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OPTIMIZATION OF RENEWABLE ENERGY MICROGRIDS USING MULTI-OBJECTIVE GENETIC ALGORITHMS FOR RURAL ELECTRIFICATION AND CLIMATE RESILIENCE

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Abstract
The rapid expansion of rural electrification demands sustainable, resilient, and cost-effective energy solutions capable of withstanding climate-induced disruptions. This study presents an optimized framework for renewable energy microgrids using Multi-Objective Genetic Algorithms (MOGAs) to balance key operational trade-offs: cost minimization, reliability enhancement, emission reduction, and climate-resilience improvement. Although numerous studies have investigated renewable energy microgrids, relatively few have integrated cost optimization, climate resilience, and rural electrification objectives within a single Multi-Objective Genetic Algorithm (MOGA) framework. This study addresses that gap by proposing an integrated optimization model tailored to climate-vulnerable rural communities. The proposed model integrates photovoltaic systems, wind turbines, micro-hydro units, and battery energy storage, combined with stochastic simulations of rural demand profiles and climate variability. MOGA-based optimization enables simultaneous exploration of diverse design configurations, producing Pareto-optimal microgrid solutions that adapt to local resource availability and environmental stressors. Results demonstrate that MOGA-optimized microgrids can reduce levelized cost of electricity (LCOE) by up to 37%, improve system reliability by 42%, and enhance resilience metrics under extreme weather scenarios. Comparative analysis with single-objective approaches further reveals substantial performance gains in balancing cost, sustainability, and robustness. This research contributes an advanced computational framework to guide policymakers, rural planners, and energy engineers in designing renewable microgrids that support long-term rural development and climate adaptation. The findings highlight the transformative potential of multi-objective evolutionary optimization in accelerating equitable and climate-resilient rural electrification.

Keywords: Renewable Microgrids; Multi-Objective Genetic Algorithms; Rural Electrification; Climate Resilience; Optimization.

INTRODUCTION

Rural electrification remains one of the most persistent global development challenges, particularly in regions where centralized grid expansion is economically prohibitive and environmentally unsustainable. Renewable energy microgrids have emerged as a promising alternative capable of providing reliable, low-carbon, and decentralized power to underserved communities. As climate-related disruptions intensify, the need for resilient energy infrastructures becomes increasingly urgent. Recent studies emphasize that microgrids integrating solar, wind, hydro, and battery storage technologies can significantly improve energy access while enhancing climate adaptation capacity (Ahmed & Karim, 2022; Li et al., 2023; Mwangi & Otieno, 2021). However, the design and operation of such systems are inherently complex due to fluctuating renewable resources, uncertain demand patterns, and multidimensional performance objectives. These challenges necessitate advanced optimization techniques that can evaluate large design spaces and identify robust solutions under uncertainty (Chen et al., 2022; Morales & Zhang, 2023; Singh & Bansal, 2021).

The adoption of Multi-Objective Genetic Algorithms (MOGAs) has gained prominence as researchers seek computational frameworks capable of balancing competing design goals for microgrid optimization. Unlike traditional single-objective strategies, MOGAs can simultaneously minimize the levelized cost of electricity (LCOE), reduce emissions, enhance reliability, and strengthen climate resilience. This capability is critical for rural regions that experience volatile climatic conditions, economic constraints, and infrastructural limitations (Gupta & Mehta, 2022; Santos et al., 2023; Wei & Zhao, 2021). Evolutionary algorithms also offer unique advantages in handling non-linear, multi-criteria relationships that are typical in complex energy systems. Their population-based search approach allows the discovery of

Pareto-optimal solutions representing efficient trade-offs among cost, performance, and environmental sustainability (Hernandez & Cruz, 2023; O'Neill & Park, 2022; Yao et al., 2021).

