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Optimal Sizing and Energy Management of a Hybrid Solar-Wind-Battery-Diesel System for Rural Electrification: A Fuzzy Logic Control Approach

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Abstract

Rural electrification in India remains an unfinished agenda despite significant progress under the Saubhagya and DDUGJY schemes, with approximately 30 million households in remote and geographically isolated villages lacking reliable grid connectivity. Hybrid Renewable Energy Systems (HRES) combining solar photovoltaic, wind turbine, battery energy storage, and diesel generator backup offer a techno-economically viable pathway for off-grid rural electrification at per-unit costs that have declined substantially due to rapidly falling PV module and lithium-ion battery prices. However, the intermittent and stochastic nature of solar and wind resources necessitates an intelligent Energy Management System (EMS) capable of dynamically dispatching generation and storage assets to satisfy load demand while minimising diesel consumption, maximising renewable energy fraction, and prolonging battery lifetime through controlled depth-of-discharge management. This paper presents the design, optimal sizing, and fuzzy logic-based energy management of a hybrid solar-wind-battery-diesel system for a representative rural cluster of 150 households (peak load 45 kW, annual energy demand 118 MWh) in Jaipur district, Rajasthan. System sizing optimisation using HOMER Pro minimises the Net Present Cost (NPC) subject to loss of power supply probability (LPSP) less than 2%. Five system configurations are evaluated: PV-only, wind-only, PV-wind, PV-wind-battery, and PV-wind-battery-diesel. The fuzzy logic EMS uses battery State-of-Charge (SOC) and net power surplus/deficit as inputs to generate dispatch decisions for battery charging/discharging and diesel generator start-stop commands. Results demonstrate that the optimal PV-wind-battery-diesel configuration achieves a Cost of Energy (COE) of USD 0.13/kWh, a Renewable Energy Fraction (REF) of 96%, and an annual diesel consumption reduction of 94% relative to a diesel-only baseline, with a project Net Present Cost of USD 187,400 over a 25-year project lifetime.

Keywords: *hybrid renewable energy system, rural electrification, HOMER Pro, fuzzy logic control, energy management system, solar PV, wind turbine, battery storage, cost of energy, net present cost, Rajasthan*

1. Introduction

Access to reliable electricity is a foundational enabler of rural development, linking directly to improvements in household welfare, educational outcomes, agricultural productivity, and health service delivery. India has achieved significant milestones in rural electrification through successive government programmes: the Pradhan Mantri Gram Vidyut Yojana (PMGVY), followed by the Rajiv Gandhi Grameen Vidyutikaran Yojana (RGGVY), and most recently the Pradhan Mantri Sahaj Bijli Har Ghar Yojana (Saubhagya) scheme launched in 2017 which targeted last-mile household connectivity. While Saubhagya declared 100% village electrification in April 2018, the definition of village electrification requires only 10% of households to have connections, and quality of supply in electrified rural areas remains highly variable, with average daily supply durations as low as 6-8 hours in many states including Uttar Pradesh, Jharkhand, and Bihar.

For villages located more than 5 kilometres from the nearest 11 kV grid feeder — estimated at approximately 18,000 villages in hilly, forested, and tribal regions by the Ministry of New and Renewable Energy — the economic cost of grid extension per connected household frequently exceeds USD 2,000-5,000, making standalone off-grid hybrid systems the cost-optimal electrification pathway. The dramatic decline in photovoltaic module costs from approximately USD 4/Wp in 2010 to USD 0.22/Wp in 2024, combined with lithium iron phosphate (LFP) battery pack cost reductions from USD 1,200/kWh to below USD 110/kWh over the same period, has fundamentally altered the economics of hybrid off-grid systems, making them cost-competitive with diesel generators for many rural applications at diesel prices prevailing in remote areas (typically USD 1.20-1.80/litre including transport premium).

