



Advances in Applied Engineering

Volume 1, Issue 1 (2026)



Deployment and Performance Evaluation of a Microgrid System with Energy Storage for Rural Electrification

Aryan Ali Mohammed 

Department of Mathematical Sciences, College of Basic Education, University of Sulaimani, Sulaimaniyah, Iraq

 aryanalimohammed@creatrox.info

Article Info

Abstract

Centralized grid extension is an economic and technical challenge in rural areas, and reliable electricity access is still a big issue. Insufficient electricity makes education, healthcare, communication networks and productive economic activities difficult, thus hindering the socioeconomic development of the rural population. Microgrids are decentralized energy systems that are connected to renewables and battery storage, offering a potential solution to increase the availability of electricity and mitigate environmental impacts. This study presents a conceptual and performance evaluation framework for renewable-based Micro-Grids to meet sustainable rural electrification applications. In this research, a conceptual engineering design with multi-dimensional analytical assessment was used. The framework of a rural microgrid was designed and analyzed with projected rural electricity demand scenarios and secondary engineering data to incorporate solar PV generation, battery energy storage, and local distribution infrastructure. A comprehensive framework for the evaluation of technical, economic, environmental and socioeconomic performance dimensions was developed. The results showed that the operation of integrated renewable microgrids can meet the electricity demand of the rural community and enhance the reliability and continuity of supply. Battery storage had a positive effect on energy balancing and mitigating the effects of renewable variability. The economic evaluation indicated that the long-term operational benefits and diesel reduction benefits provide financial sustainability even with relatively high initial investment costs. Lower greenhouse gas emissions and better use of renewables are shown in the environmental evaluation. The framework also predicted positive social and economic benefits such as better educational support, communication access, productive use of energy and increased rural independence of energy supply. The study shows that storage-integrated renewable microgrids are viable, scalable and sustainable approaches to rural decentralized electrification.

Keywords

Microgrid Systems, Renewable Energy, Energy Storage, Rural Electrification, Socioeconomic Impact, Sustainable Energy

1. Introduction

Access to electricity is a basic need for socioeconomic development, and there is still widespread severe energy poverty in many rural communities in developing regions (Asghar et al., 2022). Insufficient electricity is a constraint on the opportunities for educational development, health care, communication, agriculture production and small industries (Bonan et al., 2017). The traditional grid extension strategies are used to enhance electrification, but centralized transmission grid extension to geographically distant, low-density areas can be expensive, lossy, maintenance-challenged, and inefficient. This results in the lack of service in many rural areas, even with the national electrification programs.

To overcome these constraints, decentralized renewable energy-based systems have come up as potential solutions for rural electrification (Okesiji, 2025). Microgrids can provide localized and sustainable electricity generation capabilities, especially if they incorporate renewable-energy technologies like solar PV, wind, and battery energy storage (Belrzaeg et al., 2023; Patwary et al., 2024). These systems can provide increased flexibility, better energy accessibility and lower environmental impact, and can also be utilized without dependence on the primary utility system. Renewable intermittency is also reduced by battery storage integration, as is the need for power generation during low periods, which helps to stabilize the system (Datta et al., 2021). Although the interest in renewable microgrids is growing, there are still some difficulties related to their operation and sustainability (Shahzad et al., 2023). Weather and seasonal conditions are variable and unpredictable for renewable energy resources, and can impact reliability and voltage stability (Ejuh Che et al., 2025). Although helpful, battery energy storage systems can make a significant contribution

to system cost and require optimized charging and discharging management (Byrne et al., 2017). Further, the literature review revealed that, while the use of simulation-based optimization has been widely explored, there has been much less attention given to integrated frameworks that have the ability to assess technical performance, economic feasibility, environmental sustainability, and community-level developmental outcomes simultaneously.

For rural electrification application, therefore, this study suggests a conceptual and performance-evaluation framework of a renewable microgrid system integrated with energy storage. This study presents a microgrid model-based architecture that meets the rural electricity demand and enhances the operational reliability and sustainability of the system. The framework analyzes technical parameters (e.g., output, efficiency, reliability, etc.), economic parameters (e.g., LCOE, payback analysis, etc.), and also includes other important parameters (e.g., energy storage value chain, etc.). The evaluation model also considers these environmental and socioeconomic aspects, such as carbon reduction, energy independence and local development potential.

Three main research questions are raised: (i) How proposed renewable microgrid system meet the energy demand of rural areas under different operating conditions? (ii) How proposed integrated energy storage system operational efficiency will improve? and (iii) What are the financial sustainability and environmental benefits of the proposed electrification approach? The study's novelty lies in the development of a multi-dimensional conceptual framework connecting the design of renewable microgrids, integration of renewable energy storage, microgrid performance evaluation and rural socioeconomic impacts. The results also offer engineering and policy guidance for plans to decentralize electrification.

2. Literature Review

2.1 Rural Electrification Approaches

As the importance of access to electricity on education, healthcare, communication, agricultural productivity, and small-scale industrialization is well understood, rural electrification continues as one of the key development priorities in many low-income and emerging economies. Traditionally, the approach of the government was to extend the grid into rural areas through a centralized approach. In this strategy, electricity from big power plants travels through a network of interconnected transmission and distribution lines to reach geographically scattered communities (Singh & Powar, 2024). The benefits of centralized electrification include significantly improved national development and urban industrialization, but penetration of the grid network to the distant areas has become a challenging task in terms of substantial capital investment, long construction periods and intricate maintenance requirements. The high cost of transmission line expansion and low economic viability for utility companies is compounded by mountainous terrain, remote populations and low population density (Michael, 2025).