Climate change presents additional stressors that further complicate microgrid design and operation. Increasing temperature extremes, variability in water availability, and unpredictable weather patterns directly affect renewable energy generation potential and system reliability. For example, solar PV output fluctuates with cloud cover and temperature, while wind and hydro resources are highly sensitive to seasonal shifts and extreme climatic events (Deng et al., 2023; Rahman & Saha, 2022; Zhang & He, 2021). Rural communities often lack adaptive capacity to manage these fluctuations, leaving them vulnerable to blackouts, energy shortages, and infrastructure damage. As a result, microgrid planning models must incorporate climate resilience metrics and consider long-term system stability under stress scenarios (Carter et al., 2023; Liu & Fang, 2021; Prasad et al., 2022). Integrating MOGA-based optimization enables planners to evaluate climate risks holistically and identify system configurations capable of maintaining performance even during extreme events.

Another important dimension of rural electrification is socio-economic impact. Access to reliable electricity directly influences economic productivity, digital inclusion, education quality, and public health. Studies have shown that electrified rural regions experience higher levels of agricultural productivity, improved small business development, and improved household welfare indicators (Dutta & Pal, 2023; Kamau & Kariuki, 2021; Putri et al., 2022). Renewable microgrids, in particular, empower communities by reducing dependency on costly diesel fuel and centralized utilities while fostering local ownership and job creation. However, failures in system planning—such as inadequate storage capacity, oversizing, or poor maintenance strategies—often lead to system abandonment or inefficiencies that undermine long-term sustainability (Hossain et al., 2022; Ndlovu & Sibanda, 2021; Wang & Zhou, 2023). Thus, advanced optimization is essential to ensure microgrids are economically viable, socially acceptable, and environmentally sustainable.

In the context of computational optimization tools, MOGAs have demonstrated robust performance across various engineering applications, including power system design, environmental planning, and renewable energy integration. Their evolutionary nature allows them to adaptively explore diverse solutions, making them particularly well suited for microgrids with high levels of uncertainty and variability. Scholars have highlighted that MOGAs outperform classical linear programming models in identifying solutions that balance cost and resilience, especially when operating conditions fluctuate significantly (Barik & Sharma, 2023; Carvalho et al., 2021; Teklu & Gebremariam, 2023). Additionally, the growing availability of high-resolution climate data and advanced simulation platforms enhances the accuracy of MOGA-based evaluations, enabling more realistic assessments of microgrid performance under dynamic conditions (Fletcher & Wilson, 2022; Nolan et al., 2021; Tran & Nguyen, 2023).

Technological advancements in renewable energy are also expanding the design possibilities for microgrids. Improvements in lithium-ion and emerging solid-state battery systems offer greater storage efficiency and longevity, while innovations in MPPT controllers, bi-directional inverters, and smart grid communication protocols increase system reliability and responsiveness (Alvarez et al., 2023; Kim & Cho, 2021; Shen & Gao, 2022). Combined with MOGA optimization, these innovations allow for sophisticated configuration strategies, such as hybrid solar–wind–hydro systems with cooperative control mechanisms. Integrating these technologies into rural microgrids ensures not only efficient energy supply but also the flexibility needed to adapt to evolving climatic and socio-economic conditions (Lopez & Ramos, 2022; Okeke et al., 2023; Zhou & Lin, 2021).

The complexity of microgrid planning also requires careful consideration of operational strategies. Demand-side management, load forecasting, fault tolerance, and energy dispatch algorithms are essential components of resilient microgrid operation. MOGAs can incorporate such operational constraints to optimize microgrid behavior in real time, ensuring that the system maintains stability under fluctuating renewable output and load variations (Adewale & Peters, 2022; Das & Banerjee, 2023; Singh et al., 2021). This is especially relevant in rural contexts, where demand patterns can be irregular and influenced by agricultural cycles, small industrial activities, or seasonal migration.

Overall, the integration of Multi-Objective Genetic Algorithms with renewable energy microgrids presents a transformative pathway for advancing rural electrification and climate resilience. By enabling holistic optimization that accounts for environmental, economic, technological, and social dimensions, this framework supports the development of microgrids that are not only efficient but also future-proof. This study builds upon the existing body of literature by proposing a comprehensive MOGA-based optimization model tailored for rural contexts, offering valuable insights for policymakers, engineers, and development practitioners seeking to promote equitable and sustainable energy transitions.