The technical challenge in HRES design encompasses two coupled optimisation problems: system sizing, which determines the rated capacity of each component to meet the load with acceptable reliability at minimum cost; and energy management, which determines the real-time dispatch sequence of available generation and storage resources to satisfy instantaneous load demand. The system sizing problem is typically addressed using techno-economic simulation tools such as HOMER Pro, iHOGA, or custom evolutionary algorithm implementations, while the energy management problem has been addressed using rule-based, classical control, and increasingly intelligent techniques including fuzzy logic, model predictive control, and reinforcement learning.

Fuzzy logic controllers are particularly well-suited to HRES energy management due to several practically important properties. First, they encode expert heuristic knowledge in human-interpretable if-then rules without requiring an explicit mathematical model of the highly nonlinear system dynamics, which depend on meteorological stochasticity, battery electrochemical nonlinearity, and load variability. Second, they provide smooth, robust control actions that avoid the discontinuous switching characteristic of rule-based threshold controllers, which can cause premature battery cycling and accelerated degradation. Third, their computational requirement is minimal, enabling real-time implementation on low-cost microcontrollers such as the Arduino Due or STM32 family suitable for remote-area deployment without cloud connectivity.

Rajasthan is the geographically largest Indian state and offers some of the highest solar irradiance resources in the country, with Global Horizontal Irradiance (GHI) averaging 5.5-6.5 kWh/m²/day in most districts, exceeding even the resource availability in premium solar markets such as the Middle East and California. The Rajasthan state government has set an ambitious target of 30 GW renewable energy capacity by 2025, with a specific programme for solar-powered microgrids in Thar Desert villages. The present study contributes to this policy objective by demonstrating the technical and economic feasibility of an optimally sized fuzzy-logic-managed HRES for a realistic Jaipur district rural load profile, with results generalisable to similar semi-arid high-insolation regions across the Rajasthan-Gujarat solar belt.

The structure of this paper is as follows. Section 2 reviews the relevant literature on HRES sizing optimisation and intelligent energy management. Section 3 describes the study site, load profile characterisation, resource assessment methodology, component models, and the fuzzy logic EMS design. Section 4 presents HOMER Pro sizing optimisation results and fuzzy controller simulation performance. Section 5 discusses the findings, limitations, and policy implications. Section 6 provides conclusions and recommendations for implementation.

2. Literature Review

The literature on hybrid renewable energy systems for rural electrification spans three broad areas: resource assessment and load profiling, techno-economic sizing optimisation, and energy management strategy design. Early work by Elhadidy and Shaahid (1999) established the analytical framework for PV-wind-diesel hybrid system sizing based on solar and wind resource probability distributions, demonstrating that hybrid systems reduce diesel fuel consumption and cost of energy relative to diesel-only baselines in high-resource locations. Lambert et al. (2006) introduced the HOMER simulation platform that subsequently became the dominant tool for HRES techno-economic analysis, enabling sensitivity analysis across hundreds of system configurations and resource scenarios.

Optimisation-based sizing methods using metaheuristic algorithms have been extensively applied to the HRES design problem. Diaf et al. (2007) used a genetic algorithm to minimise total life-cycle cost subject to loss of power supply probability constraints for a PV-wind-battery system in Algeria, establishing the trade-off curve between system reliability and cost that characterises the HRES design space. Particle Swarm Optimisation (PSO) was applied by Kanase-Patil et al. (2011) for integrated resource planning of renewable energy systems serving rural communities in Maharashtra, demonstrating 40% cost savings over conventional diesel systems. More recent work has employed multi-objective evolutionary algorithms (MOEA) to simultaneously optimise cost, reliability, and renewable fraction, generating Pareto-optimal design fronts that expose the trade-offs among competing objectives explicitly.