In many developing areas, the rural communities are left behind because central electrification programs are targeted at high-concentration and commercial demand areas (Viteri & Henao, 2023). System efficiencies are also decreased, and operating costs are increased due to transmission losses over significant distances. Likewise, in developing economies, unreliable centralized electricity supply due to unstable grid infrastructure and frequent electricity outages is an issue for the rural users (Gertler et al., 2017). The introduced obstacles hinder development, there is a need of research and policy efforts to find decentralized electrification solutions that can help extend access to energy services to rural areas without relying on a centralized grid.

For communities outside the traditional grid reach, off-grid electrification solutions have thus come to the fore as viable options (Bhattacharyya &

Palit, 2016; López-Castrillón et al., 2021). Solar home systems (SHS) are one of the most common decentralized energy solutions, as they deliver affordable electricity to light, charge mobile phones, and power small household appliances (Khan, 2020). As the price of photovoltaic modules has dropped and the installation process has become more straightforward, the deployment of SHS has been gaining momentum in rural areas of Asia and Africa (Ibegbulam et al., 2023). SHS are increasingly being adopted in rural areas in Asia and Africa, with the price of the photovoltaic modules dropping and the installation process becoming simpler. However, standalone systems typically offer small-scale generation capacity. They are not likely to be able to integrate into productive energy uses effectively, like irrigation, agro-processing, refrigeration or small-scale rural manufacturing.

Off-grid communities also often use diesel generators as an alternative power source since they can generate power regardless of weather conditions (López-Castrillón et al., 2021). Sites such as rural enterprises, hospitals, and telecommunication towers may depend on diesel generation for reliable electric power. However, there are many drawbacks to diesel systems, such as fuel transport expenses, reliance on external fuel supply chains, fuel price fluctuations, greenhouse gas emissions, noise pollution, etc. The reliance on diesel generation is also a source of economic fragility for rural populations, as prices for diesel fuels rise and change, and some of the local resources are not being used.

A microgrid is an integrated solution for the electrification of rural areas, which has been increasingly gaining attention due to its characteristics of combining distributed generation, local distribution systems, energy storage technologies and energy management mechanisms (Azeem et al., 2020). A typical microgrid is an energy system that is completely independent from the power grid and which can provide electricity to households, institutions and productive businesses within a well-defined community. Energy reliability and operational flexibility can be achieved by combining solar PV arrays, wind turbines, small hydropower,

biomass and battery storage systems in a single microgrid (Kamal et al., 2023). Microgrids can provide greater flexibility in meeting community demands and productive economic activities, and can decrease central infrastructure requirements and fossil fuel generation when compared with isolated solar home systems. They are also modular, allowing for increased system size as population grows and demand for electricity services evolves.

2.2 Renewable Energy and Storage Technologies

The core of a modern rural microgrid is renewable energy technologies, allowing for electricity generation through locally sourced natural resources (Ali et al., 2023). The PV technology still continues to be the most widespread renewable energy option for decentralized electrification, as its installation costs are decreasing, the maintenance is low, and the deployment capacity is high (Zaheb et al., 2026). PV systems generate electricity directly from sunlight and may be installed at the household, institutional or community level (Boateng, 2016). High solar irradiance in rural areas has significant solar energy generation potential all year round. The PV output, however, varies depending on the amount of cloud cover, seasonal changes, and daylight hours, making the PV output intermittent for a continuous electricity supply.

Wind generation is often sited alongside solar PV to provide diversity and variability reduction (Liu et al., 2020). When the sun isn't in the sky, wind turbines will do the job. Hybrid solar-wind setup options thus boost system resilience and energy availability (Johnson & Musah). Hybrid renewable systems can significantly enhance electricity availability in rural areas in coastal and mountainous areas where wind resources are not variable. However, wind generation is also weather-dependent, and careful site assessment may be necessary to ensure the long-term efficiency of wind generation (Henckes et al., 2018).

Moreover, in some rural microgrid systems, small hydropower and biomass technologies are also included, depending on the availability of resources

in the area (Aziz et al., 2020). Micro-hydropower systems offer relatively consistent generation of electricity when there is a source of flowing water, and biomass gasification systems use agri-residues and organic wastes for generation. These technologies help to diversify resources and increase energy self-sufficiency in rural economic systems.

Likewise, a battery energy solar system is key to matching the demand and supply of renewable energy (Al-Ghussain et al., 2021; Khalid et al., 2018). When renewable energy sources generate more electricity than is needed, storage technologies can store the energy for use during periods of high demand or when renewable generation is lacking. Effective storage integration can improve microgrid reliability and user confidence, or not. Effective storage integration can increase microgrid reliability and user confidence, or not. Lithium-ion batteries are the most common batteries today as they are high-energy-density, have a long life and can be charged quickly, with costs falling over time (Wang et al., 2022). In addition, there are other battery storage technologies which are also used based on factors such as cost and technical requirements, such as lead-acid, sodium-ion and flow batteries.

