International Journal of Science and Research Archive

eISSN: 2582-8185

Cross Ref DOI: 10.30574/ijsra

Journal homepage: https://ijsra.net/

(Review Article)

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A REVIEW OF PV–BIOMASS–BATTERY HYBRID SYSTEMS FOR SUSTAINABLE ENERGY APPLICATIONS

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International Journal of Science and Research Archive, 2026, 20(02), 568–574

Publication history: Received on 13 July 2026; revised on 19 August 2026; accepted on 21 August 2026

Article DOI: https://doi.org/10.30574/ijsra.2026.20.2.1662

ABSTRACT

Hybrid renewable energy systems (HRESs) combine various energy resources to create a more resilient and sustainable power generation system. One of the possible configurations that has been gaining interest is the PV–biomass–battery storage system, which can aid in balancing the intermittency of solar energy. PV systems will generate clean energy when solar energy is available, and biomass can generate energy when solar energy is not available. Further balancing of generation and demand is provided with battery storage. Recent research related to PV–biomass–battery HRESs is reviewed, and performance, reliability and economic feasibility of such systems are discussed in detail. The reviewed studies show that the incorporation of these technologies has great potential to enhance system stability and energy availability, especially in remote and off-grid applications. The success and the economy of the HRESs, however, rely heavily upon the correct sizes of the system, energy management and operating conditions. However, further research is necessary to optimize and make systems more economical and supply a reliable and sustainable energy system.

Keywords: Hybrid renewable energy systems (HRESs), Photovoltaic (PV), Biomass, Battery storage, Renewable Energy.

1 INTRODUCTION AND LIMITATIONS OF EXISTING HYBRID RENEWABLE ENERGY SYSTEMS

Fossil fuel reserves are dwindling, and that has helped to raise environmental conservation high on the public agenda [1]. If PV modules are modeled separately, simulated power output fluctuations are quite large as a function of the input parameters [2].

A relatively practical reason has captured the interest of hybrid renewable energy systems or HRES: They increase reliability, reduce running costs, and reduce environmental impacts, all of which are more important in locations where the grid is not reliable. PV with storage has been investigated extensively in the context of houses and institutional buildings, in particular PV with battery storage. The combination is known to increase self-consumption and to reduce dependence on the utility grid [3, 4]. However, PV–battery systems have their limits. The cost of the batteries, degradation over time and the amount of storage they can provide over a long time all detract from the idea.

PV has delivered tangible impacts to grids, microgrids and to electricity markets. Nevertheless, it has an ongoing disadvantage. Its operativeness follows the weather and is not as high as the values measured under standard test condition, and the cost of maintenance is not low either [5].

To address the problem of solar intermittency, a widely used solution is to combine PV arrays with other power generation technologies, renewable or not. There are number of studies that have addressed sizing of PV–wind–diesel and PV–wind–battery configurations and in all cases a better reliability and reduced unmet load has been demonstrated when compared to single-source systems [6, 7]. There is one problem, however. Until these hybrids remain dependent upon diesel generators, they continue to have a limited environmental advantage, and diesel generates fuel price volatility and greenhouse gas emissions.

2 OVERVIEW OF RENEWABLE ENERGY SYSTEM ARCHITECTURE

In broad terms, a hybrid energy system is any setup that draws on two or more renewable-energy (RE) sources to serve an electrical load. These fall into two categories: standalone and grid-connected. Table 1 groups RE systems by generation capacity.

Table 1: Classification of renewable energy systems based on generation capacity.

Type	Capacity (Generation)	Typical Load / Application
Large-scale	>100 kW	Regional loads
Medium-scale	5–100 kW	Isolated off-grid communities
Small-scale	<5 kW	Remote homes

