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Optimization Of Hydro-Solar-Biogas Hybrid Systems For Off-Grid Rural Electrification: A Review With Focus On Developing Countries.

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ABSTRACT

Access to reliable, affordable, and sustainable electricity remains a major challenge for many rural communities in developing countries. Although governments continue to expand national power grids, a large number of rural settlements are still either unconnected or experience frequent power outages due to inadequate infrastructure, transmission losses, and poor system maintenance. This persistent energy gap constrains socioeconomic development, restricts access to quality healthcare and education, and contributes to increased rural–urban migration. Hybrid Renewable Energy Systems (HRES), particularly those integrating hydro, solar, and biogas resources, present a viable solution for decentralized and off-grid electricity supply that aligns well with the resource conditions of many rural areas. However, designing and operating these hybrid systems involves significant technical complexity. Challenges related to optimal system sizing, energy scheduling, and operational control under fluctuating demand and intermittent renewable resource availability remain critical. Without effective management, these systems may suffer from reduced efficiency, higher costs, or unreliable power supply. This review presents a comprehensive evaluation of optimization techniques applied to fully renewable hydro–solar–biogas hybrid energy systems. It synthesizes existing literature on optimization algorithms, performance assessment metrics, and practical implementation challenges, with the aim of providing useful insights for researchers, system designers, and policymakers.

INTRODUCTION

Access to electricity is one of the most critical drivers of economic growth, social inclusion, and improved quality of life. However, in many developing countries, rural communities remain disproportionately underserved due to high urban electricity demand, inadequate transmission infrastructure, remoteness, and inaccessible terrain, which make conventional grid extension technically and economically unattractive (Ohiare, 2015). As a result, decentralized off-grid renewable energy systems have emerged as a viable alternative for expanding electricity access in these regions.

Off-grid renewable energy systems improve electricity availability, operational efficiency, and supply reliability in areas without grid-based power infrastructure (Adebanji *et al*., 2017; Amanze and Amanze, 2021). These systems typically harness locally available renewable resources such as small hydropower, solar energy, biogas, wind turbines, and energy storage technologies, thereby promoting sustainable development and reducing dependence on fossil fuels (Ajenikoko *et al.*, 2024). In developing countries, particularly in agrarian and rural settings, the abundance of water resources, high solar irradiation, and organic waste further strengthen the case for renewable-based off-grid solutions.

Despite their advantages, standalone renewable energy systems often fail to meet rural electricity demand due to the intermittent and seasonal nature of individual resources (Azzuni *et al*., 2021). To overcome this limitation, hybrid renewable energy systems (HRES), which combine multiple renewable sources, have been widely adopted to enhance supply reliability and system resilience. Hybridization enables complementary resource utilization, ensuring continuous power generation across varying climatic and operational conditions (Ashok, 2017).

Among various configurations, hydro–solar–biogas hybrid energy systems are particularly well-suited for rural electrification in developing countries. Hydropower provides relatively stable base-load generation, solar energy contributes daytime power, and biogas offers dispatchable electricity while addressing organic waste management and environmental sanitation challenges. Although previous studies have explored hybrid systems for rural electrification, many focuses on dual-source combinations or incorporate non-renewable components such as diesel generators, which increase operational costs and environmental impact. Moreover, the stochastic nature of mixed renewable and non-renewable systems complicates system sizing and optimization using conventional tools such as HOMER.

In view of these limitations, this review focuses exclusively on fully renewable hydro–solar–biogas hybrid energy systems for off-grid rural electrification. The study critically examines system configurations, optimization techniques, performance metrics, and socio-economic impacts, with particular emphasis on applicability in developing-country contexts. By synthesizing existing research and identifying key gaps, this review aims to support the design of reliable, cost-effective, and sustainable hybrid energy solutions for rural communities. The summary of the review is shown in Table 1.

OVERVIEW OF GRID SUPPLY SYSTEM

A grid supply system, often referred to as a large-scale or macro-grid, consists of the interconnection of multiple power generation stations capable of producing electricity in the range of several hundreds of megawatts to gigawatts. These generating units are linked through an extensive network of transmission, sub-transmission, and distribution lines that deliver electricity to end users.

A national grid represents an integrated network across a country's geographical extent. One of the key advantages of a grid-based power system is its operational flexibility; failures in individual generation units or network components rarely result in total power outages, as supply can be maintained through alternative sources within the interconnected grid (Suwal *et al.,* 2020).

