamlessly integrate energy storage into the broader system.
- Enhancing system efficiency and optimization: By upgrading energy management systems with AI capabilities, the framework supports better predictions, real-time decision-making, and improved system

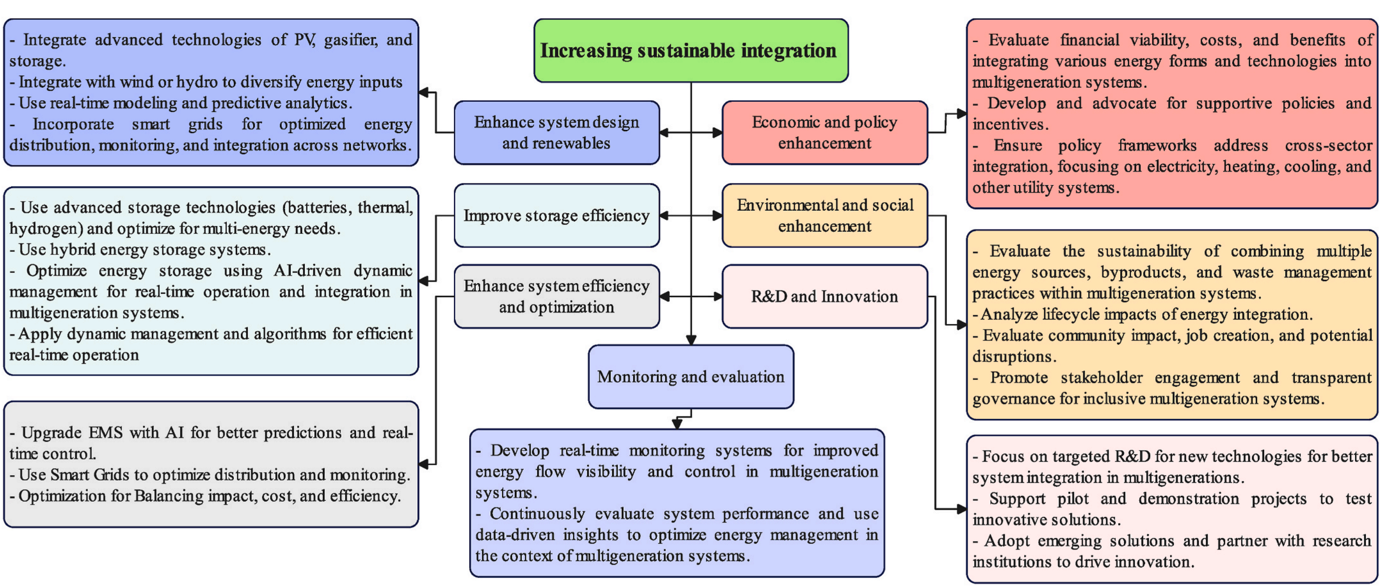

Fig. 5. Framework for progressively enhancing sustainable hybridization of PV, BG, and ES in multigeneration systems.

efficiency. Smart grids play a key role in optimizing energy flow distribution and monitoring, balancing cost, impact, and efficiency within multigeneration systems.
- Economic and policy enhancement: This element evaluates the financial feasibility of integrating diverse energy forms and technologies, advocating for supportive policies and incentives. A cross-sectoral approach to policymaking is recommended, addressing electricity, heating, cooling, and utility integration to achieve holistic energy system management.
- Environmental and social enhancement: Sustainability is at the core of the framework, with LCA evaluating carbon footprints, land use, and biodiversity impacts. Social considerations, such as job creation, community well-being, and stakeholder engagement, are also integral. Transparent governance and inclusive development practices are emphasized to ensure equitable distribution of benefits.
- Research and innovation: Continuous research and development (R&D) efforts are directed at advancing hybrid PV-BG-ES systems. Pilot and demonstration projects are encouraged to validate innovative solutions, with collaborations among research institutions driving technological progress and adaptation.
- Monitoring and Evaluation: Real-time monitoring systems provide enhanced visibility and control over energy flows. Data-driven performance evaluation models are recommended to identify inefficiencies, optimize operations, and adapt to evolving system demands, ensuring the long-term resilience of multigeneration frameworks.

This framework serves as a strategic roadmap for engineers, researchers, policymakers, and community leaders to systematically improve the sustainable hybridization of PV, BG, and ES technologies. By addressing technical, economic, environmental, and social dimensions, this approach aims to develop efficient, reliable, and inclusive multigeneration energy systems, contributing to a sustainable energy future.