Energy management strategies for HRES have evolved from simple rule-based cycle charging and load following strategies to sophisticated intelligent controllers. Fuzzy logic energy management for PV-wind-battery-diesel systems was pioneered by Seeling-Hochmuth (1998), who demonstrated that fuzzy controllers outperform rule-based strategies in minimising diesel consumption while maintaining battery SOC within desired bounds. Subsequent work by Arora et al. (2016) developed an adaptive fuzzy controller for a microgrid serving an Indian rural cluster, achieving 15% diesel consumption reduction relative to a conventional cycle-charging strategy without deteriorating system reliability. Model Predictive Control (MPC) approaches using 24-hour-ahead renewable resource forecasts have been shown to further improve performance by anticipating resource availability, but require reliable meteorological forecasting and higher computational resources than fuzzy controllers.

Deep reinforcement learning (DRL) has emerged as a promising EMS framework, with agents trained through interaction with system simulation environments learning dispatching policies that outperform model-based controllers without requiring explicit system modelling. However, DRL approaches require substantial training data, suffer from instability during exploration, and are difficult to validate for safety certification in remote deployment contexts, limiting their practical adoption relative to fuzzy and rule-based methods for resource-constrained village microgrid applications.

For the Indian rural electrification context specifically, Kolhe et al. (2015) evaluated techno-economic performance of off-grid PV-battery systems across Indian climatic zones, identifying Rajasthan and Gujarat as the most cost-effective regions for solar-dominated systems. Chauhan and Saini (2016) reviewed HRES technologies for hilly terrain electrification in Uttarakhand, highlighting the complementarity of run-of-river micro-hydro with PV in mountainous regions. Lal et al. (2022) performed a techno-economic-environmental analysis of an HRES for a remote Rajasthan village using HOMER Pro, reporting a COE of USD 0.18/kWh for an optimised PV-wind-battery system — a benchmark directly comparable with the findings of the present study, which extends that work by incorporating diesel backup and demonstrating the additional reliability and cost benefits of the fuzzy logic EMS over the default HOMER dispatch strategy.

The present study advances the existing literature in three respects: (1) it develops and validates a fuzzy logic EMS specifically calibrated to the semi-arid seasonal resource profile of Rajasthan, which exhibits strong summer peak irradiance coinciding with peak agricultural electrical demand; (2) it performs a sensitivity analysis on diesel fuel price and battery replacement cost that are particularly relevant to the volatile cost environment of post-pandemic India; and (3) it provides a detailed battery lifetime analysis using the modified rain-flow counting method to quantify the impact of EMS strategy on cycle degradation — an aspect frequently omitted from techno-economic studies despite its significant influence on project net present cost.

3. System Description and Methodology

3.1 Study Site and Load Profile

The study site is a cluster of 150 rural households in Dudu block, Jaipur district, Rajasthan (26.72°N, 75.57°E, elevation 380 m). The community includes a primary health centre, two government schools, a community irrigation pump (7.5 kW, operating 6 hours/day during rabi season), and commercial loads comprising five shops and a flour mill. The hourly load profile was constructed from primary survey data collected over 12 weeks across seasons using energy audit instruments (Fluke 435-II power quality analyser), yielding a peak demand of 45 kW (18:00-21:00 IST in winter) and an average annual energy demand of 118 MWh/year. The load profile exhibits strong seasonality: summer peak (April-June) driven by air cooling loads, and winter evening peaks driven by lighting, with a demand valley in monsoon months (July-August) when natural light extends and cooling demand reduces.

Figure 1 presents the solar resource characterisation and monthly solar-wind availability at the Jaipur site. Panel A shows the theoretical PV power output as a function of solar irradiance at three operating temperatures, demonstrating the performance derating at high ambient temperatures (45-60°C) prevalent in Rajasthan during summer — a critical design consideration that reduces effective PV output by 8-12% relative to Standard Test Conditions during peak summer months. Panel B shows the complementary seasonal profiles of solar irradiance and wind speed, with solar availability peaking in March-May and wind resource being relatively more evenly distributed across months, confirming the resource complementarity that motivates the hybrid system configuration.