Electricity supply systems are broadly classified into on-grid and off-grid configurations. On-grid systems rely primarily on the national grid, with power generation, transmission, sub-transmission, and distribution infrastructures operating as interconnected components of the grid network (Curto *et al*., 2019). In contrast, off-grid or stand-alone power systems operate independently of the main grid.

Table 1: Summary of various studies and their limitations

S/N	Author(s)	Title of the Paper	Method/Limitation
1.	Chiyembekezo *et al.*, (2012)	Hydropower in the context of sustainable energy supply: a review of technologies and challenges	The hydropower energy used contributes a smaller share to the global primary energy supply
2.	Askari *et al.* (2015)	Hydroelectric energy advantages and disadvantages	The proposed method was only applied to a typical rural village
3.	Kaur and Brar (2016)	Solar-biogas-biomass hybrid electrical power generation for a village	The Finite Element Method used was not sufficient to find an optimal solution for Solar Thermal Energy conversion
4.	Adebanji *et al.*, (2017)	Optimal Sizing of an Off-Grid Small Hydro-Photovoltaic-Diesel Generator Hybrid Power System for A Distant Village	The complement and the environmental benefit of the design generator were not taken to full advantage of
5.	Jurasz *et al*. (2017)	Integrating a wind and solar-powered hybrid into the power system by coupling it with a hydroelectric power station with a pumping installation	The approach was not sufficient to find an optimal solution for the generator magnetic problem
6.	Li *et al.* (2019)	Long-term complementary operation of a large-scale hydro-photovoltaic hybrid power plant using explicit stochastic optimization	The economic value of the power system employed for the rural community was not presented
7.	Aziz *et al.,* (2020)	Rural electrification through an optimized off-grid microgrid based on biogas, solar, and hydro power	Different components and the economic value of the DG system employed to the rural community were not presented
8.	Aduroja, (2021)	Biogas, a viable source of energy: case study, Nigeria	The impact of renewable energy was not analysed.
9.	Abdelhamid *et al*. (2022)	Comparative analysis of hybrid renewable energy systems for off-grid applications in Chad	The economic impact of the hybrid system was shown to be limited to an increase in income of small businesses.

10.	Agajie *et al.,* (2023)	Optimal sizing and power system control of a hybrid solar PV-biogas generator with an energy storage system power plant	The method used may not be sufficient to supply electricity to the selected town.
11.	Garip *et al.,* (2024)	A Renewable Microgrid with Hydrogen for Residential Use: Fuzzy Logic for Multi-Objectives	The approach was not sufficient to find an optimal solution for RES.

These systems are typically smaller in scale and utilize localized power generation to meet electricity demand within a specific area (Deppe and Jeremy, 2022). Off-grid power supply systems are commonly deployed in remote or geographically isolated locations where connection to the national grid is technically challenging or economically unviable due to terrain, distance, or geotechnical constraints. Additionally, renewable energy–based power plants are often implemented as off-grid systems due to their relatively small capacity and location in resource-rich but grid-distant areas (Agajie *et al*., 2023).

RENEWABLE ENERGY SOURCES

Renewable energy sources are the energy obtained from the repetitive currents on energy recurring in the natural environment" or as "energy flows which are replenished at the same rate as they are used. It includes wind, solar, hydro, biogas, oceanic and geothermal energy (Weldegiyorgis *et al.,* 2021). The basic concept of renewable energy concerns sustainability, renewability, and pollution reduction. Renewable energy technologies are designed to run on a virtually inexhaustible supply of natural fuels. The use of renewable energy sources promotes sustainable development because they rely on infinite energy sources (Mohapatra *et al.,* 2020).

Renewable energy can be divided into two categories; those used to provide energy for domestic use (predominantly cooking and heating) and those used to supply electricity. Those used to produce energy for domestic use exploit modern fuels or utilise traditional fuels in new and improved ways. Renewable energy technologies that generate electricity can do so either as part of an off-grid system or as a grid-tied system (Mesfin *et al*., 2017).

Thus, using renewable energy sources, rural communities can build their own off-grid electricity supply within a short period. These off-grid power projects across the country increase access to electricity supply and improve the well-being of the rural populace. Hence, there is a need to harness the potential of various renewable energy sources to broaden the energy supply mix, thereby ensuring greater energy security for Nigeria (Adepoju and Adebanji, 2016; Aziz *et al.,* 2020). This paper, therefore, examined the effectiveness of hydro-solar-biogas hybrid power system complementation in supplying electricity to off-grid rural areas.

