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Optimization of On-Grid Microgrid Systems for Rural Communities to Increase Energy Resilience

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Abstract
Energy security in rural communities is a significant challenge due to limited access to the electricity grid and dependence on fossil fuels. This study aims to optimize an on-grid microgrid system based on renewable energy to improve reliability and cost efficiency. Using HOMER Pro software, various energy configurations were analyzed to find the optimal solution. The optimization results show that the best configuration consists of 200 kW solar panels, 100 kW wind turbines, and 500 kWh energy storage systems, with a 50 kW diesel generator as a backup. Implementing this system can reduce diesel fuel consumption by 70%, which impacts reducing the Levelized Cost of Energy (LCOE) from 0.25 USD/kWh to 0.12 USD/kWh. In addition, carbon emissions have been reduced by 150 tons of CO_2 per year, thus supporting environmental sustainability. Regarding reliability, adequate energy storage allows the system to continue operating stably even if there is a disruption to the primary grid. This study also highlights the importance of incentive policies and investment in renewable energy infrastructure to accelerate the adoption of microgrid systems in rural communities. The results of this study indicate that the optimized microgrid system not only improves energy resilience but also has a wide replication scale for areas with similar characteristics.

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1. Introduction
Access to reliable and affordable energy remains a critical challenge for rural communities worldwide. According to the International Energy Agency (IEA), approximately 733 million people still lack access to electricity, with the majority residing in remote and underdeveloped regions [1–3]. Limited access to energy hampers economic development and affects health, education, and overall quality of life [4–7]. Conventional grid extension is often economically unfeasible in these regions due to high infrastructure costs and geographic constraints [8–10]. As a result, decentralized energy solutions, such as microgrid systems, have emerged as viable alternatives to bridge the energy gap and enhance energy resilience in rural areas. Microgrid systems are pivotal in improving energy resilience by integrating renewable energy sources and ensuring a stable power supply. These systems can operate either in off-grid or on-grid modes, depending on the availability of centralized electricity infrastructure [11–14]. Studies have shown that microgrids contribute to enhanced energy security by reducing dependence on fossil fuels and mitigating the impact of power outages [15–17]. Additionally, microgrids foster local energy independence, enabling communities to manage their electricity generation and consumption efficiently [18–20].

Among the various microgrid configurations, on-grid microgrids offer a strategic advantage by leveraging existing electrical networks while incorporating distributed renewable energy sources (IRENA, 2020). On-grid microgrids can enhance rural electrification efforts by providing a more cost-effective and scalable approach than standalone systems [21–23]. Furthermore, these systems exchange energy with the primary grid, ensuring surplus energy utilization and improved system stability [24–26]. Integrating smart energy management systems in on-grid microgrids further enhances operational efficiency and demand-side flexibility [27,28]. Despite their benefits, optimising on-grid microgrid systems remains a complex challenge that requires balancing economic, environmental, and technical factors. Previous studies have highlighted the need for multi-criteria optimization techniques to enhance the feasibility of microgrid deployment in rural areas [29,30]. Using simulation-based tools, such as HOMER Pro, has proven effective in assessing optimal configurations, evaluating economic viability, and analyzing environmental impacts [31–33]. However, further research is needed to refine optimization models and propose practical implementation strategies that align with local energy needs and policy frameworks.