7.4. Scalability considerations in hybrid PV, BG and ES systems

In this section, to complete the framework for sustainable hybridization of PV, BG, and ES systems within multi-generation applications. We now comprehensively address the scalability of hybrid renewable energy systems, incorporating PV, BG, and energy storage systems in the context of multi-generation applications. Scalability is a critical parameter for the broader implementation of these hybrid systems, as it determines the system's ability to adapt and expand to meet increasing energy demands while ensuring efficiency and sustainability.

Although small-scale hybrid renewable energy systems (HRES) are generally successful, scaling them to larger capacities presents challenges, including the need for advanced control systems, inverters, and enhanced communication between energy sources. These factors add both complexity and cost. For example, the IEA 2021 report [9] indicates that scaling a system from 100 kW to 500 kW can increase costs and complexity by as much as 30 %. Despite these challenges, economies of scale can help make larger systems more efficient and cost-effective. As demand for renewable energy grows, HRES can be scaled up to meet these needs, with cost reductions of up to 20 % due to improved system performance [207]. Technological innovations in PV, smart grid technology, and energy storage systems are expected to further drive down costs and improve the feasibility of large-scale HRES implementations. New advancements in solar cells, grid management, and storage solutions will boost overall system efficiency. Study [9] predicts that these innovations could enhance energy output by 30 % by 2025, making large-scale hybrid systems more economically viable. Biomass gasification, as a technology, offers significant scalability by enabling the use of a wide range of feedstocks, such as agricultural residues, municipal solid waste, and other carbon-rich materials, to produce syngas. This versatile process supports both energy production and the creation of value-added products. The scalability of biomass gasification is further enhanced by its integration with gas fermentation technologies, which allow to produce biofuels, bioplastics, and proteins for feed and food [208]. Additionally, biomass gasification contributes to waste valorization, reducing the environmental impact of methane emissions from waste [208]. The modular nature of flow batteries and other energy storage systems (ESS) further supports scalability. These systems can be expanded to meet growing energy demands, and their efficiency continually improves through innovations in electrolyte and membrane technologies [209]. The integration of hybrid energy storage systems (HESS) across different regional contexts, along with robust techno-economic models and financial assessments, will optimize system performance in diverse grid environments, ensuring both efficiency and sustainability [209].

By addressing scalability in both energy generation and material production, HRES can play a pivotal role in the development of a sustainable and efficient energy future. Biomass gasification stands as a key component of this transition. Continued advancements in biomass gasification, coupled with smart grid solutions and energy storage technologies, will enhance the sustainability and efficiency of hybrid systems, ensuring their viability for large-scale deployment in the future.

To further respond to implementation-focused concerns and clarify the practical path from concept to scale, Table 8 introduces a strategic roadmap that complements the technical workflow. It highlights key decision gates, critical evaluation stages, and stakeholder roles in moving hybrid PV-BG-ES systems from feasibility to real-world, scalable deployment. This visual framework is intended to assist planners, policymakers, and project developers in managing risk, aligning responsibilities, and ensuring readiness at each deployment stage.

8. Comparative evaluation of this review with existing literature

To provide an overall view of the current work about the existing literature, a comparative summary of key attributes of hybrid renewable energy system in review papers is presented in Table 9. The comparison includes aspects such as the types of renewable technologies considered, application scope (e.g., multigeneration vs. general hybrid systems), primary objectives of the review, depth and focus of results discussion, and the presence or absence of structured frameworks for system integration.

Although the focus of this review, sustainable hybridization of PV,

Table 8
Stage-gated roadmap from feasibility to scalable deployment of PV-BG-ES -multigeneration systems.

Stage	Key Actions	Decision Gate	Stakeholders
1. Feasibility & Planning	Resource assessment, Demand profiling, Policy alignment	Is the site viable and policy-compliant?	Researchers, Planners, Local government
2. System Design & Modeling	Technology selection, System sizing, Digital modeling	Do simulations show technical and economic viability?	Engineers, Modelers, Tech Vendors
3. Optimization & Evaluation	Multi-objective optimization, LCA, Financial and social sustainability metrics	Are trade-offs acceptable and sustainable?	Researchers, Analysts, Regulators
4. Pilot Deployment	Small-scale prototype, EMS setup, Monitoring	Does the pilot meet performance thresholds?	Developers, Local Authorities, Community
5. Scale-Up Planning	Design refinements, Financing, Stakeholder buy-in	Are all conditions met for full deployment?	Investors, Utilities, Policymakers
6. Full Deployment & O&M	Installation, Predictive maintenance, Upgrades	Is the system performing as planned?	Operators, Community, O&M Teams

Table 9
Overview of key differences between this study and prior hybrid renewable energy reviews.