Complementation of Renewable Energy Sources

Renewable energy complementation is the combination of different renewable energy sources, such as solar, wind, hydro, geothermal, and biomass, so that they compensate for each other's variability (Juraz e*t al.,* 2019). No single renewable resource is perfectly reliable at all times, so using them together improves stability, reliability and overall energy output. Figure 1 shows how hydro-solar biogas complement each other in balancing both time-based and seasonal variability. Biogas and hydropower sources can adjust to provide grid stability, especially during periods of low solar output (e.g., cloudy days, nighttime). Although solar is variable, it adds a significant contribution during peak daytime hours.

Reasons for Renewable Energy Complementation

There are several reasons why renewable energy complementation is important for off-grid electrification:

- Mitigates Variability and Improves Grid Stability: Different renewable sources peak at different times. Solar energy peaks during the day and drops at night. Hydropower can provide a steady baseload or flexible backup. Biomass provides baseload power, filling gaps when hydro and solar aren't generating enough. By integrating these sources, the overall system exhibits less variability, making it easier to manage energy supply and demand (Panwar et al., 2011).
- Enhances Energy Security: Complementary systems reduce dependence on a single resource. If one source is unavailable due to weather conditions, others can fill in (Hirth, 2015).
- Improves Cost Efficiency: Complementing high-variability sources (like solar) with dispatchable renewables (like hydro, or biomass) reduces the need for expensive energy storage and peak-load fossil plants (Hirth, 2015).
- Enables Better Use of Natural Resources: Different regions have different renewable potentials. Complementary planning allows optimal use of local or regional combinations of solar, biomass, hydro, and many other renewable resources (Hoogwijk *et al,* 2009).
- Supports SDG Goals: A diversified renewable energy mix enables deep reductions in CO_2 emissions while maintaining a reliable electricity supply.

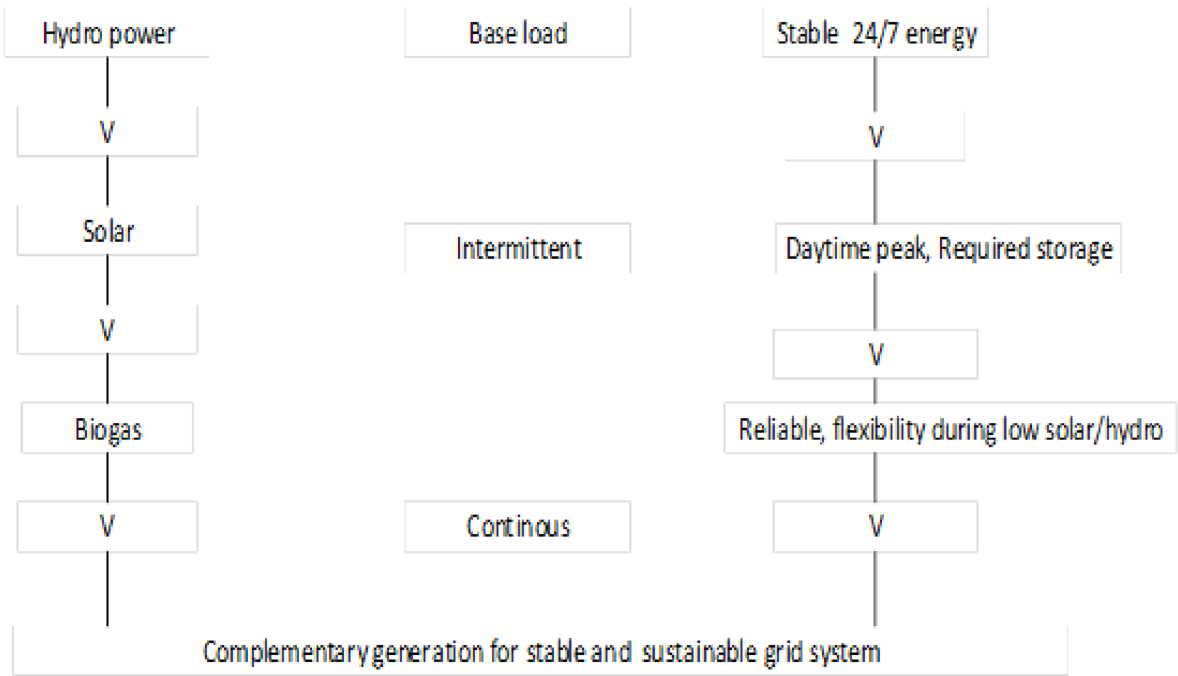

Figure 1: Renewable Energy Complementation.

