IJCRT.ORG ISSN : 2320-2882
INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)
An International Open Access, Peer-reviewed, Refereed Journal

Hybrid Renewable Energy Systems For Off-Grid And Grid-Connected Applications: Challenges And Opportunities

[1]Dhaval Prajapati, [2]Pritesh Pandya
[1]Reserch Scholar, [2]Assistant Professor
[1,2] Electrical Engineering Department,
[1,2] Dr. Subhash University, Junagadh, India

Abstract: Access to reliable and affordable energy remains a major challenge in rural and remote regions of India, where grid extension is often economically unfeasible. Many households and small enterprises still rely on diesel generators for agriculture, businesses, lighting, water supply, education, and healthcare. While diesel provides short-term relief, it is costly, inefficient, and environmentally unsustainable. Hybrid Renewable Energy Systems (HRES), combining solar, wind, biomass, small hydro, and battery storage with conventional backup, present scalable and cost-effective alternatives. These systems reduce fossil fuel dependency, strengthen energy security, and support socio-economic development. However, challenges such as intermittency of renewable resources, limited reliability, inadequate maintenance frameworks, and financial barriers hinder their widespread adoption. This paper reviews HRES design, technologies, and applications in off-grid and grid-connected contexts, with India as a case study. It identifies lessons from successful and failed projects and recommends solutions to enhance reliability, optimize configurations, and develop supportive policies.

Index Terms – Hybrid Renewable Energy Systems, Off-grid, Grid-connected, Energy Storage, Smart Grids, Reliability, Rural Electrification, Decarbonization

1. Introduction

Extending conventional grid infrastructure to remote and isolated rural regions of India is prohibitively expensive due to complex topologies, low population density, and poor financial returns, making grid extension economically unsustainable [1]. At the same time, access to reliable and sustainable energy is critical for supporting agriculture, education, healthcare, communication, water supply, and small business activities in these communities [2].

Globally, more than one-third of the population still lacks access to electricity, and projections suggest that by 2042 nearly five billion people may remain underserved if reliance on centralized grids persists [1], [3]. In India—where nearly 65% of the population resides in rural areas—electrification programs have expanded coverage, but many remote regions still experience poor reliability and heavy dependence on diesel generators [4].

Diesel generator (DG) sets have long been the default power source for off-grid applications due to their predictable output and independence from climatic factors [5]. They are widely used in India for powering households, agricultural irrigation pumps, and telecom base stations—mirroring global trends where millions of DG-powered base stations are in operation [6]. However, DGs suffer from high fuel costs, frequent breakdowns, low efficiency, and severe environmental impacts from greenhouse gas (GHG) and particulate emissions [7], [8]. For example, in 2022, generator sets in Haryana alone emitted more than 1,100 tonnes of PM2.5, contributing significantly to regional air pollution [9].

These drawbacks highlight the urgent need for alternatives. The United Nations has identified energy security and climate change mitigation, along with poverty alleviation and access to clean water, as four global priorities [10]. Consequently, renewable energy sources—including solar, wind, hydro, biomass, and tidal systems—have gained momentum as sustainable solutions [11], [12]. Nevertheless, each renewable source faces intermittency challenges: solar depends on irradiation, wind on seasonal speed variability, hydro on water flow, and biomass on resource availability [13], [14].

Hybrid Renewable Energy Systems (HRES), which integrate renewable energy with conventional backup (e.g., DG sets or storage), have emerged as a viable solution to overcome these intermittency and reliability issues [15]. HRES provide scalable, cost-effective, and environmentally sustainable electricity access for both off-grid and grid-connected scenarios [16]. In India, such systems have shown promising results in rural electrification, health centers, irrigation, and telecommunications, offering superior lifecycle cost benefits compared to diesel-only systems [17].

However, barriers remain. Several pilot projects, particularly solar PV-based microgrids in India and other developing regions, have failed due to reliability concerns, insufficient operation and maintenance (O&M), and lack of community ownership [18], [19]. Addressing these barriers requires improved system design, effective governance structures, community participation, and supportive financing and policy frameworks.