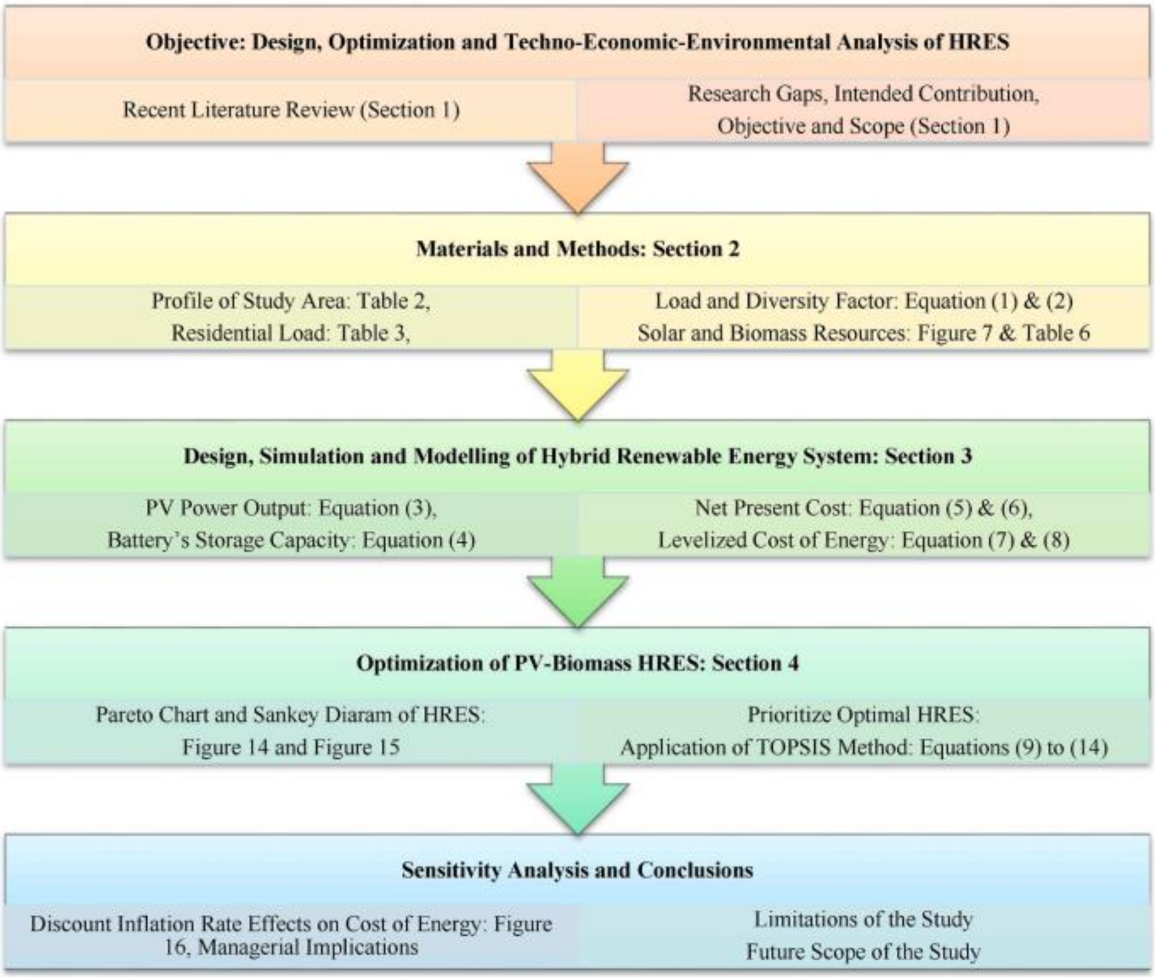

Figure 1. HRES flow chart by HOMER Pro [31]

The research focuses on case studies of rural communities where on-grid microgrids have been implemented or have the potential for deployment. The study considers various renewable energy sources, such as solar, wind, and biomass, in conjunction with grid-connected systems. A simulation-based analysis using HOMER Pro is employed to assess different microgrid configurations. The analysis includes technical performance assessments, economic feasibility evaluations, and environmental impact studies. Sensitivity analyses are conducted to account for variations in renewable energy availability, demand profiles, and policy incentives.

The findings of this study contribute to the growing body of research on microgrid optimization, particularly in the context of rural electrification. By leveraging advanced simulation tools and multi-criteria decision-making approaches, this research provides insights into the most effective strategies for enhancing energy resilience through on-grid microgrid solutions. The novelty of this study lies in its comprehensive approach to optimizing microgrid configurations while considering real-world constraints and policy implications. Unlike previous studies, this research integrates techno-economic, environmental, and policy perspectives to provide a holistic framework for decision-making in rural electrification. The results offer valuable recommendations for policymakers, energy planners, and rural communities seeking sustainable and resilient energy solutions.