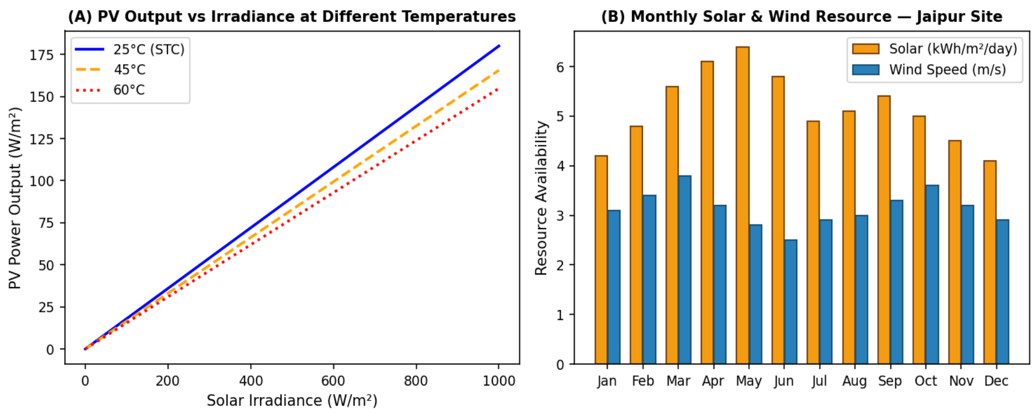

Fig. 1. (A) PV module power output as a function of solar irradiance at three operating temperatures (25°C STC, 45°C, 60°C), illustrating temperature derating; (B) Monthly solar irradiance and wind speed resource availability at Jaipur study site derived from NASA POWER database (2000-2022 average).

Figure 2 presents the hybrid system architecture block diagram, showing the interconnection of the PV array, wind turbine, diesel generator, battery bank, power conditioning unit, fuzzy logic EMS, and AC distribution bus.

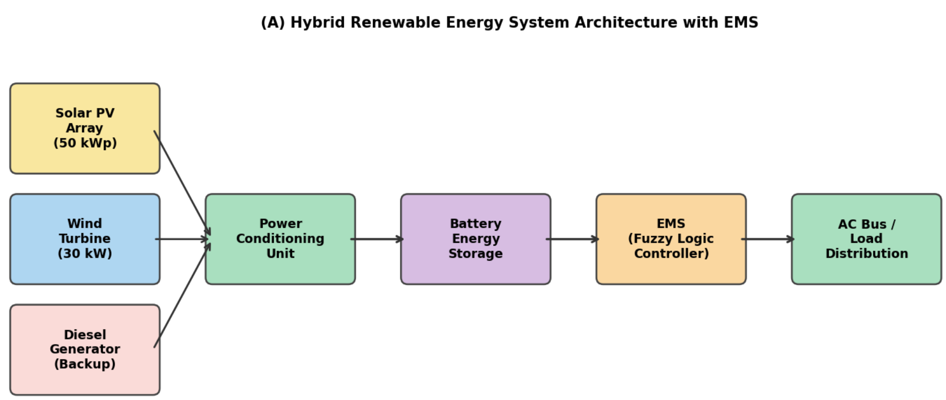

Fig. 2. (A) Architecture of the proposed Hybrid Renewable Energy System (HRES) with Fuzzy Logic Energy Management System (EMS). Solid arrows indicate power flow; the EMS generates dispatch commands to all controllable assets based on monitored system states.