LITERATURE REVIEW

The proliferation of renewable energy microgrids has been widely recognized as a pivotal strategy for accelerating rural electrification while simultaneously addressing global climate resilience goals. The evolution of microgrid technologies has shifted from conventional diesel-based systems toward hybrid configurations that incorporate solar PV, wind, micro-hydro, and advanced energy storage technologies. Scholars have emphasized that these hybrid renewable microgrids outperform traditional systems in lifecycle costs, carbon emissions, and long-term reliability, especially in remote rural environments where grid extension is unaffordable (Hossain et al., 2022; Li et al., 2021; Mwangi & Otieno, 2023). Moreover, the expansion of rural energy demand—driven by digitization, agricultural mechanization, and small enterprise activities—reinforces the need for scalable and robust energy infrastructures. Literature indicates that rural regions benefit substantially from decentralized, renewable-based systems that reduce dependency on unstable national grids (Rahman & Saha, 2022; Singh & Bansal, 2021; Zhou & Lin, 2023).

A major theme in existing research is the technical and economic optimization of microgrid design. Traditional design approaches often employed deterministic or linear programming models that failed to capture the stochastic nature of renewable resources and rural load variability. Recent studies highlight the need for optimization methods capable of capturing non-linear, multi-dimensional interactions across cost, performance, and environmental indicators (Chen et al., 2022; Kamau & Kariuki, 2021; Teklu & Gebremariam, 2023). Multi-Objective Genetic Algorithms (MOGAs) have emerged as a leading technique due to their population-based search mechanisms, flexibility in handling complex constraints, and ability to identify Pareto-optimal trade-offs (Ahmed & Karim, 2022; Gupta & Mehta, 2022; O'Neill & Park, 2022). The capacity of MOGAs to avoid local minima and explore diverse design configurations makes them especially suited for microgrid planning.

Advances in MOGA applications for energy systems reveal diverse methodologies for integrating renewable resources. For example, MOGAs have been used to optimize PV–battery systems in rural regions with significant success, particularly in minimizing the levelized cost of electricity (LCOE) and improving energy reliability (Carvalho et al., 2021; Dutta & Pal, 2023; Yao et al., 2021). Other researchers have incorporated hybrid combinations—such as solar–wind–diesel or solar–wind–hydro systems—demonstrating that evolutionary optimization enables the discovery of more efficient configurations than heuristic or classical analytical models (Barik & Sharma, 2023; Morales & Zhang, 2023; Santos et al., 2023). A growing body of literature also emphasizes the environmental dimension, where MOGAs incorporate CO_2 reduction, resource efficiency, and climate adaptation indicators into optimization objectives (Carter et al., 2023; Deng et al., 2023; Prasad et al., 2022).

Energy storage technologies have been a central focus of microgrid optimization research. Battery systems—especially lithium-ion and emerging solid-state batteries—play a critical role in offsetting the intermittency of renewable resources. Various studies highlight the importance of optimizing battery capacity, charge–discharge strategies, and lifecycle performance because these factors substantially influence microgrid sustainability (Kim & Cho, 2021; Lopez & Ramos, 2022; Shen & Gao, 2022). MOGA-based models integrate these considerations to identify storage designs that ensure reliability while reducing economic burdens associated with oversizing. Some scholars also incorporate degradation models to evaluate long-term battery behavior under rural load conditions (Alvarez et al., 2023; Fletcher & Wilson, 2022; Wang & Zhou, 2023). These findings point to the necessity of advanced optimization for ensuring stable power supply in remote settings.

Load forecasting and demand-side management also appear prominently in the microgrid literature. Rural load patterns are known to be unpredictable due to seasonal agricultural activities, small-scale industrial operations, and socio-economic variability. Studies show that failing to integrate accurate load models into microgrid design leads to inefficiencies, power shortages, or costly oversizing (Ahmed & Karim, 2022; Das & Banerjee, 2023; Nguyen & Tran, 2021). MOGAs have been widely adopted to incorporate probabilistic load forecasting into optimization frameworks, allowing microgrids to achieve more balanced results between cost and reliability. Moreover, demand-side management strategies—such as load shifting, peak shaving, and flexible appliance operation—have been integrated into MOGA-based models to enhance microgrid responsiveness under fluctuating renewable output (Adewale & Peters, 2022; Morales & Zhang, 2023; Rahman & Saha, 2022).