Energy storage system

Energy storage (battery) is a technology that can take in energy during charging, retain it for a finite time, and release it during discharging when required. They are used as a backup system and also maintain constant voltage across the load. A battery is an energy storage system, such as lead-acid, nickel-cadmium, sodium-sulfur, or lithium-ion, that stores electrical energy in an electrochemical form and is the most widely used energy storage device across a variety of applications. Battery energy storage technologies are very versatile and can be used for both power and energy applications depending on the specific technology (Akinwale, 2010).

Batteries may be connected in series to increase the battery bank voltage and in parallel to increase the capacity. The batteries in a bank should all be of the same brand, model and age. This is due to different battery brands having different charging and discharging characteristics, with some accepting a charge or delivering current faster than others. However, the most important factors to be taken into consideration as per steady supply and control are: (1) battery configuration and (2) capacity. Once the overall battery bank capacity has been selected, the size of each battery type must be chosen accordingly (Nelson, 2009).

Hybrid Energy System

A hybrid energy system is a combination of one or more renewable resources such as solar, wind, micro/mini-hydropower, biogas and biomass with other technologies such as batteries, supercapacitors, Fuel Cells (FC), Super Magnetic Energy Storage System (SMES) and diesel generator (Wang *et al.,* 2021). Figure 2 shows a hybrid system that combines multiple renewable energy sources with energy storage (battery). The hybrid system has the capability to satisfy the power demand irrespective of the atmospheric conditions such that the capacity shortages of power from one source are compensated by other available sources (Ying *et al.,* 2021).

The main purpose of multi-energy systems is to supply the load without interruption. Other benefits include improved reliability, reduced emissions and noise pollution, increased operational lifetime of components, reduced costs, and the resourceful and efficient use of locally available energy resources (Vahabzadeh *et al.,* 2012). The energy system is a good way to provide power to many rural areas where the costs of large-scale expansion of electrical grids are high, and the transportation costs of diesel fuel are also very high (Moses and Oludolapo, 2022). The hybrid energy systems may be independent from the central electrical grid (off-grid) or grid-connected and can be divided into three categories based on their technological configuration: ac-coupled hybrid system, dc-coupled hybrid system, and mixed-coupled hybrid system (Mohd *et al*., 2017; Guichi *et al.,* 2021).

AC- coupled hybrid system

An AC-coupled hybrid system typically combines multiple power sources, such as solar PV, wind energy, a generator set, and battery storage, with the grid, enabling flexible energy management. In this system, all the energy-generating components and the energy storage technologies are connected to the AC bus in line with the load or directly to the load, as shown in Figure 3 (Hu *et al*., 2020). It gives room for easy multi-terminal matching, and there is a well-established scale of economy for consumers and existing utilities (Girish 2006).

DC- coupled hybrid power system

A DC-coupled hybrid system integrates multiple power sources and battery storage on the DC side, offering efficient energy management.