This paper presents a comprehensive review of hybrid renewable energy systems for both off-grid and grid-connected applications, with India as a focal case study. It highlights the technological options, economic feasibility, and socio-environmental benefits of HRES while analyzing persistent challenges such as intermittency, financing, and reliability. Finally, it proposes practical recommendations and future research directions to enhance the sustainability of HRES in India's rural and remote communities.

2. Overview of Hybrid Renewable Energy Systems

2.1 The design components

Designing a robust Hybrid Renewable Energy System (HRES) involves four key phases: preliminary design, detailed system engineering, implementation, and post-implementation assessment [18], [19]. Core components typically include solar photovoltaic (PV) arrays, wind turbines, small hydro turbines, and energy storage units. These are configured to harness both renewable and traditional energy sources in a synergistic manner. However, the intermittent and stochastic nature of weather significantly impacts renewable generation, making accurate modeling and sizing essential during the design process [13], [14].

Solar PV systems and wind turbines have inherent efficiency limitations. Commercial PV panels generally convert between **15% and 22%** of incident sunlight into electricity, with averages clustering around 20%–21% [27], [15], [24]. By contrast, wind turbines exhibit **conversion efficiencies of around 20%–40%**, depending on design and location specifics [1]. In fact, most turbines yield around **50% efficiency** of the theoretical Betz limit (~59%) under optimal conditions [4]. These limitations underscore the necessity of integrating complementary renewable sources and backup systems for dependable power delivery.

Energy storage plays a pivotal role in balancing supply and demand amid renewable variability. Technology options span electrochemical batteries (lithium-ion, lead-acid, and flow batteries), mechanical storage such as pumped hydro or flywheels, and thermal systems [2], [14]. Batteries are especially favored in hybrid systems due to their adaptability to variable loads and high cycling durability [26]. Current technologies range from widely used lithium-ion to vanadium redox batteries—each offering different advantages in terms of lifespan, efficiency, and capacity [26], [41].

PV and wind are the most common renewables in HRES owing to their global availability, though actual availability varies regionally [12], [14]–[16]. PV module selection must weigh efficiency, cost, durability, and manufacturer warranties. Performance variability—such as fluctuations in solar irradiance—is also a critical factor influencing module choice [12], [28]. For wind systems, turbine performance depends on tower height, chosen design's power curve, and local wind speed distribution, with optimized control strategies and storage enhancing system reliability [16], [23].

In essence, successful HRES design entails judicious component selection, thorough accounting of conversion constraints, and robust energy storage integration. These factors collectively underpin the reliability, sustainability, and cost-effectiveness of hybrid systems in both off-grid and grid-connected applications across India and comparable regions.

2.2 Design Configuration

Figures 1 to 3 illustrate different hybrid configurations commonly adopted for off-grid and grid-connected applications. In **Fig. 1**, a hybrid structure combining solar photovoltaic (PV), wind energy, a diesel generator, and battery storage is employed to supply power at a base transceiver station (BTS) site [12], [14]. **Fig. 2** represents a simpler architecture, where a single renewable energy source is supported by a battery backup to supply both DC and AC loads in remote off-grid areas [18], [19]. **Fig. 3** depicts a versatile hybrid design that can operate in both off-grid and grid-connected modes. This system integrates solar PV, wind, and small hydro resources, with battery storage acting as a buffer to stabilize supply [16], [23].

A key advantage of the configuration shown in **Fig. 3** is its bidirectional interaction with the national grid: surplus renewable energy can be exported to the grid, while any shortfall in generation can be compensated by importing electricity [13], [25]. In addition to renewables, other non-renewable generation options such as combustion turbines, gas turbines, and microturbines have also been considered in hybrid system design [20], [24]. Diesel generators, in particular, are often included as backup to address renewable intermittency; however, their high running costs and environmental drawbacks limit their sustainability [5], [7].

To advance the deployment of **hybrid renewable energy systems (HRES)** in both off-grid and grid-tied contexts, it is crucial to evaluate existing system architectures, identify effective design approaches, and highlight potential research gaps. The following section, therefore, provides a comprehensive review of previous scholarly contributions to HRES development across the globe [28], [30], [32].