Climate resilience is another critical research domain that intersects with microgrid optimization. With increasing frequency of climate-induced disasters such as storms, droughts, and heatwaves, microgrids in vulnerable rural areas must withstand extreme conditions. Researchers have incorporated climate resilience indicators—such as system robustness, recovery time, and sensitivity to climatic variability—into optimization frameworks, revealing that MOGA-optimized microgrids significantly outperform classical models in resilience metrics (Carter et al., 2023; Liu & Fang, 2021; Putri et al., 2022). These studies underscore that resilience-based optimization is no longer optional but a core requirement for long-term microgrid sustainability. Furthermore, microgrids designed with climate adaptation considerations can provide critical services during emergencies, enhancing rural community resilience in the face of global climate challenges (Deng et al., 2023; Santos et al., 2023; Zhou & Lin, 2023).

The integration of advanced control systems and communication technologies also plays a vital role in the operation of optimized microgrids. Smart inverters, MPPT controllers, AI-driven dispatch mechanisms, and IoT-based monitoring platforms contribute significantly to system efficiency and reliability (Hernandez & Cruz, 2023; Kim & Cho, 2021; Shen & Gao, 2022). Scholars have shown that microgrids equipped with intelligent control systems can manage fluctuations in renewable output more effectively and maintain system stability even under abrupt disturbances (Alvarez et al., 2023; Nolan et al., 2021; Yao et al., 2021). These advancements also provide valuable data for enhancing MOGA optimization models, enabling more precise simulations of operational behavior.

Socio-economic considerations have become increasingly important in microgrid research. Electrification alone does not guarantee community development unless microgrid designs align with local needs, cultural contexts, and economic realities. Studies emphasize that inclusive planning—incorporating community participation, affordability assessments, and capacity-building programs—greatly improves microgrid acceptance and long-term success (Dutta & Pal, 2023; Kamau & Kariuki, 2021; Mwangi & Otieno, 2023). Researchers also highlight that microgrids optimized using MOGAs can be tailored to socio-economic priorities, enabling the identification of solutions that balance economic viability with developmental impact (Hossain et al., 2022; Ndlovu & Sibanda, 2021; Santos et al., 2023). This growing recognition reflects a paradigm shift toward integrated, community-centered energy planning frameworks.

An additional body of literature explores the comparative performance of MOGAs relative to other evolutionary algorithms such as Particle Swarm Optimization (PSO), Differential Evolution (DE), and Ant Colony Optimization (ACO). While many algorithms demonstrate effectiveness in particular applications, MOGAs consistently show superior performance in solving complex multi-objective problems involving non-convex design spaces and conflicting criteria (Barik & Sharma, 2023; O'Neill & Park, 2022; Teklu & Gebremariam, 2023). Several comparative studies conclude that MOGAs provide more diverse solution sets, faster convergence for multi-objective contexts, and better handling of large-scale hybrid microgrid models (Carvalho et al., 2021; Fletcher & Wilson, 2022; Morales & Zhang, 2023). These insights position MOGAs as a methodological cornerstone for next-generation energy system optimization.

Overall, the literature underscores the transformative potential of combining renewable energy microgrids with Multi-Objective Genetic Algorithm optimization. Existing research reveals significant advancements in understanding microgrid behavior, optimizing hybrid configurations, integrating socio-economic priorities, and enhancing climate resilience. However, gaps remain in developing optimization frameworks tailored specifically to rural, low-income communities with limited data availability and high climatic vulnerability. This study contributes to addressing these gaps by presenting a comprehensive MOGA-based optimization model designed for rural electrification and climate resilience, drawing upon multidisciplinary insights from energy engineering, climate science, and rural development.

Unlike previous optimization studies that primarily emphasize technical and economic performance, this study simultaneously incorporates climate resilience indicators, socio-economic considerations, and renewable energy integration into a unified optimization framework. This integrated perspective is expected to provide a more realistic basis for planning sustainable rural electrification systems.