2.1 Stand-alone system

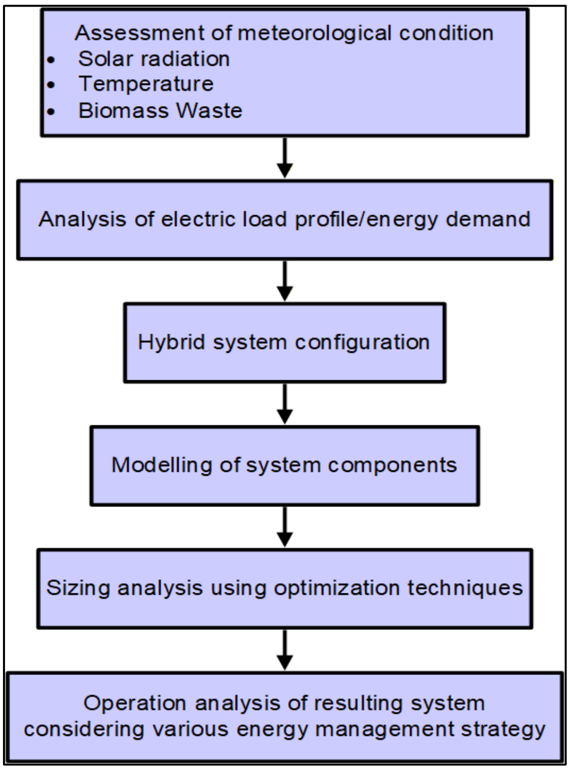

Figure 1: Key stages in the planning and design of a standalone energy system.

A stand alone or autonomous system is a system that is not connected to the grid and must meet the load on its own at any given time. The resources that it feeds on are variable, so it is often not reliable [8]. That is why standalone systems are usually only practical in off-grid applications, where it would be impractical to bring a grid connection out to the site [9]. For a typical case, the planning and design process for one of these can be summarized as follows in Fig. 1.

2.2 Grid-connected system

When a standalone RE system is instead tied into a larger network, usually the public utility grid, the result is called a grid-connected system, or GCS [10]. Surplus power gets exported to the grid; when the RE system falls short, the grid picks up the slack.

3 OPTIMIZATION DESIGN VARIABLES

Design variables are selected before the optimization algorithm can be executed, they are also called control parameters. Their behavior can be either discrete or continuous or mixed discrete and continuous, and they may have one or many variables involved [11]. Realistically, some combination of types of components must be optimized at the same time within the RE system. PV and wind turbines (WT), batteries (BT), hydrogen tanks (HT), fuel cells (FC), and electrolyzers (EL), and inverters all enter the equation. Storage is typically rated based on size (capacity) and power (rated power); generators are rated by number and power (rated power). The typical steps in carrying out this type of problem are illustrated in Fig. 2.

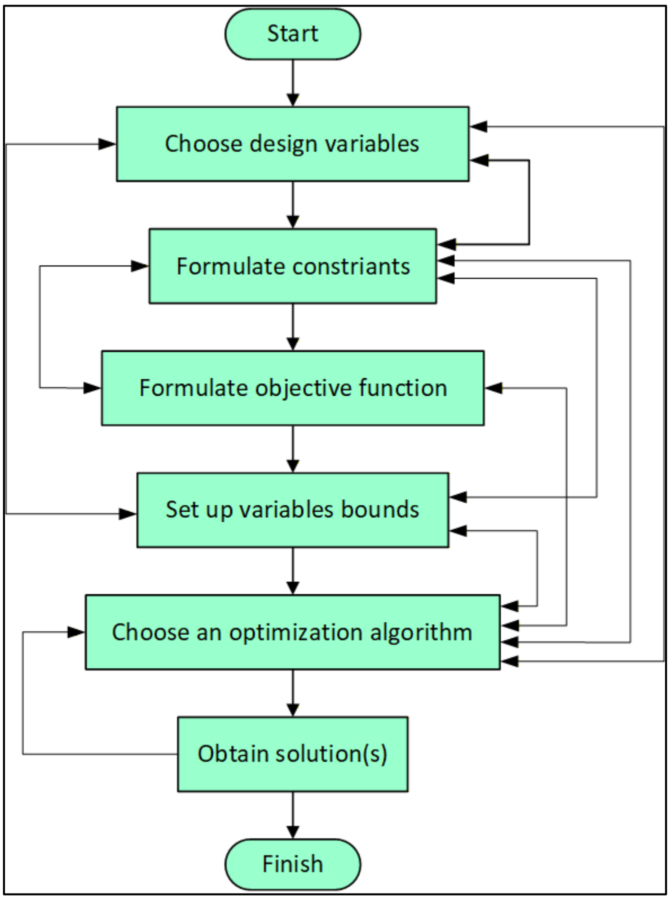

Figure 2: Flowchart illustrating the optimization problem formulation process.