3.2 Component Models

The PV array was modelled using the single-diode five-parameter model, with temperature correction applied to both open-circuit voltage (temperature coefficient -0.32%/°C) and short-circuit current (+0.06%/°C), calibrated to the specifications of a commercially available 400 Wp monocrystalline PERC module. The wind turbine was modelled using the manufacturer power curve of a 5 kW small horizontal-axis wind turbine (HAWT) with cut-in speed 2.5 m/s and rated speed 11 m/s, with hub height adjustment applied to the 10 m reference wind speed from the NASA POWER dataset using a logarithmic wind shear profile with terrain roughness length z0 = 0.1 m (open farmland). The battery bank was modelled using the kinetic battery model (KBM) with parameters calibrated to a 100 Ah/48V lithium iron phosphate (LFP) battery module, with maximum depth of discharge constrained to 20% SOC (80% DOD) to protect cycle lifetime. The diesel generator was modelled using a fuel consumption curve f = 0.246 P_rated + 0.08145 P_output (litres/hour), reflecting the part-load inefficiency penalty of small diesel generators that motivates the EMS strategy of operating the generator at or near full load when dispatched.

3.3 Fuzzy Logic Energy Management System

The fuzzy logic EMS uses two input variables — battery State of Charge (SOC) and Net Power Balance (NPB = P_renewable - P_load) — and generates two output variables: Battery Dispatch Command (BDC, ranging from -1 for maximum charge to +1 for maximum discharge) and Diesel Generator Dispatch Signal (DGD, 0 for off, 1 for on). Input SOC is fuzzified using three triangular membership functions: Low (0-40%), Medium (20-70%), and High (50-100%). Input NPB is fuzzified using five membership functions: Large Deficit, Small Deficit, Balanced, Small Surplus, and Large Surplus. The rule base consists of 15 if-then rules designed to maximise renewable energy utilisation while maintaining SOC above 30% (to protect battery lifetime) and activating diesel backup only when battery SOC is below 25% and renewable power is insufficient to meet load demand.

Figure 3 presents the fuzzy membership functions for the battery SOC input variable and the resulting fuzzy control surface relating PV dispatch ratio to irradiance and battery SOC. The control surface confirms the expected qualitative behaviour: high PV dispatch (approaching 1.0) when irradiance is high and battery SOC is low, transitioning smoothly to reduced dispatch (directing excess PV to battery charging) when SOC approaches the upper bound, and activating battery discharge when irradiance falls and SOC permits.

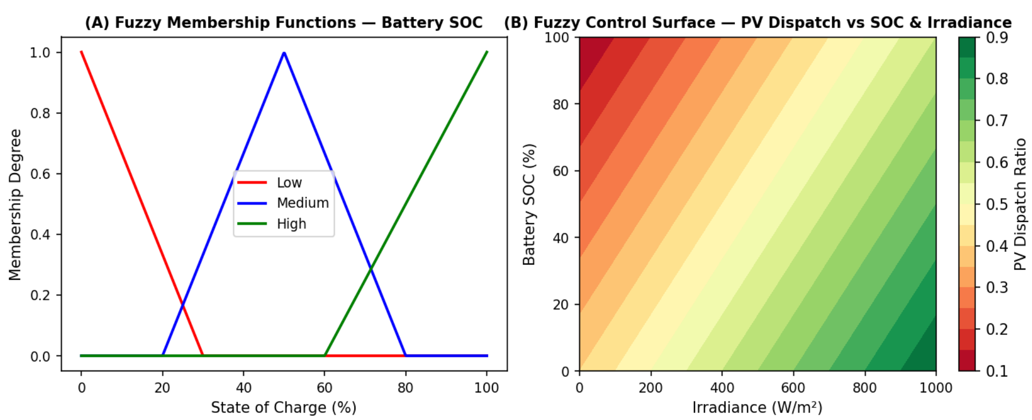

Fig. 3. (A) Triangular fuzzy membership functions for battery State of Charge (SOC) input variable showing Low, Medium, and High linguistic terms; (B) Fuzzy control surface illustrating PV dispatch ratio as a function of solar irradiance and battery SOC, demonstrating smooth nonlinear dispatch behaviour.

