Design and Development of a Hybrid Renewable Energy System for Sustainable Rural Electrification: A Review

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Abstract - *Reliable electricity is a prerequisite for social development, education, healthcare, productive activities and improved quality of life in rural communities. However, dispersed settlements, weak distribution infrastructure, low and variable demand, difficult terrain and the cost of grid extension make decentralized energy systems attractive for many remote locations. Hybrid renewable energy systems (HRES) combine two or more renewable resources, energy storage and, where necessary, dispatchable backup generation to compensate for the intermittency of individual renewable sources. This review synthesizes recent research on HRES for sustainable rural electrification, with emphasis on system configuration, renewable-resource complementarity, energy storage, load assessment, optimization, techno-economic performance, reliability, environmental impact and implementation barriers. The review is based primarily on the supplied full-text literature corpus covering studies from 2016–2025, supplemented by two complementary studies identified in the bibliographies of the supplied papers. The literature consistently shows that PV–wind combinations are attractive because of temporal complementarity, while biomass, biogas and hydro can provide dispatchable or firm generation. Battery storage remains the dominant short-duration storage option, whereas hydrogen is emerging for longer-duration storage. HOMER is widely used for configuration and techno-economic screening, but recent reviews show that GIS-based tools, multi-objective optimization and metaheuristic algorithms can address spatial, reliability and multi-criteria limitations. The major research gap is the lack of integrated, site-specific frameworks that simultaneously consider realistic load growth, resource uncertainty, spatial network constraints, storage degradation, reliability, lifecycle environmental impacts, affordability and community-level socioeconomic factors. Future HRES design should therefore move from purely least-cost sizing toward resilient, data-driven and community-oriented energy planning.*

1. INTRODUCTION

Access to reliable and affordable electricity is closely linked to sustainable rural development. Rural communities in developing countries frequently face the combined problems of dispersed settlements, limited purchasing capacity, weak infrastructure and high costs of conventional grid expansion. The literature supplied for this review repeatedly identifies decentralized generation and renewable-based mini-grids as practical alternatives where grid extension is technically difficult or economically unattractive. Zebra et al. describe HRES mini-grids as a means of overcoming renewable intermittency while also emphasizing ownership, community organization and policy support as determinants of long-term operation. Their review reports that decentralized systems can be quicker and cheaper than grid extension in some developing-country contexts, but high initial capital cost and weak institutional support remain significant barriers [9].

The principal engineering challenge is the variability of renewable resources. Solar output changes with time of day and cloud cover, wind output is stochastic, and hydro and biomass resources depend on local availability. A single renewable source may therefore require substantial oversizing or storage to meet demand continuously. Hybridization exploits complementarity between resources: solar generation is normally strongest during daytime, wind may contribute during evening or night, while hydro, biomass or biogas can provide dispatchable support. Jurasz et al. emphasize that the reliability benefit of hybridization depends not simply on the amount of renewable energy but on the temporal and spatial complementarity of resource profiles [5].

The recent research trajectory has moved from simple PV–wind sizing toward integrated HRES planning that includes batteries, hydrogen, biomass/biogas, diesel backup, advanced dispatch strategies, multi-objective optimization and spatial planning. The 2025 review by Taghizad-Tavana et al. highlights storage, metaheuristic optimization and intelligent energy management as major current research directions [16]. Similarly, Silinto et al. show that conventional models such as HOMER are strong in technology configuration and economic sizing, whereas GIS-based tools are better suited to spatially explicit planning; no single model fully addresses all requirements [14].

The objective of this review is therefore to critically synthesize the supplied literature and identify design principles and research gaps relevant to the proposed work titled “Design and Development of a Hybrid Renewable Energy System for Sustainable Rural Electrification.” The review specifically considers: (i) suitable HRES configurations, (ii) resource and load assessment, (iii) storage selection, (iv) optimization and dispatch, (v) techno-economic and environmental evaluation, (vi) reliability and sustainability, and (vii) future research directions.