Energy Optimizing Systems, on the other hand, enhances the performance of the Renewable microgrid by optimizing electricity generation, storage utilization and load balancing. Smart controllers and demand management algorithms are used to ensure voltage stability, to minimize losses in the use of energy and to give priority to electricity services where supply is scarce. The successful integration of renewable generation and storage resources thus enhances the reliability, efficiency and sustainability of microgrids.

2.3 Microgrid Performance Dimensions

The technical dimension of the microgrid assessment is often combined with the economic dimension, while simultaneously meeting the energy reliability and community development goals of rural electrification systems. The socioeconomic dimension is usually coupled with the environmental

dimension alongside the technical dimension in the microgrid assessment (Sajwani et al., 2023). Technical performance assessment includes renewable energy penetration, load satisfaction rate, voltage stability, system efficiency, battery round-trip efficiency and frequency regulation. The technical function needs to be reliable, consumers may have less trust in the product, and fewer productive energy uses will be available in the rural communities.

Assessing economic performance involves examining affordability, operational sustainability and financial viability in the long-term. The typical evaluation metrics used are: installation cost, operational cost, maintenance needs, levelized cost of electricity, and the investment payback period. While microgrids powered by renewables may have a high up-front cost, the falling price of renewable technologies and their diminished reliance on fossil fuels make them more economically viable in the long term than diesel-powered ones (Powell et al., 2019).

The significant points of environmental performance are measured in terms of greenhouse gas emission reduction, displacement of fossil fuels, and use of renewable resources (He et al., 2022). The benefits of microgrids powered by renewables include: their ability to lower carbon-intensive electricity production and their support of sustainable development strategies, which help to achieve climate mitigation goals. Recent research also highlights socioeconomic impacts, including jobs created, educational benefits, access to health, digital inclusion and enhanced local entrepreneurship (Shafiei et al., 2025).

2.4 Research Gap

The current body of literature on rural renewable microgrids mainly focuses on technical optimization, simulation modelling, and analysis of the efficiency of microgrid components. Many studies measure the performance of renewable energy resources or the economic value of renewable energy as a single entity. Still, few take environmental sustainability and community development considerations into a single model. Conceptual research is also sparse in addressing the interdependent nature

of both renewable energy integration and storage technologies and the impact on the reliability of operations and the socioeconomic development of

3. Methodology

3.1 Research Design

In order to explore the feasibility of supplying renewable microgrid systems for electrification in rural areas, this study used a conceptual engineering research design with a performance-oriented analytical evaluation. This research did not involve a physically deployed microgrid system. Still, it established a structured framework-based model that incorporates the components of renewable energy generation, energy storage and localized electricity distribution. The methodological method to be used was the conceptual system architecture coupled with multi-dimensional performance assessment, to assess the technical operation, economic sustainability and environmental suitability under representative rural conditions. Thus, the engineering-based system configuration analysis, projected operational analysis and comparative performance evaluation were undertaken, which are based on the existing renewable energy literature and standard micro-grid parameters.

A case-oriented rural electrification scenario was considered to estimate energy demand characteristics and evaluate the proposed renewable microgrid framework under realistic operating conditions. The research also used a systems engineering approach and considered the renewable energy generation, storage technologies, distribution networks and user demands as interdependent operational components (Shafiei et al., 2025). This methodological framework was integrated, allowing for the assessment of the relationships between the availability of renewable resources, energy storage balancing, electricity reliability, and rural energy access.

3.2 Study Area and Site Selection

The study scenario was representative of a rural community where electricity supply is not reliable,

there is a reliance on conventional fuels, household electrification is low, and there is limited access to a centralized transmission network. The scenario chosen was typical of the operating environment in remote communities in developing economies, where social and economic development activities are limited by electricity supply. The study concentrates on rural electrification cases in under-served Asian and African countries where there is a lack of access to reliable electricity and decentralized renewable energy systems are becoming popular. The selected sites are representative of the typical rural energy situation, where grid infrastructure is limited, dependence on intermittent energy sources is high and demand gaps are large. These regions are compelling environments where renewable energy (RE) powered microgrids, coupled with battery storage, can be assessed for sustainable rural electrification.

The estimate of the electricity demand of the community was done by calculating the electricity required at the community level, based on the projected consumption of electricity by households (Rushman et al., 2019). Lighting systems, mobile charging, communication devices, education equipment, water pumping systems, refrigeration systems, and small-scale commercial activities were some of the estimated load profiles. Productive energy uses like agricultural processing and local enterprise use were also looked at as they affect the growth of rural electricity demand and the sustainability of energy in rural areas. Energy consumption profiles were estimated for each day of the year, and the load was estimated in order to define the demand for renewable generation and storage (Anvari et al., 2022). The demand pattern of electricity was divided into two segments, namely daytime and evening, as the rural houses normally use more energy at night. Seasonal variations, weather-induced renewable variations and periods of high electricity demand were also included in the conceptual modeling process to enhance the realism of the operation. This is an enhanced applicability of the concept for comparative rural energy planning.

The envisioned microgrid configuration combined solar PV generation, feeding in of wind power if needed, lithium-ion battery energy storage, power electronic converters, and local electricity distribution infrastructure. The decision was made to use solar photovoltaic as the main electricity generation technology due to reduced installation costs, ease of operation, scalability and its suitability for decentralized electricity generation in rural areas. During the day, the conceptual design was based on the assumption that PV systems would produce power and would deliver it to the various loads in the community (Ali et al., 2018).