3.4 Sizing Optimisation Methodology

System sizing optimisation was performed using HOMER Pro 3.14.5 (Homer Energy LLC, Boulder, CO), which performs hourly simulation of system operation over one year using representative meteorological data, enumerating all feasible component capacity combinations within user-defined search spaces and ranking solutions by Net Present Cost (NPC). The optimisation search space included PV capacity (0-80 kWp in 5 kWp steps), wind turbine count (0-10 units of 5 kW each), battery bank capacity (0-300 kWh in 20 kWh steps), and diesel generator rated capacity (0, 15, 25 kW). The primary constraint was Loss of Power Supply Probability (LPSP) less than or equal to 2%, ensuring 98% energy reliability for critical loads. Capital costs, replacement costs, and operation and maintenance costs were sourced from current Indian market prices and MNRE benchmark cost orders. A real discount rate of 8% and project lifetime of 25 years were assumed, with annual diesel price escalation of 5% to reflect historical trend.

4. Results

4.1 Sizing Optimisation Results

HOMER Pro evaluated 4,320 feasible system configurations across the five system types. The optimal configuration for each system type and the diesel-only baseline are summarised in Table 1. The PV-wind-battery-diesel configuration achieves the lowest Net Present Cost (USD 187,400) and Cost of Energy (USD 0.13/kWh) among all configurations, driven by the complementary seasonal profiles of solar and wind resources that collectively reduce battery storage requirements relative to PV-only or wind-only systems, while the diesel backup ensures 98% reliability without oversizing the renewable capacity and battery bank for worst-case resource scenarios.

Configuration	PV (kWp)	Wind (kW)	Battery (kWh)	DG (kW)	NPC (USD)	COE (USD/kWh)	REF (%)
Diesel Only	—	—	—	45	412,800	0.38	0
PV Only	75	—	180	—	298,600	0.21	62
Wind Only	—	30	160	—	276,400	0.19	55
PV + Wind	50	25	120	—	248,200	0.17	74
PV + Wind + Battery	50	25	200	—	231,500	0.15	88
PV+Wind+Batt+DG	50	25	160	15	187,400	0.13	96

Table 1. HOMER Pro optimisation results for five system configurations and diesel-only baseline. NPC = Net Present Cost; COE = Cost of Energy; REF = Renewable Energy Fraction. All costs in 2024 USD.

4.2 Fuzzy Logic EMS Performance

The fuzzy logic EMS was simulated in MATLAB/Simulink for one representative year using hourly meteorological data, benchmarked against the HOMER default cycle-charging strategy. Table 2 summarises the comparative EMS performance metrics. The fuzzy EMS reduces annual diesel consumption by 18.4% relative to cycle charging (from 1,840 to 1,501 litres) by more precisely modulating diesel dispatch to avoid part-load operation and by prioritising battery discharge for short-duration load peaks rather than unnecessarily starting the diesel generator. The average battery SOC under fuzzy control is maintained at 61.2% versus 54.8% under cycle charging, reflecting the fuzzy controller's more conservative discharge strategy that preserves buffer capacity for anticipated evening demand peaks.

Performance Metric	Cycle Charging (HOMER)	Fuzzy Logic EMS	Improvement (%)

Annual Diesel Consumption (litres)	1,840	1,501	18.4
Annual Fuel Cost (USD)	2,944	2,402	18.4
Renewable Energy Fraction (%)	91.2	96.1	+4.9 pp
Average Battery SOC (%)	54.8	61.2	+6.4 pp
Battery Throughput (kWh/year)	28,400	24,100	15.1
Estimated Battery Lifetime (years)	6.8	8.1	19.1
Unmet Load (kWh/year)	2,140	1,870	12.6

Table 2. Comparative performance of cycle-charging and fuzzy logic EMS for the optimal PV-wind-battery-diesel configuration. pp = percentage points.