Aspect	This Work	[149]	[210]	[27]	[211]	[212]
Renewable technologies for hybridization	PV, Biomass Gasification, Energy Storage	Solar, Wind, Hydro, Biomass, Geothermal, Ocean; Batteries, Hydrogen, Thermal, Flywheels, CAES, PHS	Thermal Solar, PV, Wind, Biomass, ES	PV, solar thermal collectors, hybrid PV/Thermal; solar-biomass, solar-geothermal, solar-wind/ocean hybrids	PV, Wind, Battery, Fuel Cell, Ultra-capacitor, Diesel Generator, Hydrogen (Electrolyzer & Tank)	PV, Wind, Combustion-based Prime Movers (DG, MGT, FC)
Energy generation type	Multigeneration	–	General hybrid applications (thermal & electric); mentions multi-use systems	Multigeneration	Power generation	Off-grid systems for electricity, heating, cooling, hydrogen
Goal of review	Enhance sustainable integration of hybrid PV-BG-ES in multigeneration systems	Comprehensive integration strategies for hybrid renewables and storage	Review hybrid RES by principles, sources, methods, cost, and applications	Categorization of solar-based multigeneration configurations; technical, economic, and environmental analysis	Review sizing, optimization, energy management, and modeling of HRES components	Optimize hybrid renewable multi-generation systems for energy efficiency, cost reduction, and sustainability
Results discussion	Bridging theory and practice; analysis of economic, environmental, social, policy, circular economy, reliability, scalability, energy management and control strategies for sustainability	Technological, economic, and regulatory aspects of hybrid integration	System-level simulation overview of multi-use hybrid RES; lacks deep focus	Detailed review of solar-based multigeneration system types and their techno-economic aspects	Component-level modeling, energy flow control, technical/policy challenges, tech innovation	Architecture, modeling, reliability, sizing, control, and techno-environmental-economic analysis
Frameworks	Three comprehensive frameworks for sustainable PV-BG-ES hybridization in multigeneration	–	–	–	–	Geographic-specific configuration selection; power management and algorithm analysis for self-sufficient communities

BG, and ES for multi-generation applications, has not been comprehensively addressed in existing literature, several relevant review articles were selected for comparison due to their partial overlap in scope. The comparison reveals the following.

- Technology Focus: While previous reviews such as [149,210], and [S66] provide a broad overview of various renewable sources and energy storage methods, none concentrate on the targeted hybrid combination of PV, BG, and ES, which is the core of this study.
- Application Scope: Only a few reviews (e.g., Refs. [27,212]) mention multi-generation or off-grid energy systems, but their treatment of the topic is limited or generalized. In contrast, this review offers a focused and in-depth exploration of multigeneration systems using hybrid PV-BG-ES setups.
- Sustainability Perspective: A distinguishing strength of this work is its holistic coverage of sustainability dimensions, including environmental, economic, policy, social, and circular economy considerations, an aspect largely underdeveloped or absent in the other compared studies.
- Practical Relevance: While [210,212] cover system-level or component-level modeling, our review bridges the gap between theoretical proposals and real-world implementations by analyzing both conceptual and practical barriers and offering solutions.
- Framework Development: A significant contribution of our work lies in presenting three comprehensive, scalable, and application-oriented frameworks (Section 7), which are absent from all other compared papers. These frameworks provide structured guidance for policymakers, researchers, and industry stakeholders aiming for sustainable integration of PV-BG-ES systems in multi-generation applications.

In summary, this review not only fills a notable gap by targeting an underrepresented hybrid combination (PV-BG-ES) for multi-generation but also distinguishes itself through its depth of sustainability analysis, practical orientation, and structured, novel frameworks. These features make it more complete and sustainability-focused compared to existing review literature.

9. Conclusion

This review has synthesized the state-of-the-art in hybrid multi-generation systems integrating PV, BG, and ES technologies, identifying core challenges and proposing practical strategies for their sustainable implementation. The key practical insights are as follows.