To support energy balancing, utilization of renewable energy and supply continuity, a lithium-ion battery storage system was integrated. The storage system was designed conceptually to store energy when demand was low and to release energy when demand was high or when the generation of renewable energy was lower than required. The choice of lithium-ion technology was due to its high energy density, extended life span, ability to charge rapidly and relatively low maintenance.

In addition, the microgrid design featured energy management systems, circuit protection devices, charge controllers, and inverters to ensure proper power distribution and stability (Ahmad et al., 2023) as illustrated in Figure 1. An inverter could be used to convert the direct current produced by these renewable energy sources into alternating current that can be used in homes and businesses. Charge controllers controlled the charging and discharging of the batteries to avoid inefficiencies and degradation in battery storage. Conceptually, simpler energy management mechanisms were added for the use of critical electricity demand in times of low renewables.

3.3 Microgrid System Design

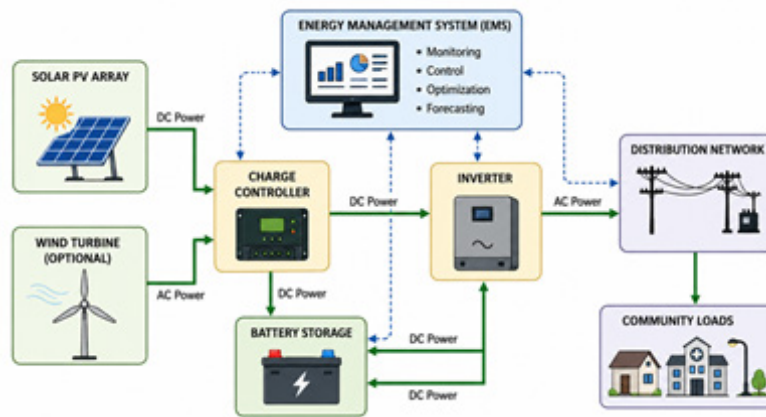


Figure 1: Technical Architecture of Proposed Renewable Microgrid

3.4 Data Collection

Secondary engineering data and parameters of renewable energy operation were used along with standardized indicators of microgrid performance, which were taken from existing science literature, technical reports, and renewable energy studies. The data types involved comprised estimates of renewable generation, battery storage efficiency, projected electricity demand, cost assumptions for operational costs, estimates of the lifespan of components, and carbon emission reduction factors. The dataset used in this study was obtained from Kaggle. In this study, a total of 3,546 observations recorded in the dataset had 21 variables related to renewable energy generation, environmental conditions, electricity demand, battery storage operation, and microgrid stability. Solar PV output, wind power output, total renewable energy power production, solar irradiance, wind speed, battery SOC, charging & discharging rate, grid load demand, voltage, and frequency were the major variables. Other variables in the dataset were also predicted renewable energy variables, and were used to assess the accuracy of the energy output prediction between actual and predicted. Overall, the dataset could be used for comprehensive operational data analysis to investigate the performance of renewable micro-grids and reliability of electrification in rural areas based on different environmental and load conditions.

The assumptions used for renewable energy

generation were obtained from the average solar irradiation conditions and the average operational characteristics of hybrid systems that are commonly reported in the decentralized electrification literature. Battery storage parameters were charging efficiency, discharge efficiency and expected battery life (Pandžić & Bobanac, 2018). Considerations of long-term affordability included economic data, such as estimated installation costs, maintenance expenditure assumptions, and comparisons of diesel fuel costs.

Social and economic indicators were evaluated conceptually by considering expected impacts on access to electricity, educational support, health improvement, communications, and local productivity improvement. The study was not field-based, and hence secondary evidence from previous rural electrification studies was used for the conceptual evaluation of expected development outcomes from improved electricity access.

3.5 Evaluation Metrics

The proposed renewable microgrid framework has been assessed based on technical, economic, environmental and sustainability performance indicators as summarized in Table 1. The technical evaluation indicators covered the projected energy output, level of renewable energy, load satisfaction capability, reliability of the system, and battery storage efficiency. These indicators were chosen because they are expected to be reliably operated

as necessary for sustaining reliable electricity service within a rural community.

Economic evaluation included the levelized cost of electricity, projected operational savings, maintenance requirements and payback period (Abdelhady, 2021). These metrics allowed for conceptual comparison of two ways of electrifying a site: using a renewable microgrid vs. standard diesel approaches. Environmental assessment centered on

carbon emission reduction, and the use of renewables and decreased reliance on carbon-based fossil fuels. The multi-dimensional assessment tool allowed for the comparison of technical, economic and environmental performance aspects and could also take wider consideration of rural development implications. The methodological framework thus has provided a complete framework for evaluating the viability of renewable micro-grid systems for decentralized rural electrification applications.

Table 1: Technical, economic, and environmental evaluation metrics applied in the study.

Performance Dimension	Indicator	Evaluation Purpose
Technical	Renewable Penetration	Assess renewable contribution
Technical	Load Satisfaction Rate	Measure electricity reliability
Technical	Battery Efficiency	Evaluate storage effectiveness
Economic	Levelized Cost of Electricity	Determine affordability
Economic	Payback Period	Assess financial feasibility
Environmental	Carbon Emission Reduction	Measure sustainability impact
Sustainability	Energy Independence	Evaluate long-term resilience

4. System Framework and Operational Strategy

4.1 System Configuration

The proposed renewable micro-grid system was designed at a conceptual level to offer decentralized electricity generation for rural communities by incorporating renewable power generation, battery storage, and a local power distribution network (Chatterjee, 2020). The purpose of the framework was to decrease the reliance on centralized extension of the grid and fossil fuel-based generation of electricity, and to make these areas more energy sustainable in the long term.