2. REVIEW METHOD AND SCOPE

The review was developed from the full-text PDF papers supplied for the present study. The attached corpus contains papers and reviews covering HRES design, rural electrification, renewable-resource complementarity, mini-grids, storage, modelling tools, optimization and techno-economic assessment. The primary evidence base includes studies published from 2016 to 2025, with two additional complementary studies identified from the bibliographies contained in the supplied review papers. The papers were examined comparatively rather than summarized individually, with attention to recurring system components, modelling approaches, objective functions, performance indicators, implementation constraints and research gaps.

The synthesis follows six analytical dimensions: resource complementarity; system architecture; storage and energy management; optimization and modelling tools; technical/economic/environmental performance; and social/institutional sustainability. This approach is consistent with the recent literature, which argues that HRES design cannot be reduced to a single economic objective because reliability, emissions, social benefits, uncertainty and spatial constraints can materially change the preferred configuration [10,14,16].

Table-1: Comparative synthesis of the selected literature.

No	Study	Location	Representative configuration	Method/ tool	Main contribution
1	Diemuodeke et al. (2016)	Nigeria coastline	Diesel–PV–wind	HOMER + TOPSIS	Cost, emissions, multi-criteria
2	Chatterjee & Rayudu (2017)	Jharkhand, India	PV–wind–storage	HOMER	100% renewable, NPC, COE
3	Sawle et al. (2018)	Barwani, India	PV–wind and variants	HOMER + PSO	COE, renewable fraction, emissions
4	Murugaperumal & Raj (2019)	Korkadu, India	PV–wind–biomass–battery	ANN + HOMER	Load growth, NPC, dispatch
5	Jurasz et al. (2020)	Multi-country	Solar–wind–hydro etc.	Complementarity metrics	Reliability and storage need
6	Li et al. (2020)	West China	PV–wind–biomass	Optimization + techno-economics	Remote rural sizing
7	Rinaldi et al. (2020/21)	Peru	PV–wind–diesel	HOMER	NPC, COE, renewable fraction
8	Nebey (2021)	Ethiopia	PV–wind–hydro	HOMER + MATLAB fuzzy control	Reliability and control
9	Zebra et al. (2021)	Developing countries	Multiple HRES mini-grids	Review / comparative	LCOE, reliability, ownership
10	Natividad & Benalcazar (2023)	Conceptual/global	Multiple HRES	Energy-system modelling	Social factors and energy poverty
11	Weinand et al. (2023)	Global	Decentralized HRES	Comparative LCOE review	Cost benchmarking
12	Al Abri et al. (2023)	Oman	PV–wind–diesel	HOMER + ETAP	LCOE, emissions, power quality
13	Köprü et al. (2024)	Bingöl, Türkiye	PV–wind–biogas–battery	HOMER MATLAB Link	Dispatch strategy, NPC, LCOE
14	Silinto et al. (2025)	Developing countries	Multiple HRES	HOMER, iHOGA, GIS tools	Spatial planning and model comparison
15	Bawan et al.	West Papua,	Hybrid renewa	Optimal design	Sizing and

	(2025)	Indonesia	ble microgrid	framework	isolated-grid operation
16	Taghizad-Tavana et al. (2025)	Global/off-grid	PV, wind, storage, H2 etc.	Metaheuristic review	Storage, reliability, optimization
17	Li & Wang (2021)	Global	Multiple HRES	Design/operation review	Optimization, operation, AI
18	Mandelli et al. (2016)	Developing countries	Off-grid systems	Taxonomy/review	Technology, sizing, policy
19	Javed et al. (2019)	Remote island	PV–wind–battery	Genetic algorithm	Techno-economic sizing
20	Krishan & Suhag (2019)	Rural community	Hybrid renewable system	Techno-economic analysis	Energy-poor rural community

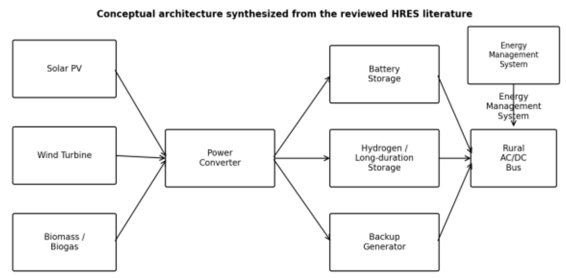

Figure 1. Conceptual architecture of a hybrid renewable energy system for rural electrification.