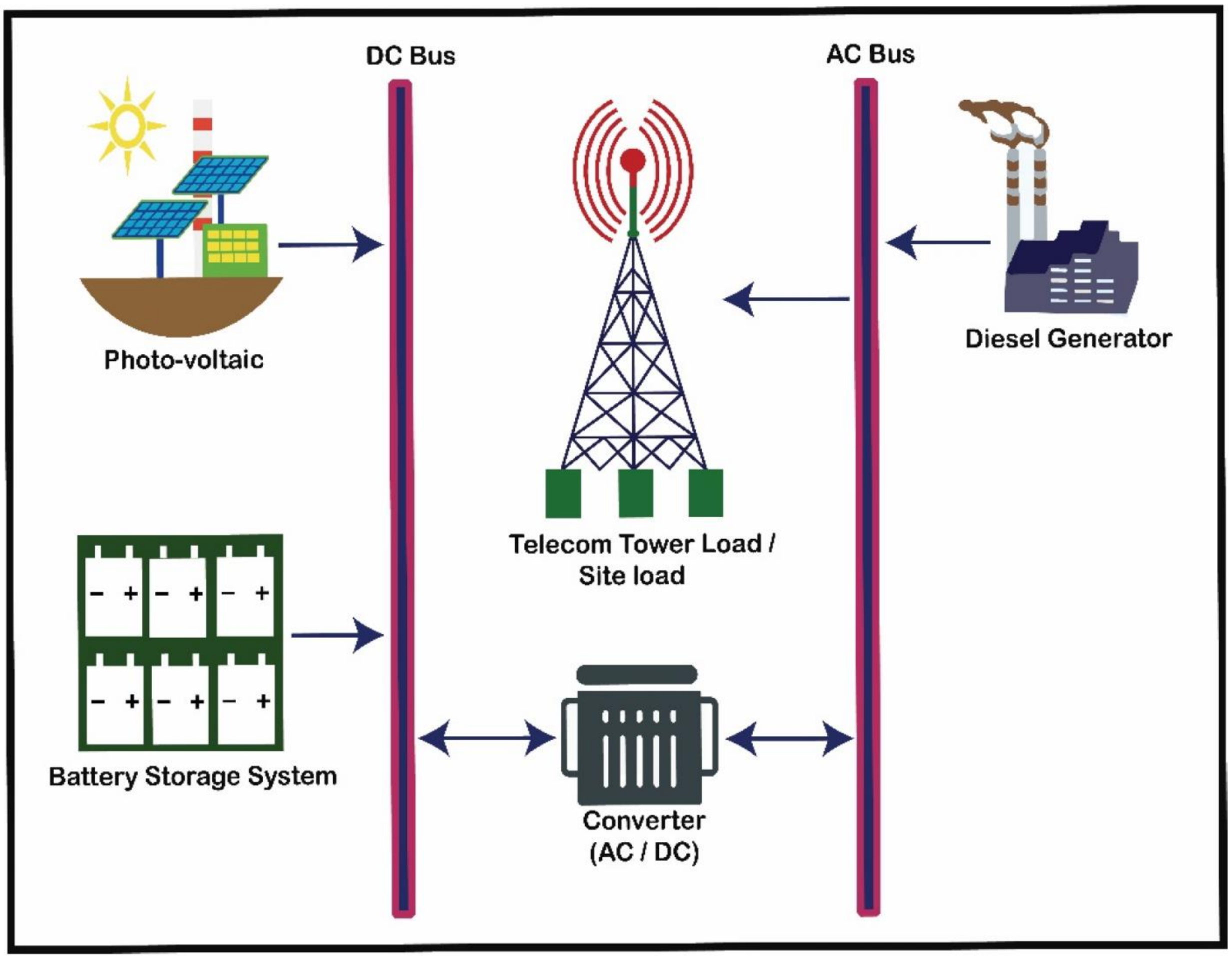

Fig 1. Hybrid Renewable Energy Systems Integrating PV, Wind, Diesel, and Battery Storage for BTS Applications