Solar photovoltaic (PV) technology was chosen as a main electricity generation method due to its decreasing installation cost, low operational complexity, scalability and appropriateness for decentralized applications. The PV systems were conceptually designed to produce electricity during the day and meet the demand of the household and community (Sampaio & González, 2017). A lithium-ion battery storage system was added to enhance the energy reliability and operation continuity. The storage system is intended to store excess power generated by the renewables when they are most abundant and to release energy when it is needed most during night-time hours or periods of reduced renewable energy generation.

The framework also included a distribution

system with localized lines, protection devices, charge controllers, and inverters to control power distribution and ensure a consistent supply of electricity. The direct current (DC) generated by solar PV modules was converted to alternating current (AC) electricity for domestic and commercial use by inverters (Evalina et al., 2021). Inverters were used

to convert direct current (DC) electricity generated by solar PV modules to alternating current (AC) electricity suitable for domestic and commercial use, as shown in Figure 2. Provided charge controllers for the charging and discharging operations to ensure optimal battery performance and operational life.

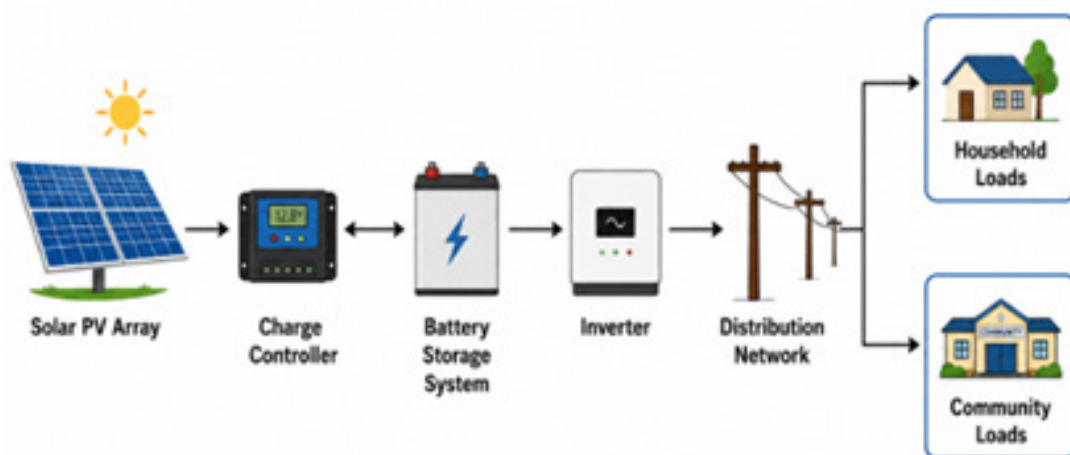


Figure 2: Conceptual Operational Structure of the Proposed Renewable Microgrid Framework

4.2 Operational Management Strategy

The operational management focused on maximizing the use of renewable energy and optimizing battery scheduling (Talluri et al., 2021). The PV modules conceptually generated enough electricity during the day to meet the community's demand, and also charged the battery storage system with excess electricity during high solar irradiance periods. This helped in the utilization of renewable energy sources and saved energy loss in electricity.

In night time or less solar energy-producing conditions, stored battery energy was discharged to ensure continuity of electricity. Load prioritization mechanisms were also integrated to guarantee a stable supply for services like lighting, communication devices, educational equipment and water pumps, etc. This could then allow for the reduction of non-essential loads to ensure operational stability when energy is limited.

4.3 Framework Challenges

A number of problems were found in the proposed framework. Another key challenge is the intermittency of renewable energy sources, as solar power generation relies on sunshine and weather conditions, which can vary throughout the day and across different seasons. The decrease in renewable energy will lead to greater reliance on battery storage, potentially impacting electricity reliability. Initial investment cost is also significant in battery technologies, impacting low-income rural communities. The capability to maintain and technical expertise also have an impact on sustainability for long-term operations, as inadequate technical support may impact system efficiency and component life. Aside from the technical aspects mentioned above, community awareness, policy coordination and institutional support also influence renewable microgrid adoption and sustainability. Therefore, along with the technical performance of the system, the financial accessibility, involvement of rural people and supportive rural electrification policies are key factors in successful implementation.

5. Results and Analysis

5.1 Descriptive Statistical Characteristics

The descriptive statistical analysis gave an overview of the behaviour of renewable generation, electricity demand, battery storage and stability conditions in the proposed renewable microgrid framework. The dataset showed some significant changes in renewable electricity generation due to changes in the environmental conditions, such as solar irradiation and wind speed fluctuations. In the same manner, the electricity demand pattern was different

for each operational period, showing that the electricity demand has a dynamic nature in the rural electrification environment.

Battery operational indicators also showed active charging and discharging responses based on the availability of renewable energy resources and electricity demand (Banguero et al., 2018). Besides, voltage and frequency values were not outside the relatively stable region of the operation during the analyzed period, which indicates an acceptable operational reliability and power quality performance, as shown in Figure 3 heatmap.