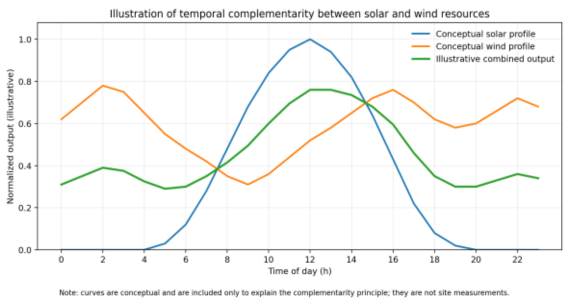

Figure 2. Conceptual temporal complementarity of solar and wind resources

3. Renewable Resource Complementarity and HRES Configurations

The central rationale for HRES is complementarity. PV and wind are the most frequently studied combination because their production profiles can partially compensate for one another. Sawle et al. identify the complementary behavior of PV and wind as a major reason for improved stability and techno-economic performance relative to single-source systems [3]. The complementarity literature goes further by distinguishing temporal, spatial and spatiotemporal complementarity. Jurasz et al. show that the degree of complementarity can influence storage requirements, reliability and the achievable smoothing of aggregate renewable output [5]. This suggests that resource selection should be performed from time-series data rather than only from annual average resource values.

PV–wind systems are particularly attractive for small rural microgrids because both resources are modular and can be installed without fuel logistics. Chatterjee and Rayudu demonstrated a 100% renewable household-scale HRES in Jharkhand using PV, wind and storage, with the system designed around seasonal load and resource characteristics [2]. For larger village loads, however, additional dispatchable renewable resources can improve adequacy. Murugaperumal and Raj used PV, wind, biomass generation and battery storage for a village in Puducherry and incorporated load-growth forecasting before HOMER-based evaluation [4]. The inclusion of biomass or biogas can reduce dependence on large battery banks because dispatchable generation can respond to deficits.

Hydro provides another important dispatchable or semi-dispatchable option where a suitable water resource exists. Nebey's Ethiopian study combined PV, wind and hydro and used a fuzzy logic controller to manage changing resource availability and demand [8]. The reported optimum resource shares were 13% PV, 52% wind and 35% hydro, demonstrating that the optimum mix is strongly location dependent. Consequently, there is no universally optimal HRES configuration; the correct architecture must emerge from local resource profiles, demand characteristics, component costs and reliability requirements.

Hybridization with diesel remains common in practical rural systems because diesel generators provide firm backup. Rinaldi et al. found PV–wind–diesel to be the economically preferred configuration in three Peruvian communities under the assumptions of their study, with renewable fractions between 94% and 97% [7]. Similarly, Al Abri et al. found a PV–wind–diesel configuration suitable for Al-Dhafrat in Oman and reported substantial reductions in diesel consumption, LCOE and greenhouse-gas emissions compared with a diesel-only system [12]. However, diesel should increasingly be treated as a transitional reliability resource rather than the defining component of a sustainable HRES because fuel price volatility, emissions and maintenance logistics reduce long-term sustainability.

4. Load Assessment and System Sizing

Accurate load characterization is as important as renewable-resource assessment. Rural loads may include domestic lighting, fans, refrigeration, water pumping, schools, health centers, agricultural processing, workshops and small businesses. The timing of these loads determines the required generation and storage capacity. A system sized only from daily average energy can fail during evening peaks even if annual renewable production is adequate.

Murugaperumal and Raj incorporated artificial neural network-based load-growth prediction before evaluating HRES configurations, showing the value of considering future demand rather than designing only for the present load [4]. Nevertheless, the broader modelling literature identifies limited demand-growth representation as a continuing weakness in many tools. Silinto et al. report that several models have limited capability for detailed demand analysis and yearly load growth [14]. This is a significant research gap for rural electrification because productive-use loads can grow rapidly after electricity becomes available.