- PV-BG-ES systems offer high potential for decarbonization and energy resilience, but their success depends on tailored configurations that consider local resource availability, socio-economic conditions, and regulatory environments.
- Energy storage is essential to ensure reliability and smooth operation, especially in off-grid and islandable modes. Practical solutions include adopting advanced storage materials (e.g., phase change materials, composite bio-PCMs) and hybrid storage strategies for improved stability.
- Biomass gasification technologies are becoming more viable, particularly with the development of catalytic and hydrothermal gasification methods that address traditional issues such as tar formation and feedstock variability. These advancements can significantly enhance system efficiency when applied contextually.
- System-level integration frameworks are critical for bridging the gap between theory and practice. The paper introduces three conceptual models focusing on integration, control, and optimization, each designed to guide real-world deployment in both rural and urban settings.
- Policy support, public engagement, and cross-sectoral collaboration are necessary to overcome adoption barriers. Successful implementation requires coordinated action among stakeholders, including policymakers, engineers, and community leaders.

In sum, this review provides a practical foundation and step-by-step roadmap for the deployment of PV-BG-ES hybrid multigeneration systems. By aligning technical innovation with regional needs and sustainability objectives, these systems can play a pivotal role in the global transition toward reliable, low-emission energy infrastructures.

Nomenclature

Adiabatic Compressed Air Energy Storage	ACAES
Annualized cost	ACS
Artificial Neural Networks	ANN
Battery energy storage systems	BESS
Battery management systems	BMS
Biomass gasification	BG
Biomass gasification combined cooling, heating and power	BGCCHP
Compressed Air Energy Storage	CAES
Capital Expenditure	CAPEX
Combined cooling, heating and power	CCHP
Combined heating and power	CHP
Computational Fluid Dynamics	CFD
Concentrated solar power	CSP
Cost of Electricity	COE
Coefficient of Performance	COP
Concentrated Photovoltaic-Thermal	CPVT
Direct normal irradiance	DNI
Distributed energy resources	DERs
Domestic Hot Water	DHW
Demand-side management	DSM
Electric vehicles	EVs
Energy payback time	EPT
Effective Price of Electricity	EPOE
Energy storage	ES
Full electricity load	FEL
Flywheels Energy Storage	FES
Flooded lead-acid	FLA
Full thermal load	FTL
Genetic Algorithm	GA
Gravity Energy Storage	GES
Ground source heat pump	GSHP
Global warming potential	GWP
Hybrid energy storage systems	HESS
Hybrid renewable energy	HRE
Internal combustion engine	ICE
Liquid Air Energy Storage	LAES
Life Cycle Assessment	LCA
Life cycle costing	LCC
Levelized cost of energy	LCOE
Levelized Cost of Storage	LCOS
Life Cycle Inventory	LCI
Lithium iron phosphate	LFP
Loss of load expectation	LOLE
Loss of load probability	LOLP
Loss of power supply probability	LPSP
Multi-criteria decision analysis	MCDA
Mixed-Integer Linear Programming	MILP
Model Predictive Control	MPC
Municipal Solid Waste	MSW
ANet Present Cost	NPC
Non-dominated Sorting Genetic Algorithm	NSGA-II
Organic Rankine Cycle	ORC
Operational expenditures	OPEX
Phase Change Materials	PCM
Proton Exchange Membrane	PEM
Pumped Hydroelectric Energy Storage	PHES
Particle Swarm Optimization	PSO
Photovoltaic	PV
Photovoltaic-Thermal	PVT
Parabolic Trough Collectors	PTCs
Power Generation Unit	PGU
Proportional Integral Controllers	PI
Pumped Hydroelectric Storage	PHES
Pumped Hydro Storage	PHS
Retired Electric Vehicle Batteries	REVB
Return on Investment	ROI
Research and Development	R&D
Solar Thermal Collectors	STC
Solar Thermal Energy	STE
Supervisory Control and Data Acquisition	SCADA
Superconducting Magnet Energy Storage	SMES
Synthetic Natural Gas	SNG
Thermal Energy Storage	TES
Transmission and Distribution	T&D
Technology Readiness Level	TRL
Weighted Average Cost Of Capital	WACC
Zero-Energy Buildings	ZEBs
Genetic Algorithm	GA
Gravity	GES
Greenhouse Gas	GHG
Global Warming Potential	GWP

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Declaration of competing interest

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Data availability

Data will be made available on request.

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