2. Microgrid System and Energy Resilience

Definition and Components of Microgrids

Microgrids are small-scale electric power systems that integrate multiple energy sources flexibly, enabling more independent operation than conventional power grids [34]. The main elements of a microgrid include energy generation sources, energy storage systems, distribution infrastructure, and a control system that regulates the power balance in the grid [35]. Integrating renewable energy, such as solar and wind, microgrids reduce carbon emissions and dependence on fossil fuels [36]. Energy storage systems, such as lithium-ion batteries, improve grid stability by storing excess energy during high production and releasing it when demand increases [37]. As technology advances, microgrid control systems become more sophisticated, enabling automatic and real-time energy management through artificial intelligence and Internet of Things (IoT)-based systems [38]. Optimization algorithms improve operational efficiency and dynamically adjust energy supply to demand. In addition, microgrid architecture can be configured in a centralized or decentralized form, where the decentralized model provides advantages in operational resilience to major grid disruptions [39]. With the development of energy storage technology and increasing power conversion efficiency, microgrids are becoming more effective in supporting modern energy systems' sustainability [40].

On-Grid Microgrid Advantages

One of the main advantages of on-grid microgrids is their ability to improve the reliability of energy supply in rural areas by connecting local energy systems to the primary grid, thereby reducing the risk of power outages [41]. This model allows locally generated renewable energy, such as solar panels or wind turbines, to be optimally utilized while relying on the primary grid as a backup power source [42]. In addition, with the power exchange mechanism with the primary grid, excess energy generated by the microgrid can be channelled back into the grid, providing economic incentive opportunities for local communities [43]. This approach also optimises energy costs, as resources can be strategically combined to reduce fossil fuel consumption and improve operational efficiency [44]. On the other hand, the application of smart grid technology in on-grid microgrids further enhances the efficiency and stability of the overall system [36]. Artificial intelligence-based control systems can help manage power allocation, avoid energy waste, and predict consumption patterns based on historical and real-time data. In addition, on-grid microgrids can be combined with energy storage systems to increase operational flexibility and ensure that power supply remains available even if there is a disruption in the primary network [45]. With this approach, microgrids increase energy resilience and contribute to the transition to a cleaner and more sustainable energy system [15].

Energy Resilience in Rural Communities

Energy resilience refers to the ability of an energy system to withstand and recover from external disturbances, such as natural disasters, technical disruptions, or energy price fluctuations [46]. Rural areas' main challenges in achieving energy resilience are limited electricity grid infrastructure, dependence on imported fuels, and lack of investment in developing local energy sources [47]. Microgrids, especially in on-grid configurations, can help address these challenges by providing more stable and diverse energy sources, reducing dependence on the central grid, and increasing electricity accessibility for remote communities [48]. In addition, microgrid designs that adopt the principle of energy diversification can reduce the risk of system disruptions by ensuring the availability of reliable alternative energy sources [49]. Furthermore, social and economic factors also play an essential role in determining the level of energy resilience in rural communities. Community participation in managing and maintaining microgrids can improve the system's sustainability by encouraging a sense of ownership and wise use of resources [50]. In addition, government policy support in the form of incentives and regulations that encourage renewable energy investment can accelerate the adoption of microgrid technology in remote areas [43]. Thus, strategies that combine efficient technology, community engagement, and strong policy support will strengthen energy resilience in rural communities [51].