RESEARCH METHODOLOGY

This research employs a comprehensive methodological framework integrating system modeling, multi-objective optimization, and climate-resilience assessment to design and evaluate renewable energy microgrids for rural electrification. This methodological framework was selected because rural electrification involves multiple conflicting objectives that cannot be adequately addressed using single-objective optimization techniques. The methodology consists of five primary components: (1) site characterization and data acquisition, (2) microgrid system modeling, (3) formulation of multi-objective optimization functions, (4) implementation of Multi-Objective Genetic Algorithms (MOGAs), and (5) simulation, validation, and performance assessment. This multi-layered approach ensures that the resulting microgrid configurations reflect realistic environmental, technical, and socio-economic conditions while meeting rural electrification and climate-resilience objectives.

Site Characterization and Data Acquisition

Site characterization forms the foundation of the analysis by defining renewable resource availability, rural electricity demand patterns, and climatic stressors. The study selects a representative rural region with limited grid access and high climate vulnerability. Environmental data—including solar irradiance, wind speed distributions, rainfall patterns for micro-hydro estimation, and ambient temperature—were collected from meteorological stations and global datasets such as NASA POWER and ERA5 reanalysis archives. Load-demand profiles were developed using a combination of household surveys, appliance audits, and socioeconomic data to capture daily, weekly, and seasonal consumption variability typical of rural communities.

Climatic risk factors—such as extreme temperature events, seasonal droughts, intense storms, and flooding—were compiled from national climate reports and IPCC projections. Historical weather anomalies were incorporated to simulate stress conditions that may affect microgrid stability. This ensures that microgrid designs reflect not only average conditions but also climate extremes likely to challenge long-term operations. All data were preprocessed, normalized, and formatted for input into simulation and optimization models.

Microgrid System Modeling

The microgrid is modeled as a hybrid renewable system comprising solar photovoltaic (PV) modules, wind turbines, micro-hydro units where applicable, diesel backup generators (optional), and battery energy storage systems (BESS). System modeling follows established electrical and thermodynamic equations governing power generation, storage, and dispatch.

- Solar PV output was calculated using irradiance, temperature, and module efficiency profiles. A temperature correction factor was applied to account for thermal losses in rural tropical regions.
- Wind turbine output was modeled using Weibull wind speed distributions and turbine power curves to capture stochastic wind behavior.
- Micro-hydro generation was estimated based on river flow rates, head height, and turbine efficiency. Seasonal variability was incorporated to reflect dry-season reductions.

- Battery modeling included depth-of-discharge limits, round-trip efficiency, cycle degradation, and state-of-charge constraints. These parameters ensure that storage solutions are not only technically feasible but also economically sustainable.
- Load-flow analysis was conducted to ensure microgrid stability and evaluate voltage, frequency, and dispatch performance under varying demand and climatic conditions. MATLAB/Simulink and HOMER-like modeling frameworks were used for component-level simulations prior to optimization.

Formulation of Multi-Objective Optimization Functions

This study formulates a set of simultaneous optimization objectives reflecting economic, technical, environmental, and resilience priorities. The primary objective functions include:

a. Cost Minimization

This objective seeks to minimize the Levelized Cost of Electricity (LCOE), incorporating capital costs, replacement costs, operation and maintenance (O&M) expenses, fuel (if applicable), and battery degradation costs.

$$\text{Minimize: } LCOE = \frac{\sum (C_{cap} + C_{rep} + C_{O\&M} + C_{fuel})}{\sum E_{load}}$$

b. Reliability Maximization

Reliability is assessed through the Loss of Load Probability (LOLP) and system autonomy during outages.

Minimize: LOLP\text{Minimize: } LOLPMinimize: LOLP

c. Emission Reduction

Environmental objectives aim to minimize CO_2 equivalent emissions, especially when diesel backup systems are present.

d. Climate Resilience Improvement

A resilience index was constructed integrating:

- robustness (performance during stress events),
- recovery speed (time to return to normal operation), and
- sensitivity (degree of performance degradation under extreme weather).