4 BIOMASS INTEGRATION IN HYBRID ENERGY SYSTEMS

Biomass keeps coming up as a dispatchable renewable resource, one capable of offsetting the swings in solar generation. According to techno-economic studies, biomass can provide a reliable baseload energy generation whilst reducing the operating costs of the system and CO2 emissions at the same time, and this is most pronounced in locations where agricultural residues can be readily found [12].

Renewable energy integration for buildings in Iraq is still limited and most of the existing research focuses on PV–wind or PV–battery systems. Research on power management in smart grids often addresses renewable energy in its broad sense; however, it does not focus on locally available biomass which can be dispatched as a flexible energy source in institutional buildings [13]. That gap is important: No one has been able to do a detailed analysis that brings these four components together—PV, biomass, battery storage, and energy management—in a realistic load and climate context.

5 ENERGY MANAGEMENT STRATEGIES IN HYBRID ENERGY SYSTEMS

The performance of a hybrid renewable energy system is generally considered to be one of the most important factors, and that is where an Energy Management System (EMS) is found. Flexible source coordination, monitoring of battery state of charge, and prioritization of renewable generation are among the factors that can be coordinated by EMS, which can lead to improved efficiency and reliability, as noted in review papers [14]. Artificial Intelligence and Reinforcement Learning methods based EMS designs have also been used to assist with real-time operating decisions in multiple flexible resources microgrids [15]. But there is a persistent issue. Many of these studies assume that the grid outages will be brief, which is not representative of the outages that are common in developing countries, which last longer and are more frequent. That sort of outages requires an EMS which is capable of managing flexion of energy sources in the short and long term, both in production and storage, throughout the forecast of weather conditions and energy demand.

6 THE SUSTAINABILITY ISSUES AND CLEAN ENERGY PRODUCTION

Energy is the fuel upon which modern society is based. The ones most heavily relied upon are fossil fuels, petrol, gas and coal and are being consumed faster than ever due to industrialisation and population growth. They have contributed significantly to the climate changes currently being experienced globally when burned for electricity. That's why current research focus has turned to reducing CO2 emissions. Interest has been generated in wind and solar as potential alternatives to conventional generation, as they offer significant potential but are intermittent and will typically need to be supplemented with other power sources and storage to balance out. The batteries are the current preferred storage method, but hydrogen technology is becoming more viable in the long term [17, 18]. The electricity-to-hydrogen-to-electricity cycle could form the basis of a new electricity storage model altogether [19, 20]. Fuel cells powered by hydrogen are also comparable to the diesel generators which have been the standard for the last ten years – fewer maintenance requirements, no emissions during operation, and if paired with hydrogen, allow the battery to be smaller and reduce degradation, while boosting overall performance. But all of this does not happen of its own accord. Realizing these gains requires optimization of the system and an EMS layered on top. The optimization process determines a cost optimal combination of components, and the EMS subsequently ensures that the system is operated as desired. The following section discusses some of the challenges to overcome in RE system design, and how to address them.

7 SOME CHALLENGES AND SOLUTIONS FACING PHOTOVOLTAIC-BIOMASS-BATTERY HYBRID SYSTEMS

- One of the more persistent challenges of PV–biomass–battery hybrid systems is the high capital cost. The total cost of PV panels, biomass conversion equipment and battery storage. However, this initial expense can be reduced by careful system design, incentives from government, sourcing biomass locally and better storage technologies. Good energy management strategy helps take the next step.
- Another issue that deserves mention is system complexity. The various types of energy sources lead to increased complexity in design, operation and maintenance when coupled with batteries and control equipment. The correct operation of the components requires a fairly advanced energy management strategy, which in turn requires relatively complex control algorithms and monitoring, and increases technical requirements and operating costs. However, this is not impossible to manage. The use of advanced management of energy, intelligent control techniques and the modular approach to the construction of the system. The operation is also easier and more reliable because of real-time monitoring and standardized architectures.
- They have their own set of problems with regard to biomass availability and storage for reliable operation. Feedstock supply fluctuates with the seasons, relies on logistics, and varies with region, all of which can disrupt the continuity of supply. But poor storage conditions make things worse: biomass decreases, energy content decreases and handling costs increase – it all adds up in terms of performance and economics. There are some ways around it. The use of locally available resources, diversifying the mix of feedstock, and efficiency through supply-chain management all help, as do pre-treatment measures such as drying and pelletizing that will maintain the quality of the fuel. This is complemented by flexibility from battery storage and enables reliable operation.
- While batteries are key to these hybrid systems, they also bring baggage: high initial cost, limited life span, degradation over time, and efficiency loss with each charge–discharge cycle. Further reduction occurs at elevated temperatures and much of this affects reliability and economic viability. Some of this can be solved with battery management systems, thermal management and better optimised charge-discharge procedures.