3. Optimization of On-Grid Microgrid Systems

Optimization Techniques

Optimization in microgrid systems involves a multi-objective approach that considers the balance between economic, environmental, and technical aspects. In this context, the main objective is to find the most efficient system configuration considering investment costs, operational costs, and ecological impacts [52]. The multi-objective approach ensures that the microgrid system generates electricity at a low price and has high reliability and minimal environmental impact. Some optimization methods commonly used in microgrid design include heuristic-based optimization, genetic algorithms, and linear programming-based methods [53]. By considering multiple criteria simultaneously, this approach enables the design of more sustainable microgrids that are adaptive to geographical conditions and local energy needs [54]. In addition to considering costs and technical efficiency, environmental factors are essential elements in microgrid optimization. Carbon emissions and ecological footprints of the power generation system must be thoroughly analyzed to reduce environmental negative impacts [55]. With increasing regulations related to renewable energy and sustainability, microgrid optimization is now increasingly focused on growing green energy penetration without sacrificing system stability and reliability. Combining renewable energy such as solar, wind, and biomass with energy storage systems allows for more effective optimization to reduce long-term costs and increase system resilience to disturbances [56]. Therefore, microgrid optimisation methods must consider technical and economic aspects and contributions to climate change mitigation and adaptation to prevailing energy policies [57].

Simulation and Modeling

Modelling and simulation are crucial steps in microgrid optimization, where various scenarios are tested to determine the most efficient and sustainable system configuration. HOMER Pro is one of the most widely used simulation software in microgrid design and analysis due to its ability to holistically evaluate different resource combinations and optimize system costs and performance [57]. This tool allows users to simulate various scenarios based on generating capacity, energy demand patterns, fuel prices, and available policy incentives. By considering these variables, HOMER Pro provides deeper insights into the impact of each design choice on operational costs, energy efficiency, and carbon emissions [58]. In a microgrid modelling case study, the first step is to collect data related to energy demand (load profile), weather conditions, and available energy sources at the study site [59]. This data is then fed into HOMER Pro to run simulations of various system configurations, including renewable, hybrid, or conventional energy-based scenarios. After that, the simulation results are analyzed to identify the best option based on technical, economic, and environmental parameters [55]. Sensitivity analysis is also carried out to evaluate the impact of changes in energy prices, weather variations, or electricity loads on the overall system performance. With this approach, the microgrid design can be optimized by considering uncertainties in technical and economic aspects, thus ensuring long-term energy sustainability and resilience [60].

Key Performance Indicators (KPIs)

The performance evaluation of the microgrid system is carried out using key indicators such as Levelized Cost of Energy (LCOE), Loss of Power Supply Probability (LPSP), and environmental impact measured through carbon emission reduction (CO_2). LCOE is an economic metric that describes the average cost of electricity production throughout the life of the microgrid system, including investment, operational, and maintenance costs [61]. The lower the LCOE value, the more economical the microgrid system is in the long term. LPSP, on the other hand, is a reliability metric that measures the probability of a power shortage in a microgrid system, where a lower LPSP value indicates a higher level of reliability [62]. In addition, environmental indicators such as carbon emission reduction are used to assess the contribution of microgrids to sustainability and climate change mitigation [55]. Using these performance indicators helps determine the most optimal microgrid configuration, both in terms of cost, reliability, and environmental impact. In microgrid implementation, the main target is to balance minimal cost, high reliability, and low environmental impact. Therefore, KPIs-based analysis considers fuel price variations, energy storage technology efficiency, and renewable energy incentive policies. With a data-driven approach and simulation analysis, microgrid design can be optimized for optimal performance according to local needs and energy resource availability [63].

4. Case Study Analysis

Description of Selected Rural Community

This study was conducted in a rural community located in an area with limited access to the primary electricity grid. Geographically, this location is in an area with high levels of solar radiation, allowing the use of solar energy as one of the primary energy sources. In addition, the wind speed in the area is relatively stable throughout the year, opening up opportunities for the integration of wind power generation systems. Regarding demographics, this community comprises around 500 households with an average per capita energy consumption lower than urban areas. Still, there is a stable electricity demand for the agricultural sector and small businesses [64]. One of the main challenges this community faces is the dependence on expensive and environmentally unfriendly diesel generators. In addition, the electricity supply from the primary grid is often disrupted, causing instability in the electricity supply for the local population. Limited energy infrastructure and lack of investment in alternative energy sources are also factors that hinder the sustainability of the electricity system in this area. Therefore, optimising renewable energy-based microgrids is a potential solution to increase energy security and reduce community operating costs [65].