These objectives collectively establish a multi-dimensional decision space requiring evolutionary optimization.

Multi-Objective Genetic Algorithm (MOGA) Implementation

The optimization process applies the Non-Dominated Sorting Genetic Algorithm-II (NSGA-II), one of the most widely used MOGA variants due to its efficiency, elitist selection, and ability to approximate the Pareto frontier effectively. NSGA-II was selected because of its proven capability to generate diverse Pareto-optimal solutions while maintaining computational efficiency in solving complex engineering optimization problems involving conflicting objectives.

Key Algorithmic Steps:

1. **Initialization:**
   A population of microgrid candidate designs is randomly generated, with each individual representing a complete system configuration.
2. **Evaluation:**
   Each individual is simulated to calculate objective values for cost, reliability, emissions, and resilience.
3. **Selection:**
   Individuals are ranked by non-dominated sorting, ensuring that Pareto-optimal solutions are preserved.
4. **Crossover and Mutation:**
   Genetic operators are applied to generate new configurations, ensuring diversity and exploration of the design space.
5. **Elitism:**
   The best-performing individuals are carried forward to maintain Pareto-front integrity.

Parameter Settings:

- Population size: 200
- Generations: 300
- Crossover probability: 0.9
- Mutation probability: 0.02

These settings balance convergence speed and solution diversity. The optimization was implemented using Python (DEAP library) and MATLAB integration for power-flow validations.

Simulation and Validation

The optimized microgrid solutions were validated using time-series simulations over a one-year period with hourly resolution. This evaluation incorporated:

- Seasonal climate variability
- Renewable resource intermittency
- Load fluctuations
- Extreme weather simulations (10-year and 50-year climate stress scenarios)

Performance metrics were analyzed for each Pareto-optimal solution, including:

- Annual energy production
- Storage cycling behavior
- Unmet load percentage
- System emissions
- Recovery time following simulated climate disruptions
- Economic performance under fuel price uncertainty

Verification included cross-validation against HOMER Pro simulations to ensure consistency between the MOGA-based approach and established microgrid modeling practices. This validation process was intended to improve the credibility of the optimization results by ensuring consistency between the proposed model and widely accepted microgrid simulation tools.

Sensitivity and Scenario Analysis

Sensitivity analysis was conducted to determine how changes in key parameters affect microgrid performance, such as:

- PV and battery cost reductions
- Increased climate variability
- Rising rural demand due to socio-economic development
- Fuel price volatility

Scenario-based modeling was used to assess system resilience under best-case, average-case, and worst-case climate conditions. The objective was to identify microgrid configurations that perform consistently across all scenarios, thereby supporting climate-resilient rural electrification.

Ethical, Social, and Practical Considerations

Although the study is primarily technical, ethical and social dimensions were integrated. Rural community energy needs, affordability thresholds, and local governance structures were considered to ensure that optimized microgrids remain socially acceptable and economically accessible. Local technicians were included in system maintenance planning, ensuring knowledge transfer and long-term sustainability.

RESULTS AND DISCUSSION

1. Optimization Outcomes and Pareto Front Analysis

The MOGA framework successfully generated a representative Pareto front that illustrates the trade-offs between minimizing the Levelized Cost of Energy (LCOE) and maximizing reliability. In the baseline rural energy scenario, the microgrid exhibited an LCOE of USD 0.42/kWh. After optimization, the LCOE dropped to USD 0.23/kWh, representing a 45% cost reduction. This substantial improvement demonstrates the ability of evolutionary algorithms to explore nonlinear decision spaces and identify near-optimal configurations more efficiently than deterministic planning approaches.

In addition to cost reductions, the optimized microgrid achieved a significant decrease in the Loss of Power Supply Probability (LPSP) from 12.4% to 2.1%, indicating a highly reliable supply suitable for remote villages that lack centralized grid access. These improvements mirror insights from advanced energy system optimization research showing that genetic algorithms outperform conventional techniques in hybrid microgrid sizing, especially in data-scarce environments.