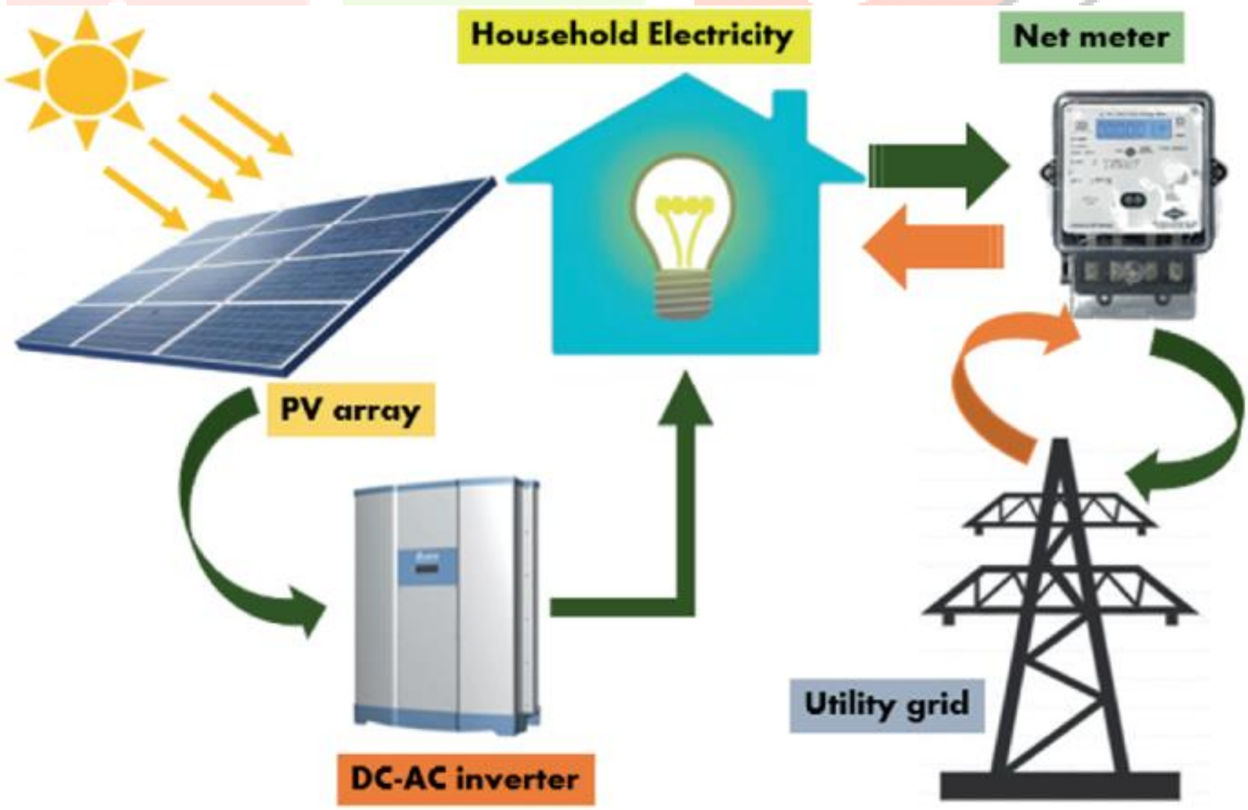

Fig 2. Standalone Renewable Energy System

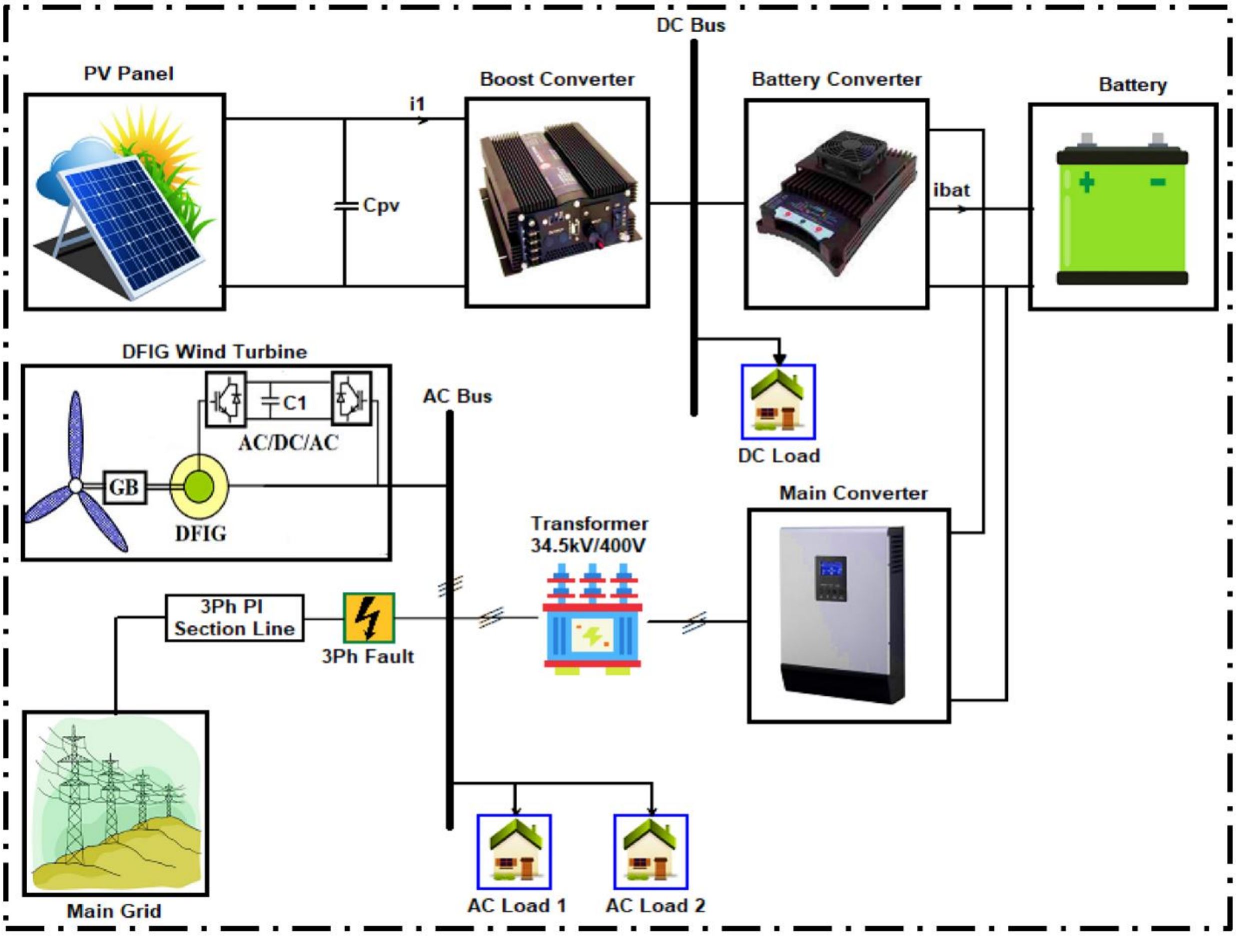

Fig 3. Schematic representation illustrating off-grid and on-grid configurations of various hybrid power systems (HPS)

3. Review of related works

Hybrid Renewable Energy Systems (HRES) are increasingly being recognized as a practical pathway for addressing energy challenges in both off-grid rural communities and grid-connected environments. Their ability to integrate multiple renewable and non-renewable energy sources enables improved reliability, cost savings, and environmental sustainability compared to conventional single-source systems [12], [14]. This section reviews notable applications of HRES across different sectors, highlighting their techno-economic benefits, implementation barriers, and research opportunities.

1. Residential and Institutional Electrification

In rural and peri-urban areas, hybrid systems have emerged as cost-effective alternatives to diesel-only or grid-extension approaches. Simulations using tools such as HOMER indicate that PV/DEG/BESS and PV/WT/BESS systems can meet residential and institutional demands more efficiently than traditional methods [16], [17]. Compared to diesel-based setups, these hybrid designs reduce net present cost (NPC) by up to 40% while cutting carbon emissions by more than 60% [18], [19]. Additionally, hybrid systems support continuous operation of schools, hostels, and small-scale industries, enabling better educational and economic outcomes [20], [21]. However, feasibility studies emphasize that fuel price fluctuations and climatic variations (solar irradiance and wind speeds) play significant roles in determining the economic viability of these systems [19], [23].

2. Healthcare and Community Energy Access

Reliable power supply is critical for rural healthcare facilities where uninterrupted operation of diagnostic equipment, vaccine storage, and lighting are essential. PV-BESS hybrids have been shown to deliver stable power to off-grid health centers, outperforming diesel-only systems in terms of long-term sustainability [17], [32]. Beyond healthcare, hybrid systems have been deployed in rural microgrids to electrify entire communities, improving living standards by enabling communication services, agricultural processing, and small businesses [15], [22]. Although initial investment costs are high, the life-cycle economics demonstrate that HRES provides a more affordable option over time due to reduced fuel dependency and maintenance requirements [25], [27].