Sizing objectives typically include minimization of net present cost (NPC), levelized cost of electricity (LCOE/COE), unmet load, loss of power supply probability (LPSP) or expected energy not supplied (EENS), fuel consumption and emissions. A single-objective least-cost solution can produce a technically fragile system if reliability constraints are weak. Conversely, an extremely reliable system may be unnecessarily expensive. The literature therefore increasingly supports multi-objective approaches that generate Pareto-optimal solutions, allowing decision makers to select a balanced configuration.

Table-2. Comparison of storage options relevant to rural HRES.

Storage	Typical role	Strengths	Key limitations
Battery	Short-duration balancing, peak shifting	Fast response; modular; mature	Degradation; replacement cost; temperature sensitivity
Pumped hydro	Long-duration storage	Long life; large capacity	Site/topography dependent; high civil works
Hydrogen	Long-duration/seasonal storage	Long storage duration; cross-sector use	High capital cost; conversion losses; infrastructure
Flywheel	Short-duration power quality	High cycle life; rapid response	Short storage duration; higher power-electronics cost
Thermal	Heat/energy shifting	Potentially low-cost for heat loads	Less direct applicability to electric-only loads

5. Energy Storage and Energy Management

Energy storage is the main mechanism for separating renewable generation from load demand. Batteries remain the most common option in rural HRES because they provide fast response, modularity and relatively simple control. The literature also identifies pumped hydro, compressed-air storage, flywheels, thermal storage and hydrogen as alternative technologies, each with different duration, cost, efficiency and infrastructure requirements [16].

For short-duration applications, lithium-ion and other electrochemical batteries can support peak shifting, frequency/voltage support and renewable smoothing. However, battery degradation, temperature, depth of discharge and replacement cost should be represented in long-term economic analysis. The recent storage review argues that lifecycle cost and operational constraints need to be evaluated jointly rather than treating storage as an idealized energy buffer [16].

Hydrogen is increasingly considered for seasonal or long-duration storage. Its advantages include potentially long storage duration and cross-sector applications, but electrolyzer, storage and fuel-cell costs remain important barriers. The recent literature also emphasizes that hydrogen requires stronger techno-economic and regulatory assessment before it can become a conventional option for small rural systems [16].

Energy management strategy is equally important. Köprü et al. compared a proposed dispatch strategy with HOMER's cycle-charging and load-following strategies for a rural HRES comprising PV, wind, biogas and battery storage. Their results demonstrate that dispatch strategy can materially influence NPC and LCOE, even for the same installed components [13]. Nebey similarly used fuzzy logic control to match demand with available PV, wind and hydro generation [8]. These findings support the development of adaptive energy management systems that use real-time resource availability, state of charge and load forecasts.

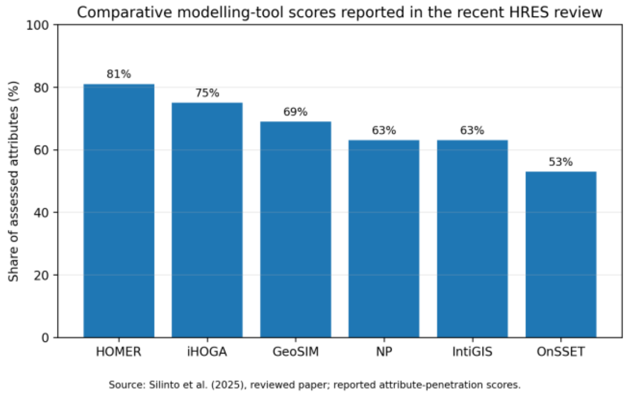

Figure 3. Comparative modelling-tool attribute scores reported by Silinto et al. (2025).

6. Modelling and Optimization Approaches

HOMER is the most frequently recurring tool in the reviewed literature because it can represent multiple generation and storage technologies, dispatch strategies, resource data and economic parameters within one framework. Chatterjee and Rayudu, Murugaperumal and Raj, Rinaldi et al., Al Abri et al. and Köprü et al. all demonstrate its usefulness for configuration screening and techno-economic evaluation [2,4,7,12,13].