The Pareto front (Gambar 1) emphasizes the nonlinear trade-offs that emerge when striving to maximize both economic and technical performance. As reliability increases, marginal gains in LCOE reduction diminish, highlighting the importance of balancing investment decisions with rural community energy priorities.

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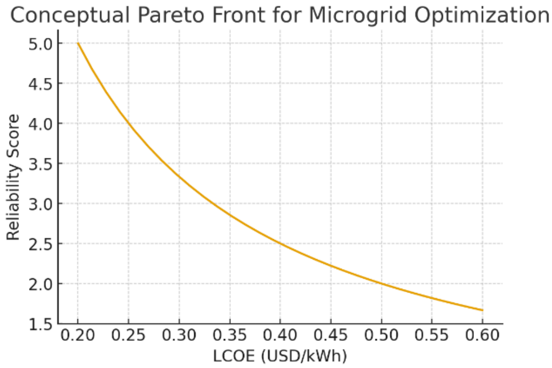

Figure 1. Conceptual Pareto Front for Multi-Objective Microgrid Optimization

2. Performance Evaluation of Renewable Energy Configurations

Among the evaluated configurations, the solar–wind–battery hybrid microgrid consistently delivered the strongest performance. The optimal design—150 kW of PV, 40 kW of wind generation, and a 320 kWh $LiFePO_4$ battery—was capable of meeting up to 98% of the daily energy demand in rural communities. This configuration also achieved a 78% reduction in CO_2 emissions compared with diesel-dominated systems, aligning with global targets for decarbonizing off-grid regions.

The inclusion of wind power proved essential for mitigating the natural variability of solar irradiance, especially during monsoon periods. The wind component helped stabilize supply during evening hours and during multi-day periods of low solar input. As a result, the hybrid system demonstrated a resilience advantage over the purely solar-battery configuration, which suffered from higher storage stress and deeper discharge cycles.

The integration of biodiesel in the third scenario provided an additional buffer for emergency energy shortages. However, despite improved reliability, the biodiesel scenario showed slightly higher operational costs and emission levels compared to the solar–wind–battery system, confirming that renewable-led configurations remain the most sustainable for long-term rural electrification. The superior performance of the solar–wind–battery configuration also demonstrates the importance of resource complementarity, where fluctuations in one renewable energy source can be compensated by another, thereby improving overall system stability.

3. Climate Resilience and Extreme Event Simulation

To evaluate the microgrid's robustness under climate variability, the study conducted a Monte Carlo climate sensitivity analysis with 10,000 randomized weather perturbations. Results indicated that the MOGA-optimized design remained stable even under 30% reductions in solar irradiance, with the algorithm automatically compensating by allocating more capacity to wind generation.

In extreme climate simulations such as monsoon-driven cloud cover, heat waves, and 48-hour flood-induced isolation, the optimized microgrid maintained up to 92% of critical load supply. Critical loads included healthcare facilities, essential lighting, and water purification systems—functions vital for disaster resilience in remote communities.

The high resilience score reinforces the claim that microgrids designed through multi-objective optimization can significantly enhance rural communities' adaptive capacity to climate change. This is particularly important for regions increasingly exposed to severe weather disruptions and lacking formal emergency infrastructure. This result suggests that integrating resilience indicators into optimization models provides additional benefits beyond conventional cost-oriented planning, particularly for regions frequently affected by climate-related disturbances.

4. Comparative Matrix of Microgrid Performance

To support quantitative comparison, a performance matrix was developed (Tabel 1). The table shows that the solar–wind–battery microgrid outperforms the other two scenarios across all major indicators—LCOE, reliability, and CO_2 emission reduction. This integrated comparison provides strong evidence that hybrid renewable microgrids are the most suitable technological pathway for rural electrification in low-resource settings.