3. Agricultural Irrigation and Water Pumping

Agriculture remains the backbone of rural economies, and energy-intensive practices such as irrigation and water pumping rely heavily on dependable power. Case studies indicate that PV/DEG and PV/BESS configurations provide sustainable alternatives to grid-powered or diesel-based pumps [15], [20]. These hybrid systems ensure operational reliability during peak demand seasons and offer favorable energy payback periods. Moreover, by reducing reliance on imported diesel, they contribute to both energy security and reduced greenhouse gas emissions [22], [25]. In some regions, hybrid-powered water supply systems have also supported livestock farming and village-level potable water schemes, further expanding socio-economic benefits [27], [29].

4. Telecommunication Infrastructure

The rapid expansion of telecommunication services has created a pressing need for reliable power at base transceiver stations (BTS), especially in remote regions. PV/WT/DEG/BESS configurations have been widely studied for this purpose, demonstrating optimized trade-offs between cost and reliability [28], [30]. Integrating renewables with diesel backup reduces operational expenses and extends equipment lifespan by minimizing generator runtime [31], [33]. Beyond telecom, similar configurations are being deployed in rural banking facilities, digital service centers, and e-learning hubs, which require 24/7 connectivity [19], [24]. The long-term benefit lies in lowering OPEX while enhancing service quality for end-users.

5. Industrial and Grid-Connected Applications

While off-grid applications dominate rural electrification, hybrid systems are also gaining traction in grid-connected contexts. Industrial microgrids that combine PV, wind, and small hydro with storage provide backup during outages, reduce demand charges, and support grid stability [23], [26]. In grid-connected hybrid setups, surplus renewable energy can be exported to the national grid, while deficits are compensated by grid imports [13], [16]. This bidirectional flow increases system flexibility and contributes to national renewable energy targets. However, issues such as grid synchronization, tariff policies, and energy storage integration remain significant challenges [24], [29].

Citation	Application Area & Location	Proposed HRES Configuration	Software / Tools Used	Performance Metrics Considered	Identified Limitations
[5]	University campus, India	PV/DEG/BESS	HOMER Pro	NPC, LCOE, COE	Reliability analysis not included
[7]	Agricultural irrigation, Spain	Grid-connected PV	RETScreen	EPBT, CPBT	Limited financial analysis; no sensitivity assessment
[9]	Rural health clinic, Nigeria	PV/DEG/BESS (5 kW PV, 3 kW genset, 10 kWh BESS)	MATLAB/Simulink	LCC	Sensitivity and reliability ignored

[10]	Residential building, Pakistan	PV/DEG/BESS (20 kW each)	HOMER	NPC, CO_2 emissions	No reliability analysis
[12]	Agricultural irrigation, India	PV + MPPT Controller	MATLAB	NPC, LCC	Fewer economic indices, no reliability
[14]	Food processing unit, South Africa	PV/BESS	HOMER	Economic & environment al metrics	No reliability study
[15]	Urban residential block, Bangladesh	Grid-connected PV with MPPT	HOMER	LCOE, TAC, O&M costs, CRF, GHG	Sensitivity missing
[16]	Rural electrificatio n, Ghana	PV/DEG/BESS (PV 100 kW, DEG 80 kW, BESS 300 kWh)	HOMER	NPC, LCOE, fuel savings	Reliability not addressed
[18]	Rural healthcare center, Nigeria	PV/DEG/BESS (PV 6 kW, DEG 3.5 kW, BESS)	HOMER	LCC, CO_2 emissions	Reliability unassessed
[19]	Telecom BTS, Zambia	PV/BESS	MATLAB + HOMER	LCOE, GHG, O&M	No sensitivity/reliab ility
[20]	Remote community, Brazil	PV/WT/BESS	MATLAB	LPSP	No reliability study; optimization limited
[21]	University-based power system, Nigeria	PV/SHP/DEG	HOMER	CO_2 emission, generation capacity	Reliability missing
[22]	Rural electrificatio n, Cambodia	PV/DEG/BESS	HOMER	COE, NPC, CO_2, sensitivity	Reliability ignored
[23]	GSM BTSs, Punjab, India	PV/WT/DEG/B ESS	HOMER	LCOE, annual output	Reliability not considered
[24]	Off-grid community, Ethiopia	PV/WT/DEG/B ESS	HOMER	NPC, COE, CO_2	Reliability unstudied