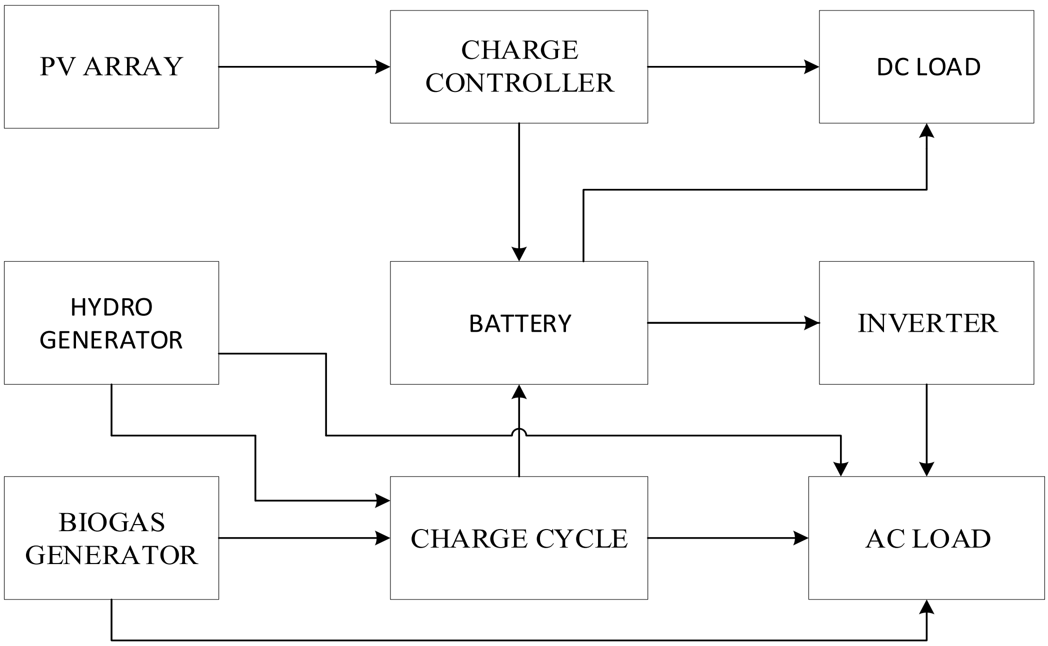

Figure 2: Block Diagram of Hybrid System

In this system, the energy conversion systems are connected to the main DC bus before being connected to the AC load side. All AC power sources are converted to DC, then connected to the AC load using an inverter, as shown in Figure 4. The merit is that demand is met without cutoffs, but it has low conversion efficiency (Hazra *et al.,* 2014).

Mixed coupled hybrid system

A mixed-coupled hybrid system combines AC-coupled and DC-coupled configurations, offering flexibility and optimization. This system allows different sources to be connected to different bus bars. Figure 5 shows the system configuration of an ac/dc-coupled system.

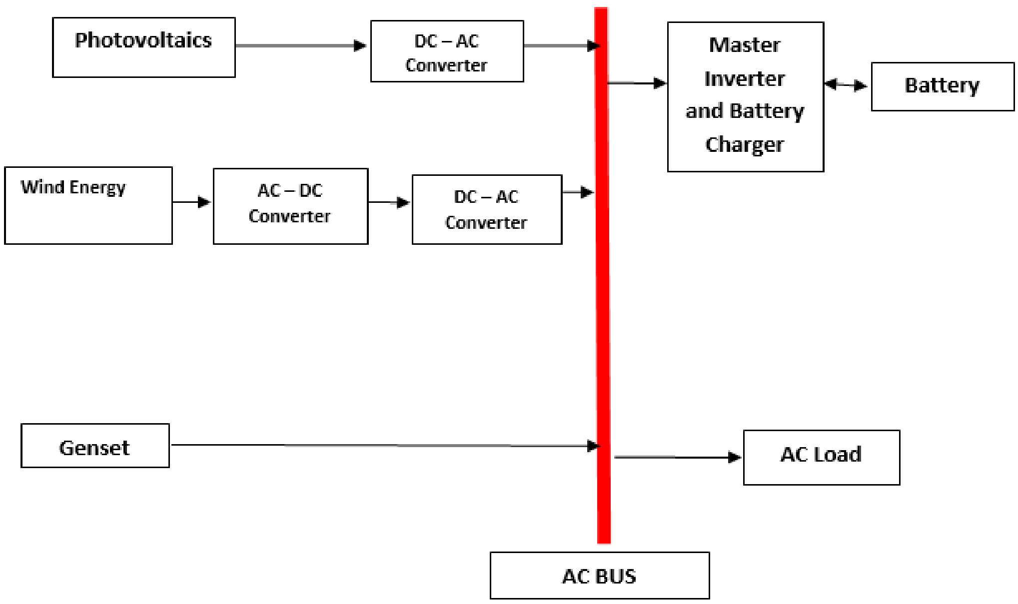

Figure 3: AC- coupled hybrid system Source: (Hu *et al*., 2020)

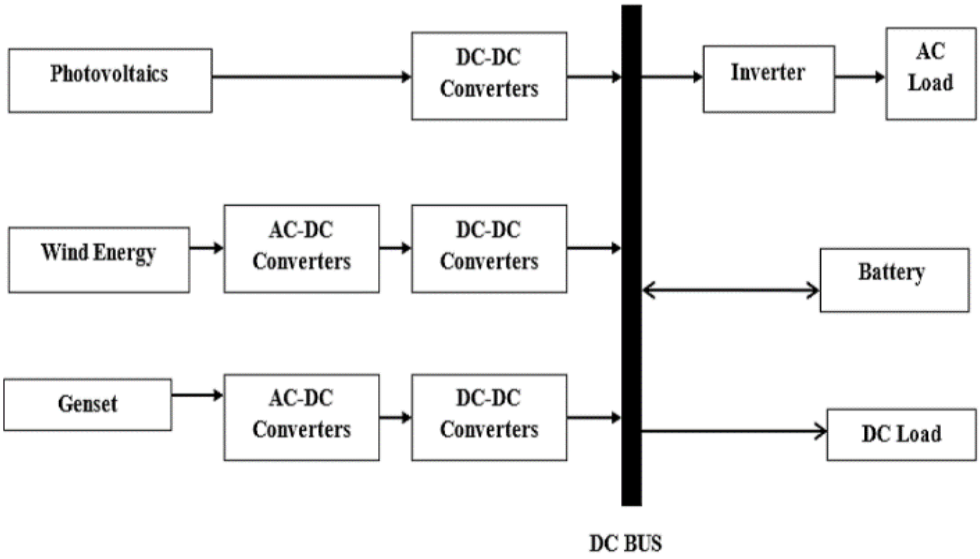

Figure 4: DC- coupled hybrid system Sources: (Hazra *et al.,* 2014)