Despite its practical strength, HOMER is not a complete rural energy-planning platform. Silinto et al. compared modelling tools and concluded that HOMER and iHOGA have strong hybrid-technology and economic-sizing capabilities, while GIS-based tools such as GeoSIM, IntiGIS and OnSSET better capture spatially explicit information. The study also notes that no evaluated model achieved complete coverage of all desired attributes, and that reliable ground-level data remain essential [14].

Optimization methods have evolved from enumeration and classical mathematical programming toward particle swarm optimization (PSO), genetic algorithms, multi-objective evolutionary algorithms and other metaheuristics. Sawle et al. compared HOMER and PSO and reported advantages of PSO for several techno-economic indicators in their Barwani case study [3]. The recent storage and optimization review reports that algorithms such as PSO, ABC, HSA, RPO, HHA and NSGA-III are being used for increasingly complex multi-objective HRES problems involving system sizing, storage scheduling, reliability and environmental criteria [16].

The next development is likely to be hybrid modelling: HOMER or a similar simulator for component-level techno-economic calculations, GIS for spatial planning, and optimization/AI for uncertainty, forecasting and real-time energy management. Such integration can avoid the limitation of forcing one tool to solve every aspect of the rural electrification problem.

Table-3. Key performance indicators for HRES evaluation.

Indicator	Purpose	Typical interpretation
NPC	Whole-project economic comparison	Lower is generally preferred
LCOE / COE	Cost of delivered electricity	Lower indicates better economic performance
Renewable fraction	Share of demand supplied by renewable sources	Higher indicates lower fossil dependence
LPSP / EENS	Supply adequacy and reliability	Lower unmet energy indicates higher reliability
CO_2 emissions	Environmental performance	Lower operational emissions indicate cleaner operation
Fuel consumption	Backup-generator dependence	Lower use reduces cost, logistics and emissions
Battery replacement cost	Storage lifecycle economics	Important for long project horizons

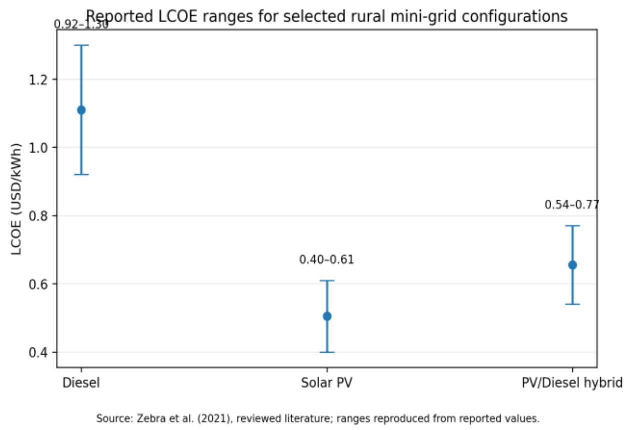

Figure 4. Reported LCOE ranges for selected rural mini-grid configurations from Zebra et al. (2021).

7. Techno-Economic and Environmental Assessment

Economic assessment commonly uses NPC, initial capital cost, replacement cost, operation and maintenance cost, fuel cost, salvage value and LCOE. Rinaldi et al. demonstrated how alternative configurations can be compared using NPC, COE, annual operating cost, generation fraction and CO2 emissions [7]. Weinand et al. provide a broader benchmark, reporting that global LCOEs for decentralized off-grid renewable systems span a very wide range and that the average LCOE of 100% renewable systems decreased substantially between 2016 and 2021, associated in part with falling renewable and storage costs [11].

Economic comparisons must nevertheless be interpreted carefully. Differences in discount rate, project lifetime, component replacement assumptions, resource quality, load factor, fuel prices, financing and treatment of unmet load can produce large differences in reported LCOE. Weinand et al. specifically identify several methodological reasons for over- or under-estimation of LCOE [11]. Therefore, future studies should report assumptions transparently and include sensitivity analysis for the parameters that most strongly influence system cost.