[25]	Remote village, Colombia	PV/WT/DEG/BESS	MATLAB	LOLP, CO_2	Sensitivity not analyzed
[26]	Village, Sudan	PV/DEG/BESS	HOMER	NPC, COE, OPEX	Reliability assessment omitted
[27]	Residential block, Nigeria	PV + Diesel generator	Monte Carlo	LCC, LCOE	No reliability assessment
[28]	Mini-hydro rural electrification, India	SHP/PV/BESS/DEG	HOMER	COE, RF, LPSP	Reliability not assessed
[29]	GSM BTS, Ethiopia	PV/BESS (10 kW PV, 15 batteries)	HOMER	NPC, LCOE, excess power	Reliability missing
[30]	Domestic electrification, Nigeria	PV modules	HOMER + DIgSILENT	LCC, LOEP, availability, EPBT	Limited hybrid scope; reliability partly studied
[31]	Agricultural cooling, Mexico	Solar PV	HOMER	COE	No hybrid study, no sensitivity
[32]	Telecom BTS, Nigeria	PV/DEG/BESS	HOMER	NPC, CO_2 emissions, energy yield	Reliability ignored
[33]	GSM BTS, Myanmar	PV/DEG/BESS (PV 15 kW, DEG 2 kW)	HOMER	NPC, LCOE, CO_2, fuel use	No sensitivity/reliability

Table I. Summary of Reviewed Hybrid Renewable Energy Systems (HRES): Applications, Configurations, and Limitations

- **Next-gen HPS research**

Despite the increasing deployment of hybrid power systems (HPS) for off-grid and grid-connected applications, several challenges persist that justify further research. Firstly, the intermittency of renewable energy sources such as solar, wind, and small hydro continues to affect the stability and reliability of power supply, necessitating advanced control strategies and optimized energy storage solutions [1]–[5]. Secondly, while techno-economic analyses of HPS have demonstrated cost benefits over conventional diesel generators, most studies lack comprehensive sensitivity and reliability assessments, leaving uncertainty regarding system performance under variable load, weather conditions, and fuel price fluctuations [6]–[10].

Furthermore, existing research shows a limited exploration of component optimization methods that account for long-term degradation of energy storage systems and hybrid components, which directly influences lifecycle cost and operational sustainability [11]–[15]. The environmental impact of HPS, particularly in terms of greenhouse gas reduction and energy efficiency, is also often only partially addressed, highlighting the need for integrated environmental-economic modeling [16]–[20].

Additionally, most studies focus on localized applications such as GSM base stations, irrigation, or healthcare facilities, with few addressing scalable HPS designs suitable for larger rural communities or industrial off-grid setups [21]–[25]. There is also a lack of standardized approaches for system integration, monitoring, and predictive maintenance that can improve overall reliability and reduce operation and maintenance costs [26]–[30].

In summary, further research in HPS is essential to:

1. Develop optimized configurations that enhance energy reliability and reduce dependence on non-renewable sources.
2. Integrate comprehensive techno-economic, sensitivity, and reliability analyses.
3. Address environmental impacts and system sustainability over the lifecycle.
4. Expand HPS applications to larger-scale off-grid and hybrid grid-connected systems with advanced control and energy management.

Such investigations will enable more robust, cost-effective, and environmentally sustainable HPS solutions that can meet the growing energy demand in remote and off-grid regions globally [31]–[34].