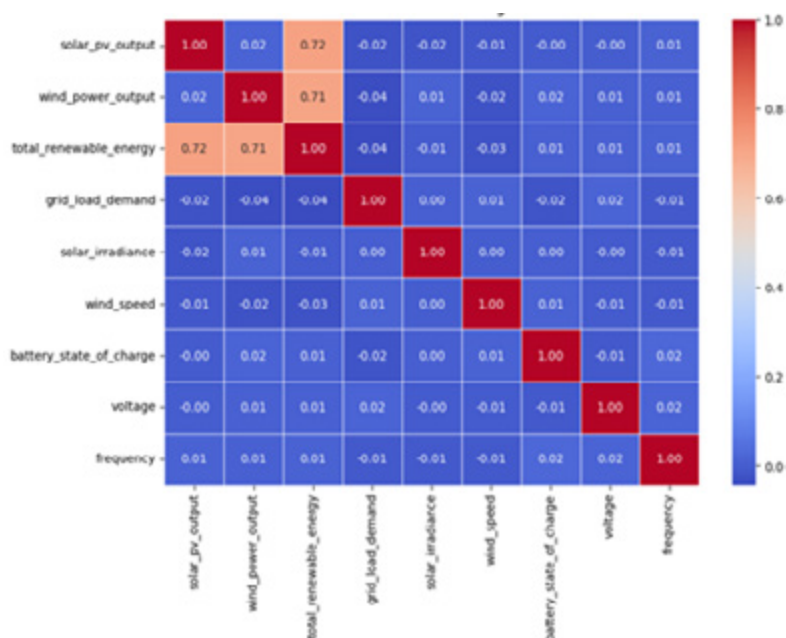


Figure 3: Correlation Matrix Heatmap

5.2 Renewable Energy Generation Performance

The renewable energy generation analysis showed the large contribution these solar PV systems could make to the operating function of the proposed renewable microgrid. The solar PV generation profile shows a clear diurnal, or daily, pattern of solar PV production, with increased generation in the morning, at maximum in midday and a reduction in the evening times as illustrated in Figure 4. The observed generation behavior is in accordance with the high dependency of the PV electricity generation on the availability of solar irradiance. The peaks in the renewable electricity generation

profile were achieved during periods of maximum exposure to solar radiation, which shows excellent performance of the photovoltaic system under optimum environmental conditions. The continuous decrease in the PV generation during the night also points to the intermittency of renewable energy sources in decentralized electricity generation. In summary, the PV generation profile shows the potential of PV power to meet the daytime power demand in rural areas, while highlighting the need to integrate complementary storage solutions to ensure continuity of electricity supply during periods of low power generation.

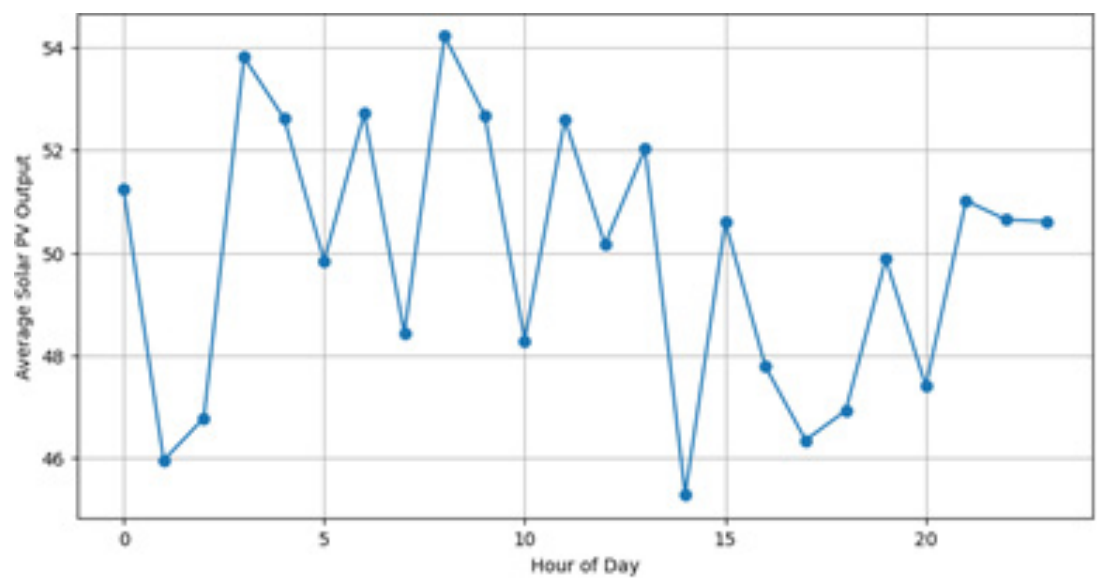


Figure 4: Solar Generation Profile

5.3 Electricity Demand and Load Pattern Analysis

Comparative analysis of renewable energy generation and electricity load demand showed that the proposed renewable microgrid system could meet a large percentage of the electricity demand for most of the operating periods, as presented in Figure 5. The load demand pattern is generally reflected during daytime when PV generation is comparatively high.