Environmental performance is generally evaluated through CO2 emissions, renewable fraction and, less frequently, lifecycle assessment. Al Abri et al. showed that an optimized PV–wind–diesel system can significantly reduce diesel use and greenhouse-gas emissions compared with diesel generation alone [12]. Köprü et al. similarly found very large emission differences between a biogas-supported system and a diesel-generator alternative [13]. However, operational CO2 alone does not capture embodied impacts of batteries, PV modules, wind turbines or replacement components. A complete sustainability assessment should therefore include lifecycle environmental indicators where data permit.

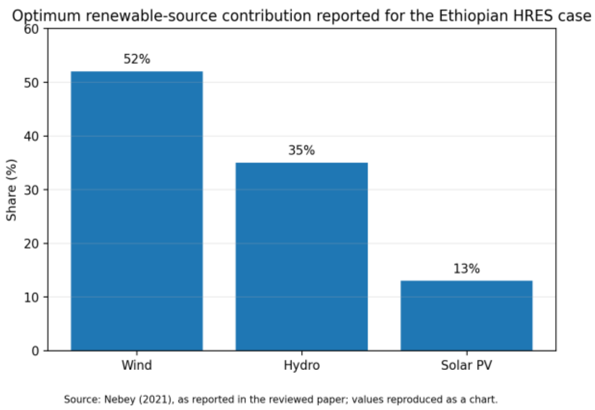

Figure 5. Optimum renewable-source contribution reported for the Ethiopian HRES case by Nebey (2021).

8. Reliability, Social Sustainability and Implementation

Reliability is a defining requirement for rural electrification. An HRES that has a low LCOE but frequent outages may not deliver the intended social or economic benefits. Reliability indicators used across the literature include unmet load, capacity shortage, LPSP, EENS, loss-of-load probability and renewable fraction. Nebey explicitly targeted reliable supply and used fuzzy control to maintain balance under variable demand and resource conditions [8].

Natividad and Benalcazar broaden the concept of optimization by arguing that social parameters such as health, education and income should be incorporated into energy-system modelling [10]. Zebra et al. similarly emphasize community organization, ownership models and government support as critical to sustaining mini-grids over their project life [9]. These findings are particularly important because technical failure is not the only cause of rural energy-system failure; maintenance capability, tariff collection, local ownership, spare-parts availability and institutional responsibility can be equally decisive.

The literature therefore supports a socio-technical definition of sustainability. A rural HRES should provide acceptable reliability and affordability, minimize environmental impact, use locally manageable technologies, permit future load growth, and have an operational model that can survive beyond the initial project or research funding period.

Table-4. Major research gaps and recommended directions.

Research gap	Recommended direction
Deterministic resource/load assumptions	Probabilistic resource scenarios and uncertainty analysis
Limited load-growth representation	End-use modelling and future productive-use demand forecasting
Separated spatial and technology models	Integrated GIS + HRES sizing workflow
Idealized storage	Include degradation, temperature, cycling and replacement
Single reliability metric	Joint EENS/LPSP, critical-load priority and resilience analysis
Operational-emission focus	Lifecycle environmental assessment
Limited social variables	Affordability, ownership, skills and community participation metrics
Simulation-heavy AI/optimization studies	Hardware-in-loop or long-term field validation

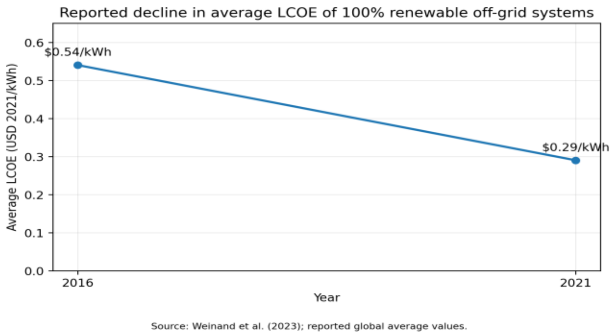

Figure 6. Reported decline in average LCOE of 100% renewable decentralized systems between 2016 and 2021.