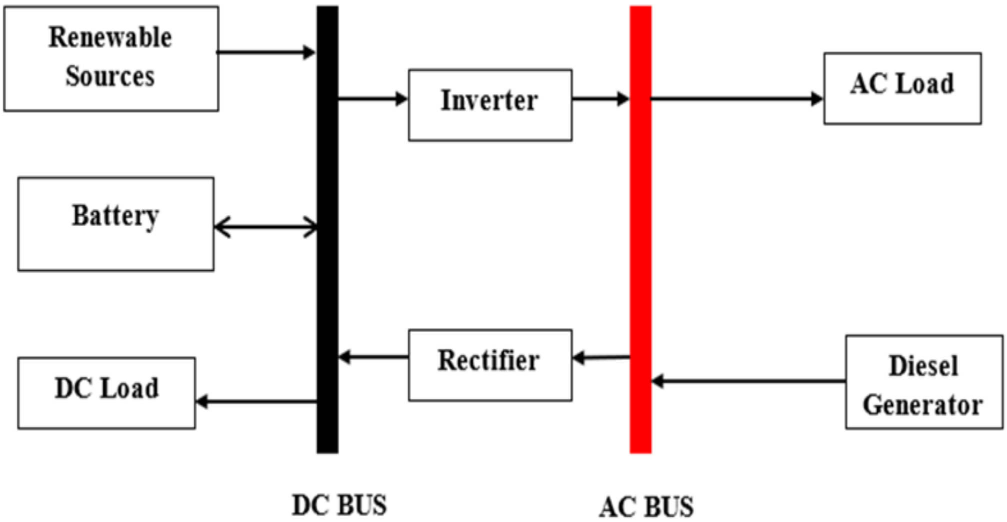

Figure 5: Mixed Coupled Hybrid Power System Sources: (Chima *et al.,* 2013)

In this system, the components are integrated without extra interfacing devices. Extra conversion losses are avoided, and capital costs for the extra interfacing devices are reduced. This configuration increases the system's overall efficiency and reduces costs. The system control and energy management of this scheme are complex; the control system must determine how power flows between the AC and DC systems (Chima *et al.,* 2013). Based on these, the mixed-coupled hybrid system is the recommended option for a complex system requiring flexibility and optimization.

Advantages of HRES over Conventional Systems

The unique design of HRES provides several advantages over traditional single-source or diesel-powered systems, including:

- Enhanced Reliability: By integrating multiple renewable sources, HRES offer a stable energy supply, reducing dependency on a single resource. This reliability is particularly beneficial in regions with variable weather patterns.

- Environmental Sustainability: HRES reduce greenhouse gas emissions and reliance on fossil fuels, contributing to environmental sustainability and aligning with global climate goals. Biomass-powered systems, when designed sustainably, can even contribute to waste management.
- Scalability and Flexibility: HRES are inherently flexible and can be scaled to meet the evolving energy needs of communities. They can function as stand-alone systems or be integrated with the main grid when it becomes accessible, offering a versatile solution for rural electrification.
- Cost effectiveness Hybrid renewable energy systems are more cost-effective in the long run than conventional energy systems. Although the initial investment may be high, operating and fuel costs are much lower because renewable resources are free and locally available. This reduces dependence on expensive fuel imports and protects users from fuel price fluctuations. Over time, this leads to more affordable and stable energy supply for communities.

Hybrid system controllers

Hybrid controller is used to implement the energy sources changeover logic based on optimal energy management strategy. Optimization of hybrid system is usually integrated with energy management strategy to control and minimize the quantity and cost of energy in their various applications. Whenever, there is more than one energy source, there is need for hybrid controller to ensure continuity of supply, increase stability and protection of components from overloading (Ying *et al.,* 2021). Some of the techniques used in controlling the charge controller are high-level supervising control (optimisation over hours/day), and real-time control (maintaining voltage/frequency stability).