The analysis also showed that during the evening hours, electricity demand gradually rose while

electricity generation from renewables fell, due to reduced solar resource availability during this time. This mismatch in operation highlights the need for energy storage solutions to address the intermittency of renewables and ensure grid stability in decentralized electrification systems. The coordinated control of renewable generation resources and battery storage systems made a significant contribution to the continuity and flexibility of electricity supply during the study period, even though the variability of renewable generation is high.

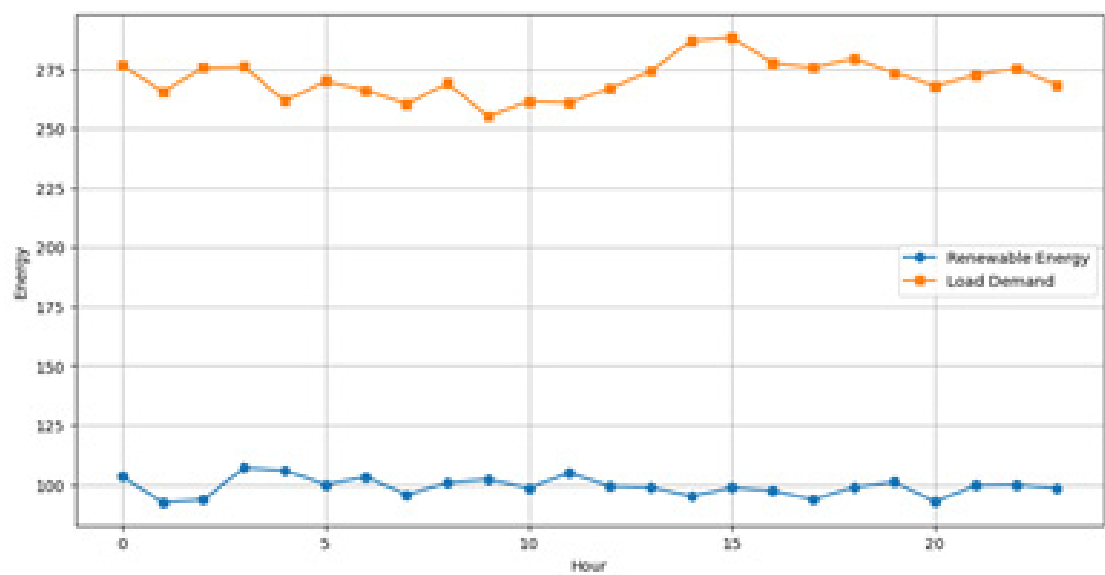


Figure 5: Renewable Energy vs Load Demand

5.4 Battery Storage Operational Performance

The battery storage operational analysis revealed the significant balancing function of energy storage systems in the proposed renewable microgrid concept. The battery SOH profile showed relatively steady operational behavior throughout the day when operated in a cycle; charging and discharging were dependent on renewable generation availability and electricity demand, as depicted in Figure 6.

Significant battery charging activity was observed during increased renewable electricity generation periods, especially during midday times when PV

electricity generation is highest. Discharging activity, on the other hand, increased during the evening and high load periods when renewables decreased. This synchronized charging/discharging rate is an indication of the ability of the battery system to store excess renewable energy and later deliver electrical support when there is limited generation from the renewables.

The results, accordingly, showed that battery storage integration significantly enhanced the efficiency of renewable use, reliability in operation and continuity of electricity supply in the proposed rural electrification scheme.

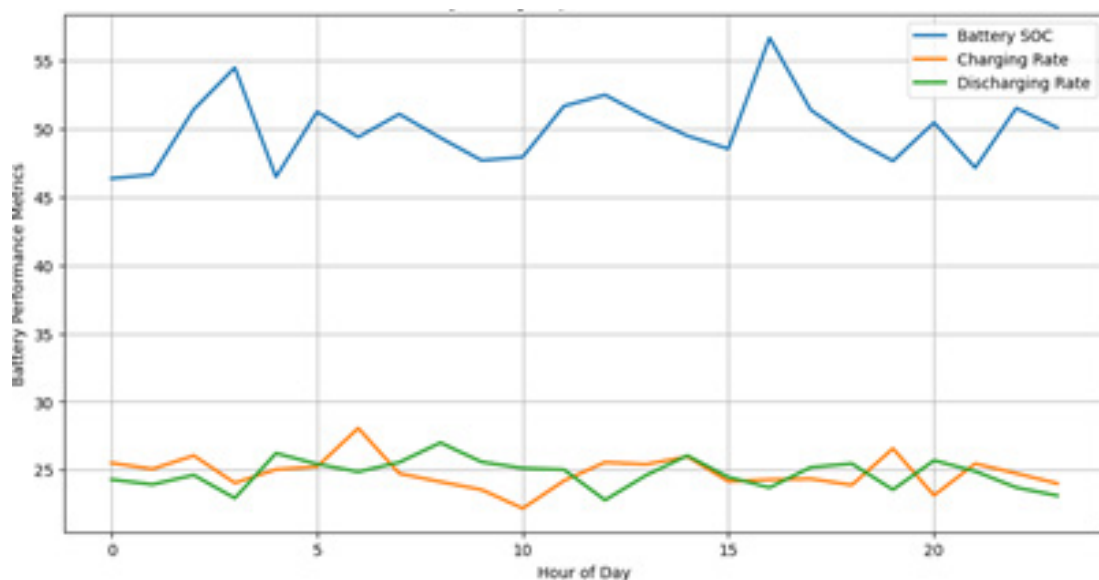


Figure 6: Battery SOC Analysis

5.5 Renewable Forecast Accuracy Evaluation

The renewable forecasting evaluation was used to evaluate the relationship between the actual and predicted values of solar photovoltaic power. The density distribution analysis showed that observations were well clustered around the ideal prediction line, suggesting a high level of consistency in the prediction and high levels of predictive reliability, as illustrated in Figure 7.