A new battery chemistry coupled with another source of energy, such as biomass, can also alleviate the battery stress and extend battery life.

8 COMPARISON OF RECENT STUDIES ON PV–BIOMASS–BATTERY HYBRID ENERGY SYSTEMS

Table 2 provides a comparison between some of the recent studies on PV/biomass/battery hybrid systems, regarding the system configuration, energy management/optimization approach, the main findings, and the research gap identified in each study. The majority of work, collectively, focus on techno-economic evaluation, system optimisation and environmental performance, employing a variety of optimisation methods.

Table 2: Summary and Comparison of Recent Studies on PV–Biomass–Battery Hybrid Systems

Ref.	Hybrid Configuration	EMS / Optimization	Main Findings	Research Gap
[21]	PV-Biomass-Battery	HOMER Pro optimization	Stand-alone PV–biomass–battery system achieved good techno-economic performance and reliable electricity supply for remote communities.	No AI-based EMS and limited validation under varying climatic conditions.
[22]	PV-Biomass	Techno-economic assessment	Solar–biomass hybrid system significantly reduced CO2 emissions and energy cost for an academic building.	Battery storage was not integrated.
[16]	PV-Wind-Battery	Linear Programming	Improved energy management and reduced grid dependency	No biomass integration
[23]	PV-Biomass-Battery	Hybrid optimization	PV–biomass–battery configuration improved renewable penetration and reliability for EV charging stations.	Application limited to EV infrastructure.
[24]	PV-Biomass	Thermoeconomic analysis	Hybrid solar–biomass systems improved efficiency and sustainability compared with single-source systems.	Battery storage and EMS were outside the study scope.
[3]	PV–Battery	Flexible Energy Management System	Enhanced economic and environmental performance	Biomass not considered
[25]	PV-Biomass	Review	Demonstrated the complementary operation of photovoltaic thermal and biomass gasification technologies.	Did not investigate electrical battery storage.
[26]	PV-Biomass-Battery	Review of integration & optimization	Comprehensive review of PV–biomass gasification–energy storage systems, highlighting optimization strategies and future implementation frameworks.	Emphasizes the need for real-world demonstrations and building-scale applications.

Many of these studies do not include one important element, typically either battery storage or an advanced energy management layer. There are several that are only related to a specific use, or that are based on simulation only and have not been validated in different operating and climatic conditions. What this suggests is a requirement for a completely combined PV–biomass–battery hybrid system with an intelligent energy management plan and testing in a realistic environment. If it is done right, it could increase reliability, optimise use of renewable generation, reduce operating costs and reduce environmental impact.

9 CONCLUSION

Overall, the literature reviewed here indicates that PV–biomass–battery hybrid systems are a viable and environmentally friendly solution to replace traditional power generation methods. PV and biomass and battery storage are perfect marriage to address solar intermittency, reinforce reliable supply, and reduce greenhouse-gas emissions.

The battery takes care of the here-and-now balancing of supply and demand, while the Biomass provides dispatchable flexibility. Optimization and EMS design prove to be very crucial in realizing technically sound and economically viable systems. But the challenges are still the same: high capital cost, battery degradation, uncertain biomass supply and the overall hassle of having multiple energy sources all under one system. Many of the current studies also limit their scope to simulation, and very little of the data for these systems actually come from the real world, while much fewer studies examine the integration of PV, biomass, battery storage, and EMS at the building level, particularly in regions that are not always supplied by electricity. Filling these gaps can get hybrid renewable energy systems closer to being sustainable, reliable and cost-effective in practice.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Acknowledgments

The authors would like to thank the University of Kufa in Iraq for supporting this work.

Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript.

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