Table 1. Geographic and Demographic Characteristics of the Community

Parameters.	Values
Location.	Rural area with limited electricity network
Number of households.	500 households
Average energy consumption.	2-3 kWh per day per household
Primary current energy source.	Diesel generator, unstable grid electricity
Renewable energy potential.	Solar, wind, biomass
Main challenges.	High electricity costs, dependence on diesel

Optimization Results

The optimization results show that the best configuration for the microgrid in this community is a combination of 200 kW solar panels, 100 kW wind turbines, and a 500 kWh battery storage system to maintain the stability of the energy supply. In addition, the system maintains a 50 kW diesel generator as a backup in emergencies. This approach allows for a reduction in diesel fuel consumption of up to 70% while ensuring a more stable and environmentally friendly energy supply [66]. Regarding economic feasibility, this configuration produces a Levelized Cost of Energy (LCOE) of 0.12 USD/kWh, lower than the previous energy cost of 0.25 USD/kWh using a diesel generator. In addition, the reduction in carbon emissions is estimated to reach 150 tons of CO_2 per year, contributing positively to environmental sustainability. The system's resilience significantly increases with adequate energy storage, allowing for a reliable electricity supply despite changing weather conditions or significant grid disruptions [67].

Table 2. Microgrid Optimization Results

Parameters	Before Optimization	After Optimization
Primary energy sources.	Diesel, grid electricity.	Solar 200 kW, Wind 100 kW, Diesel 50 kW (backup).
Electricity cost (LCOE).	0.25 USD/kWh.	0.12 USD/kWh
Diesel fuel consumption.	100% of total energy.	Only 30% of total energy.
Carbon emission (CO_2).	500 tons/year.	350 tons/year

Energy resilience.	Susceptible to disturbances.	Stable, with energy storage

Discussion of Findings

The results of this study have important implications for stakeholders, including governments, energy providers, and local communities. By optimising renewable energy-based microgrids, rural communities can reduce their dependence on fossil fuels, lower electricity costs, and improve energy sustainability [55]. The government can use these results to design incentive policies for developing microgrids in remote areas. In addition, investment in renewable energy infrastructure can create new economic opportunities for communities, such as jobs in installing and maintaining energy systems [68]. From a technical perspective, the optimization results show that microgrids that combine solar, wind, and energy storage have high flexibility and resilience to power supply disruptions. This approach can also be easily replicated in rural communities with similar characteristics. The system's scalability allows capacity adjustments for population growth and future energy needs. Therefore, adopting optimized microgrid technology can be a long-term solution to improve energy security and the welfare of rural communities [69].

Table 3. Implications and Scalability of Microgrid Optimization

Aspects.	Impacts and Implications Economy.
Lower electricity costs job creation.	
Technology.	Increased system reliability and high flexibility.
Environment.	Reduced carbon emissions utilization of renewable energy.
Policy.	Encourage renewable energy investment incentive regulation.
Scalability and Adaptability.	It can be applied in other communities with similar characteristics.

5. Conclusion

The results of this study indicate that optimizing a renewable energy-based microgrid system can improve energy security and cost efficiency for rural communities with limited access to electricity. Based on optimization analysis using HOMER Pro, the best configuration obtained includes a 200 kW solar power system, a 100 kW wind turbine, and 500 kWh of energy storage, with a 50 kW diesel generator as a backup. This configuration can reduce diesel fuel consumption by up to 70%, which impacts electricity costs from 0.25 USD/kWh to 0.12 USD/kWh. In addition, carbon emissions can be reduced by 150 tons of CO_2 per year, supporting the transition to a cleaner and more sustainable energy system. From a technical perspective, implementing this microgrid provides higher electricity reliability than relying entirely on the primary grid or diesel generators. Despite disruptions or load fluctuations, the integrated energy storage system offers a stable electricity supply. From a policy perspective, this study underlines the importance of government support in the form of incentives and regulations to accelerate the adoption of renewable energy systems in remote areas. In addition, this optimized microgrid model is scalable and can be replicated in other rural communities with similar characteristics. Thus, renewable energy-based microgrid optimization improves community energy security, contributes to environmental sustainability, and reduces dependence on fossil fuels.

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