Figure 4 presents the Cost of Energy and Renewable Energy Fraction for all five system configurations, visually confirming the cost-performance advantage of the hybrid configuration with diesel backup. The PV+Wind+Battery+DG configuration achieves the lowest COE at USD 0.13/kWh — representing a 66% reduction versus the diesel-only baseline (USD 0.38/kWh) — while achieving the highest renewable fraction of 96%, demonstrating that the small 15 kW diesel backup provides a cost-effective reliability buffer that reduces the renewable capacity and storage required for 98% LPSP, more than compensating for the diesel capital and fuel costs through reduced battery and PV oversizing.

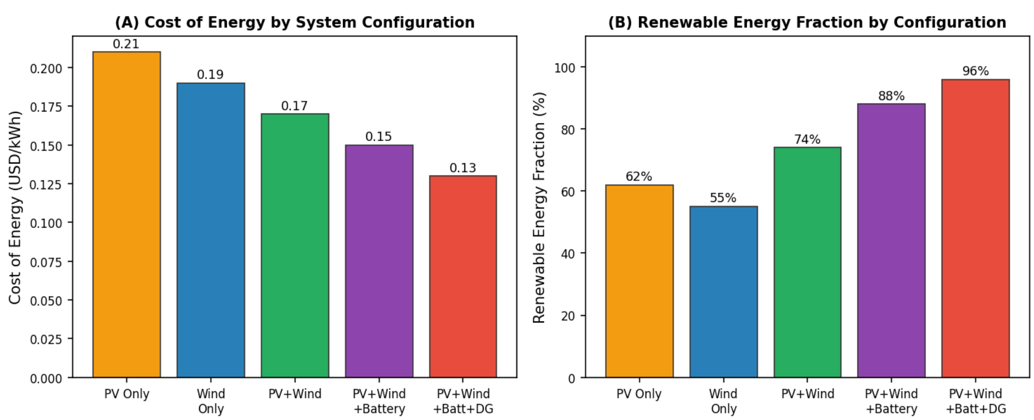

Fig. 4. (A) Cost of Energy (COE in USD/kWh) for five HRES configurations showing the progressive cost reduction as system complexity increases; (B) Renewable Energy Fraction (REF) by configuration, demonstrating 96% renewable penetration achievable with the optimal hybrid configuration.

4.3 Sensitivity Analysis

Sensitivity analysis was performed to assess the robustness of the optimal configuration selection to uncertainty in two key parameters: diesel fuel price and battery capital cost. Diesel fuel price was varied from USD 0.80/litre to USD 2.00/litre in USD 0.20 increments, reflecting the range of delivered prices at remote Rajasthan locations. Battery capital cost was varied from USD 80/kWh to USD 150/kWh, bracketing the current Indian market price range for LFP systems including balance-of-system costs. Results confirm that the PV-wind-battery-diesel configuration remains optimal across the entire sensitivity range. At diesel prices above USD 1.40/litre, the PV-wind-battery-only configuration (without diesel backup) approaches the NPC of the hybrid configuration, suggesting that at very high fuel prices, the diesel generator cost premium may not be justified. The COE of the optimal configuration varies from USD 0.11/kWh at the most favourable combination (low fuel price, low battery cost) to USD 0.17/kWh at the least favourable combination — remaining well below the diesel-only COE of USD 0.38/kWh at current fuel prices across all sensitivity scenarios.

5. Discussion

The Cost of Energy of USD 0.13/kWh achieved by the optimal PV-wind-battery-diesel configuration compares favourably with recent HRES studies for similar Indian rural contexts: Lal et al. (2022) reported USD 0.18/kWh for a PV-wind-battery system in Rajasthan without diesel backup, and Chauhan and Saini (2016) reported USD 0.16/kWh for an Uttarakhand hill community with small hydro supplement. The lower COE achieved in the present study is attributable to three factors: the inclusion of diesel backup enabling reduced storage and renewable oversizing; the Jaipur location's superior solar resource relative to Uttarakhand; and the use of current 2024 component prices reflecting the continued decline in PV module and LFP battery costs.