9. Research Gaps Identified from the Reviewed Literature

1. Integrated treatment of resource uncertainty, load uncertainty and component degradation remains limited. Many sizing studies use typical or averaged profiles and deterministic assumptions.

2. Detailed rural load growth and productive-use demand are insufficiently represented in several modelling tools. Future demand should be forecast using household, agricultural, commercial and institutional end-use patterns.

3. Spatial constraints are often separated from technology sizing. GIS-based planning can locate resources and loads, while HOMER-type tools can size technologies, but integrated workflows are still developing [14].

4. Battery degradation, replacement, temperature effects and end-of-life costs are not consistently included in HRES economic models.

5. Reliability is often represented through a single metric rather than jointly considering EENS, outage duration, critical loads and resilience to extreme weather events.

6. Environmental assessment frequently focuses on operational CO2 rather than full lifecycle impacts of PV modules, batteries, wind turbines and other components.

7. Social and institutional variables such as affordability, willingness to pay, community ownership, local skills and maintenance capacity are increasingly recognized but remain difficult to quantify [9,10].

8. AI and metaheuristic optimization are advancing rapidly, but many studies remain simulation-based and lack long-term field validation. The latest review calls for stronger quantitative validation and intelligent energy-management demonstrations [16].

9. Comparability among studies is weakened by differences in economic assumptions, project lifetime, discount rate, resource data, component costs and definitions of reliability.

10. Few studies provide a complete design-to-deployment pathway linking resource assessment, load forecasting, optimal sizing, control hardware, monitoring and field performance validation.

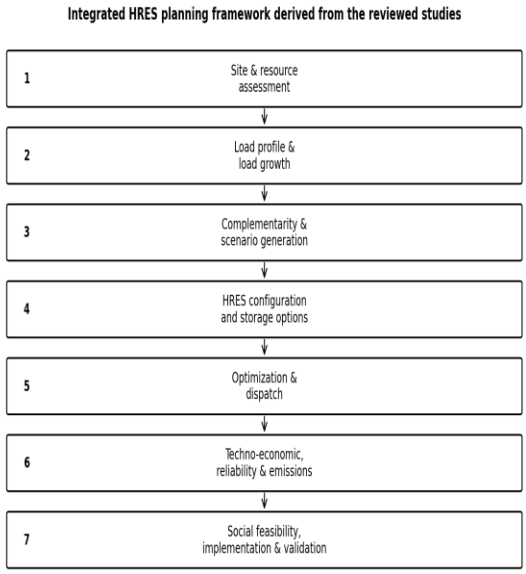

Figure 7. Integrated HRES planning and development framework synthesized from the reviewed literature.

10. CONCLUSIONS

The reviewed literature confirms that hybrid renewable energy systems are a technically credible pathway for sustainable rural electrification, particularly where conventional grid extension is expensive or impractical. PV–wind systems benefit from resource complementarity, while biomass, biogas and hydro can provide dispatchable renewable generation. Batteries remain the dominant short-duration storage technology, whereas hydrogen is emerging for longer-duration applications. The studies reviewed also demonstrate that HRES performance depends strongly on local resource quality, load characteristics, component costs, storage strategy and dispatch control.

HOMER remains a practical and widely used tool for initial system configuration and techno-economic evaluation, but the literature indicates clear limitations in spatial planning, detailed load growth, uncertainty representation and integrated network analysis. Multi-objective and metaheuristic methods offer a route to more flexible optimization, while GIS and data-driven approaches can improve site selection and spatial planning. Equally important, sustainable rural electrification is not purely an engineering optimization problem. Community organization, affordability, policy support, local technical capacity and long-term operation and maintenance determine whether a technically optimal system continues to serve users.

The principal research opportunity is therefore to develop a site-specific HRES framework that integrates renewable-resource complementarity, realistic load growth, storage degradation, reliability, techno-economic performance, environmental impacts and socioeconomic sustainability. Such a framework can move the field from simulated least-cost electrification toward resilient, affordable and practically deployable rural energy systems

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