Cost Assessment of Hybrid Power System

The energy investment plans and strategies remain vague on off-grid electrification and dissemination of HRES, even though HRES has been found to offer several advantages, such as: lower storage requirements than systems consisting of only one energy source, reduced operating time of the diesel generator, reduced operating cost as well as reduced fuel consumption, reduces environmental pollution and increases system reliability among others (Zhao and Li, 2019, Onuba *et al.*, 2021).

However, to evaluate the reliability of the optimal design of hybrid power system either as a constraint or a goal to be achieved in the optimization process, some certain indices such as loss of Power Supply Probability (LPSP), Expected Energy Not Served (EENS), Net Present Cost (NPC) and Cost of Energy (COE) among others need to be evaluated (Ayalew *et al.*, 2019). Among these indices, the most commonly employed by researchers are NPC and COE. These two-performance indices are subsequently presented.

Net present cost

The Net Present Cost (NPC) or life-cycle cost of a component is the present value of all the cost of installing and operating the component over the project lifetime, with the present value of all the revenues that it earns over the project lifetime. Mathematically, the total NPC is given as in equation (1) (Okozi *et al.,* 2018):

$$NPC = CC + O\&MC + RC + FC \quad (1)$$

where, CC is the capital cost, $O\&MC$ is the maintenance and operation cost, RC is the cost of replacement and FC is the cost of fuel and all the system components.

Cost of energy

The levelized Cost of Energy (COE) is a measure of the average NPC of electricity generation for a generating plant over its lifetime. It is used for investment planning and to compare different methods of electricity generation on a consistent basis. Mathematically, the COE is given as in equation (2) (Sumedha and Udara, 2020):

$$COE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^2}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^2}} \qquad (2)$$

where;

I_t is the investment expenditures in the year *t*,

M_t is the operations and maintenance expenditure in the year *t*,

F_t is the fuel expenditures in the year *t*,

E_t is the electrical energy generated in the year t,

r is the discount rate, *n* is the expected lifetime of the system or power station.

Optimization Technique for Hybrid Power Systems

Optimization of sizes of different components of the multi energy system is one of the important issues that should be considered while designing or modelling the hybrid energy system. Maximizing utilization of the renewable source, minimizing the cost of generating energy and minimizing the pollutant emissions are objective functions of this optimization. Several optimization techniques have been employed to optimize and simulate hybrid energy systems. These optimization tools can be classified as conventional technique and meta-heuristic optimization algorithms (Aduroja, 2021).

Based on literature, the majority of studies rely on HOMER and other conventional optimization algorithm for techno-economic optimization, but there is a growing trend to use custom meta-heuristics optimization algorithm for better handling of multi-objective problems.

Optimization of Hybrid Renewable Energy

A primary feature of HRES is its ability to integrate many energy sources, each tailored to distinct environmental conditions (Sharafi, *et al*, 2015). Optimizing HRES facilitates the equilibrium of energy creation among various resources, hence enhancing the probability of stable power output (Sharafi, *et al*, 2015). Key factors in optimizing the energy mix include:

- The performance of a hybrid renewable energy system improves significantly when energy sources are selected based on their complementary characteristics. For instance, solar photovoltaic and wind energy are commonly combined because solar power is available during daylight hours, while wind speeds are often higher at night (Verma *et al.*, 2024). In addition, small hydropower or biomass-based generators can serve as reliable backup sources during periods of low solar or wind availability. By tailoring the energy mix to local resource conditions, overall energy production is enhanced, and the need for extensive energy storage is reduced (Basnet *et al.*, 2023).

- Load Management and Demand Response: Effective load management is essential for maintaining the efficiency and reliability of hybrid renewable energy systems, as it ensures a balance between energy supply and demand. HRES can incorporate demand response strategies that adjust electricity consumption in response to variations in energy availability, particularly during periods of low generation (Verma *et al*., 2024). For instance, during overcast weather or low wind conditions, the system can prioritize critical loads such as lighting and essential medical equipment while temporarily limiting non-essential power use.

- Small Business Development and Entrepreneurship: Access to reliable electricity enables local entrepreneurs to establish and operate businesses that depend on a continuous power supply, such as small-scale manufacturing units, retail outlets, and agricultural processing facilities. This improved energy access stimulates local economic activity, creates employment opportunities, and enhances household income, thereby contributing to greater financial stability and stronger rural markets.
- Job Creation in Installation and Maintenance**:** The deployment of hybrid renewable energy systems creates employment opportunities both during the installation phase and throughout the system's operational lifetime (Verma *et al*., 2024). Jobs are generated in construction, system installation, operation, and routine maintenance, providing direct employment for local residents. In addition, technician training and capacity-building programs enhance long-term employment prospects by developing a skilled local workforce capable of managing and maintaining renewable energy installations.