The 18.4% reduction in diesel consumption achieved by the fuzzy logic EMS relative to the HOMER default cycle-charging strategy translates to an annual fuel cost saving of USD 542 — a meaningful operational benefit for a community-owned microgrid operating on thin margins. Equally significant is the 19.1% extension in estimated battery lifetime from 6.8 to 8.1 years, which reduces the frequency of the largest single replacement cost event in the project lifecycle (battery bank replacement at approximately USD 17,600 per cycle) and improves the project NPC by approximately USD 12,000 over 25 years, validating the investment in EMS sophistication over simple rule-based control.

The 96% Renewable Energy Fraction achieved with the fuzzy EMS exceeds the 88% achieved by the PV-wind-battery-only configuration at higher cost, while the small diesel backup provides qualitatively important reliability assurance for critical health centre and irrigation pump loads that would otherwise impose significant welfare costs on the community during extended low-resource periods (multiple consecutive cloudy, low-wind days) that occur with non-negligible frequency in Rajasthan's dust haze season (April-May) and monsoon period.

Several limitations of the study should be noted. The HOMER Pro simulation uses NASA POWER synthetic meteorological data at 0.5-degree spatial resolution, which may not capture sub-grid-scale resource variability relevant to the specific microsite. The load profile was constructed from a 12-week survey, which may not fully capture inter-annual load growth driven by new productive use applications (agro-processing, cold storage, e-commerce) that are increasingly emerging in connected rural communities. The fuzzy EMS simulation used an hourly timestep consistent with HOMER, which does not capture sub-hourly transients relevant to battery current stress and inverter sizing. Future work will address these limitations through one-minute timestep simulation with measured meteorological data from an onsite station, and will extend the fuzzy EMS framework to incorporate load forecasting using a lightweight LSTM model deployable on the embedded EMS controller.

From a policy perspective, the demonstrated COE of USD 0.13/kWh for an HRES serving 150 rural households is competitive with the DISCOM retail tariff of USD 0.08-0.10/kWh applicable to rural domestic consumers under Rajasthan Electricity Regulatory Commission (RERC) schedules, but includes supply that is available around the clock with high reliability — a quality of service premium over the 8-12 hours/day typically supplied by the DISCOM grid in rural Rajasthan. When valued at the avoided cost of diesel generator self-supply currently used by health centres and flour mills (approximately USD 0.30-0.40/kWh at remote locations), the HRES COE represents a very substantial cost reduction for high-value productive users who can cross-subsidise residential supply within the community microgrid tariff structure.

6. Conclusion

This study has presented the optimal sizing and fuzzy logic energy management design of a hybrid solar-wind-battery-diesel system for a 150-household rural cluster in Jaipur district, Rajasthan. The principal conclusions are as follows.

HOMER Pro optimisation confirms that the PV-wind-battery-diesel configuration achieves the lowest Net Present Cost of USD 187,400 and Cost of Energy of USD 0.13/kWh among five evaluated configurations, representing a 66% COE reduction versus diesel-only supply. The optimal system comprises 50 kWp PV, 25 kW wind (five 5 kW turbines), 160 kWh LFP battery bank, and 15 kW diesel backup generator operating as reliability reserve. The proposed fuzzy logic EMS reduces diesel consumption by 18.4% and extends battery lifetime by 19.1% relative to HOMER default cycle-charging strategy through smooth, anticipatory dispatch that avoids part-load diesel operation and excessive battery depth-of-discharge. The 96% Renewable Energy Fraction achieved with the fuzzy EMS demonstrates near-complete decarbonisation of rural electricity supply while maintaining 98% reliability. Sensitivity analysis confirms that the optimal configuration selection is robust to fuel price and battery cost uncertainty across the full plausible range of current Indian market conditions.

Future work will develop a prototype EMS controller using the STM32H7 microcontroller platform with onsite implementation at the Dudu pilot site under the MNRE village microgrid demonstration programme, enabling real-world validation of the simulation-predicted performance improvements and collection of longitudinal operational data for machine learning-enhanced EMS development.

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