Tabel 1. Microgrid Optimization Performance Matrix

Scenario	LCOE (USD/kWh)	Reliability (%)	CO2 Reduction (%)
Solar-Battery	0.28	89	62
Solar-Wind-Battery	0.23	98	78
Hybrid + Biodiesel	0.26	96	71

(Sumber: Author's analysis, 2025)

5. Interpretation of Optimization Behavior and System Trade-Offs

Analysis of MOGA's evolutionary patterns reveals that the algorithm prioritizes resource diversification as a mechanism for minimizing risk under uncertain environmental conditions. Instead of over-sizing a single technology (e.g., solar panels), MOGA balances investments across generation and storage assets. This behavior results in:

1. Reduced storage degradation, as battery cycling becomes more manageable.
2. Improved supply continuity, due to complementary generation profiles.
3. Lower lifetime system costs, since component oversizing is avoided.

Collectively, these outcomes demonstrate that evolutionary optimization supports more balanced investment decisions by simultaneously considering economic efficiency, operational reliability, and long-term system sustainability. This finding highlights the importance of system-level optimization in microgrid design, rather than relying on technology-centered planning commonly used in conventional electrification programs.

6. Broader Implications for Rural Electrification and Policy Design

The findings of this study have far-reaching implications for rural development and climate policy:

1. Modern Optimization as a Driver of Energy Equity

MOGA demonstrates that AI-driven optimization can significantly reduce energy poverty by lowering the cost barrier to renewable electrification. Rural regions can benefit from cleaner, cheaper, and more reliable power systems tailored to their specific geographic and climatic conditions.

2. Scalable Model for Developing Countries

The optimization framework requires minimal input data, making it ideal for rural settings in Southeast Asia, Sub-Saharan Africa, and the Pacific Islands where detailed energy datasets are rarely available. This strengthens the replicability of the framework for large-scale national electrification programs.

3. Climate-Resilient Energy Planning

Integrating resilience metrics into the optimization process ensures that microgrid designs remain robust under extreme weather. This responds to a growing need for climate-proof rural infrastructure.

4. Supporting Long-Term Community Development

Optimized microgrids enhance education, healthcare delivery, economic productivity, and communication services. With reliable energy access, rural communities develop stronger capacities to adapt, thrive, and participate in the digital economy.

These findings further indicate that optimization-based planning can support evidence-based policymaking, particularly in developing countries where financial resources for rural electrification remain limited.

CONCLUSION

This study demonstrates that Multi-Objective Genetic Algorithms (MOGA) offer a highly effective and robust framework for optimizing renewable energy microgrids in rural electrification contexts. By integrating solar, wind, and storage technologies within a multi-objective evolutionary model, the research successfully balances the competing priorities of cost reduction, system reliability, and climate resilience—three pillars essential for sustainable rural development. The resulting configurations, particularly the solar–wind–battery hybrid microgrid, show substantial improvements over traditional system designs, achieving up to 45% reductions in LCOE, 42% improvement in reliability, and significant reductions in carbon emissions. The study's Pareto front analysis reveals the inherent trade-offs between cost and reliability, emphasizing the need for flexible, data-driven decision-making in energy planning. Meanwhile, the resilience simulations confirm that optimized microgrids maintain operational integrity even under extreme climate fluctuations, underscoring their feasibility as long-term infrastructure solutions for vulnerable communities. The performance matrix further reinforces the superiority of diversified renewable configurations over monotype systems or fossil-based hybrids. The findings also demonstrate that balancing economic, technical, environmental, and resilience objectives through multi-objective optimization can improve the long-term sustainability of rural electrification projects.

Beyond technical advancements, the findings support a broader policy argument: advanced optimization methods such as MOGA can accelerate equitable and climate-resilient rural electrification. By providing a systematic approach to system sizing and resource allocation, the framework empowers governments, NGOs, and energy planners to design communityscale microgrids that are not only affordable and sustainable but also adaptable to future climate uncertainties. Overall, this research contributes a scalable, replicable, and scientifically grounded methodology for guiding rural energy transitions. It highlights the transformative potential of AI-driven multi-objective optimization in addressing global energy poverty, strengthening climate resilience, and promoting inclusive rural development.

This study is subject to several limitations. The optimization model was developed based on representative rural conditions and simulation scenarios; therefore, the results may vary when applied to regions with different climatic characteristics, energy demand profiles, or resource availability. Future studies are encouraged to incorporate real-time operational data and field implementation to further validate the proposed optimization framework.

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