Performance Evaluation and Socioeconomic Impacts

In rural areas, having access to dependable energy is a major driver of economic growth. The efficacy and functionality of Hybrid Renewable Energy Systems (HRES) are essential for guaranteeing a dependable, uninterrupted, and economical energy supply for rural electrification. HRES seeks to optimize energy production by integrating renewable energy sources such as solar, biomass, and hydropower, thereby diminishing reliance on a singular source and enhancing overall system reliability (Bajpai and Dash, 2012). These socio-economic benefits are direct outcome of a successfully optimized and reliable technical system.

Challenges facing the Hybrid Energy System

i. High Initial Costs and Limited Financing Options: The high initial capital needed for system design, purchasing, transportation, and installation is one of the biggest obstacles to the implementation of HRES (Verma *et al*., 2024). Low-income rural communities may find these upfront expenses unaffordable, especially in developing nations where access to reasonably priced financing options is restricted.

ii. Technical Challenges. HRES installation, operation, and maintenance need technical know-how. Effective HRES deployment is severely hampered in many rural regions by a shortage of skilled workers and restricted access to technical assistance.

iii. Cultural Acceptance. Community acceptance of new energy technology can occasionally be a hindrance. Adoption of HRES may be influenced by social and cultural factors, such as limited knowledge of renewable energy, regional preferences for conventional energy sources, or concerns about technological reliability.

iv. Environmental and Resource Constraints. Even though HRES are more environmentally beneficial than systems that rely on fossil fuels, they may still face resource and environmental limitations, especially in places with limited renewable resources.

Solution to the Challenges facing HRES adoption

i. Financial barriers can be overcome if Governments and development organisations could offer grants, low-interest loans, and subsidies to reduce upfront expenses. Furthermore, HRES can be made more accessible to rural communities through creative financing approaches such as pay-as-you-go, microfinance, and community-based funding (Bello et al*.,* 2024).

ii. Training initiatives can give local communities the know-how to oversee HRES, generating a workforce that is available locally to maintain and repair systems (Bello *et al,* 2024).

iii. Involving communities in HRES project planning and decision-making can enhance acceptability and cultivate a feeling of pride. Building trust in HRES can be facilitated by education and awareness initiatives that educate communities about the benifits of renewable energy (Seiyefa *et al.,* 2024).

iv. Long-term resource availability can be ensured by reducing the environmental impact of biomass and hydropower systems through sustainable sourcing methods and environmental impact assessments (Seiyefa *et al.,* 2024).

CONCLUSION AND RECOMMENDATION

In developing nations, hybrid renewable energy systems (HRES), particularly combinations of hydro, solar and biogas resources, offer a promising solution for providing decentralised, off-grid power supplies tailored to resource availability in many rural settings. This system leverages the complementary qualities of these energy sources to provide a steady power supply, even in situations when individual supplies are erratic. Specifically, in isolated areas where fuel transportation is difficult, HRES offer the potential to lessen reliance on fossil fuels, which are expensive and hazardous to the environment.

HRES promotes socioeconomic development, improves access to quality health care and education, mitigates rural-urban migration, boosts agricultural production, supports small businesses, and generates jobs in system installation, operation, and maintenance. Because HRES reduces greenhouse gas emissions, its environmental benefits are equally important and support long-term sustainability by providing a cleaner substitute that is in line with Sustainable Development Goal (SDGs) of which is clean energy and rural development.

Despite these numerous benefits, a number of obstacles prevent HRES from being widely used, which include: the complexity involved in the optimal sizing, scheduling, and operation of such hybrid systems, especially under variable demand and intermittent renewable resources availability, high upfront expenses, lack of or few financing alternatives,
and improper management of HRES pose significant challenges, particularly in rural, low-income communities where funding and technical know-how are sometimes limited. Implementation is made more difficult by legislative and regulatory barriers, such as ambiguous off-grid system regulations and a lack of incentives for renewable energy. Another challenge may be social and cultural acceptance, since some groups may be reluctant to embrace new technologies.

Future research should focus on a metaheuristic optimisation algorithm that can better handle the constraint nature of hybrid-renewable energy systems and the uncertainty in biomass feedstock availability. Concerns about land use, noise, and visual impact should be mitigated through careful planning. Locals should also be educated about the environmental benefits of renewable energy. With cooperation from governments, private sector partners, and local communities, hybridisation of renewable energy resources can be a game-changer for rural dwellers, providing significant social, economic, and environmental benefits that contribute to a more resilient and equitable future.

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