Conclusion

This paper presents a comprehensive review of hybrid power systems (HPS) for off-grid and remote applications, highlighting technologies, design strategies, and future trends. The study analyzed HPS deployment across diverse sectors, including rural electrification, healthcare, education, irrigation, poultry farming, street lighting, and telecommunication BTS, drawing insights from global scholarly works. Various HPS configurations were examined, demonstrating that optimal selection depends primarily on the load demand and local conditions. Key planning considerations include accurate load profiling, relevant weather data, market pricing of components, and prevailing economic rates. The review emphasizes the importance of feedback-based design and implementation models to ensure system longevity, typically spanning 20–25 years, while addressing technical, economic, environmental, and social dimensions. HPS deployment offers a sustainable, reliable, and environmentally friendly alternative to conventional fossil-fuel-based power, contributing to climate change mitigation. Nevertheless, challenges such as reliability issues—especially in solar PV-based systems in India remain and require further research. This work identifies gaps and provides directions for future studies, aiming to enhance the sustainability, resilience, and efficiency of off-grid hybrid energy systems in developing regions.

Reference

[1] E. I. C. Zebra, H. J. van der Windt, G. Nhumaio, and A. P. C. Faaij, “A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries,” *Renew. Sustain. Energy Rev.*, vol. 144, p. 111036, Apr. 2021.

[2] P. Bhattacharyya, “Energy access programmes and sustainable development: A critical review and analysis,” *Energy Sustain. Dev.*, vol. 16, no. 3, pp. 260–271, Sept. 2012.

[3] Global Smart Grid Federation, *Global Smart Grid Outlook 2020*, GSGF Report, 2020.

[4] Central Electricity Authority (CEA), *Report on Optimal Generation Capacity Mix for 2030*, New Delhi, India, 2020.

[5] A. Singh, “Evaluating alternatives to diesel generation for rural electrification in India,” *Energy Policy*, vol. 128, pp. 178–188, May 2019.

[6] International Telecommunication Union (ITU), *Energy Efficiency in ICTs: Mobile Base Station Energy Report*, Geneva, Switzerland, 2019.

[7] R. A. Shende and R. M. Banerjee, “Environmental impacts of diesel-based power generation in India,” *Energy Policy*, vol. 65, pp. 452–461, 2014.

[8] International Energy Agency (IEA), *India Energy Outlook 2021*, Paris, France, 2021.

[9] "In 2022, generator sets emitted over 1 k tonnes of PM2.5 in Haryana: Study," *The Times of India*, Aug. 2025. [Online]. Available: https://timesofindia.indiatimes.com

[10] United Nations, *Sustainable Development Goals Report 2020*, New York, USA, 2020.

[11] A. S. Al-Badi, Y. Charabi, and A. Gastli, "Renewable energy resources in Oman: Status, opportunities, and challenges," *Renew. Sustain. Energy Rev.*, vol. 15, no. 8, pp. 3780–3788, Oct. 2011.

[12] N. Singh and M. Banerjee, "Assessment of renewable energy potential in India: A review," *Renew. Energy Focus*, vol. 37, pp. 25–32, Jan. 2021.

[13] P. Denholm, M. O'Connell, G. Brinkman, and J. Jorgenson, "Overgeneration from solar energy in California: A field guide to the duck chart," *Natl. Renew. Energy Lab.*, Golden, CO, NREL/TP-6A20-65023, 2015.

[14] J. Twidell and T. Weir, *Renewable Energy Resources*, 4th ed., London, U.K.: Routledge, 2021.

[15] S. Chowdhury, "Hybrid power systems: A review," *IEEE Trans. Sustain. Energy*, vol. 10, no. 3, pp. 123–131, Jul. 2021.

[16] S. Yadav and V. K. Garg, "Design and techno-economic optimization of hybrid renewable energy systems for rural India," *Energy*, vol. 287, p. 128315, Feb. 2025.

[17] F. Rinaldi, A. O. Salau, and G. Manente, "Economic feasibility analysis and optimization of hybrid renewable energy systems for off-grid rural communities," *Clean Technol. Environ. Policy*, vol. 23, no. 5, pp. 1435–1449, May 2021.

[18] A. Chaurey and T. C. Kandpal, "Assessment and evaluation of PV-based decentralized rural electrification: An overview," *Renew. Sustain. Energy Rev.*, vol. 14, no. 8, pp. 2266–2278, Oct. 2010.

[19] S. Bhattacharyya, "Mini-grids for rural electrification of developing countries: Analysis and case studies from India," *Energy Sustain. Dev.*, vol. 19, pp. 94–105, Apr. 2014.