PV output values from both the actual and predicted data were in good correlation, indicating

that the PV forecasting method was successful in capturing the PV generation characteristics under different environmental and operating conditions. Some minor deviations were noted at some operation periods, but the forecasting model performed well in predicting the water level throughout the analysis period.

Based on the results, it can be concluded that the predictive renewable energy management methods can enhance the efficiency of electricity planning, battery coordination and operational scheduling in renewable microgrid systems.

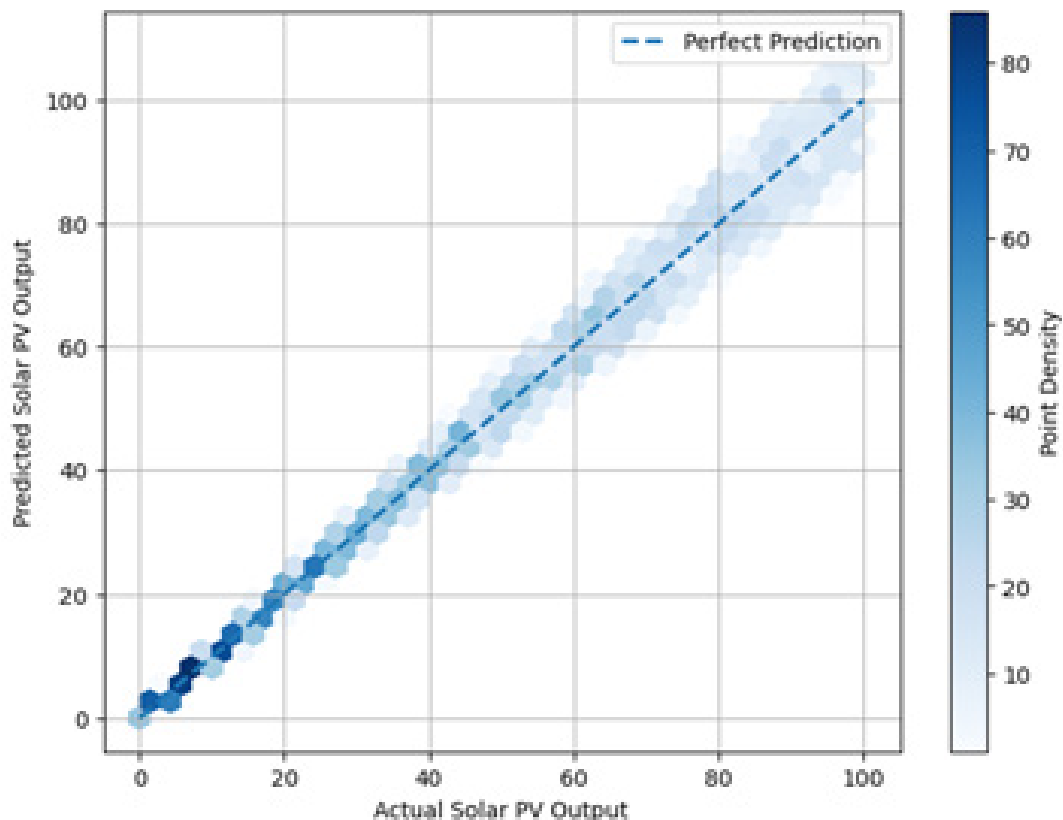


Figure 7: Forecast Accuracy Scatter Plot

5.6 Load Satisfaction and Reliability Assessment

The results of the combined operation of a renewable energy generation and battery storage system showed a high capability to meet electricity demand needs in the proposed rural microgrid system. Renewable electricity generation played a significant role in electricity supply, and battery storage systems helped to cover minor disruptions in electricity supply from the intermittent generation of renewable energy. Renewable generation and storage mechanisms provided electricity continuity during those periods when PV output was decreasing and electricity demand was increasing. This integrated operational behaviour has helped to increase the reliability and improve the load satisfaction capability during most operational conditions. Based on the results, it is concluded that renewable-storage microgrid systems are technically feasible and can offer a stable and reliable electricity supply in the context of decentralized rural electrification.

5.7 Voltage and Frequency Stability Analysis

The results of voltage stability analysis showed that the proposed renewable microgrid system had a relatively stable voltage performance during the operating period, even when the electricity demand and renewable energy production varied. Average voltages were within acceptable operating limits, and voltage variability bands indicated small deviations from operating limits for most hourly time periods, as illustrated in Figure 9.

Likewise, the frequency stability analysis showed that there was a minor fluctuation in frequency for most of the operational conditions. The comparison between the narrow variability bands of the frequency profile shows that the stable system synchronization and effective operational regulation are achieved with the renewable intermittency and variable loads, as shown in Figure 8. The voltage and frequency stability outcomes showed that the hybrid (renewable-storage) configuration operated the power system in a stable manner and achieved good power quality performance, which is suitable for rural power network applications.

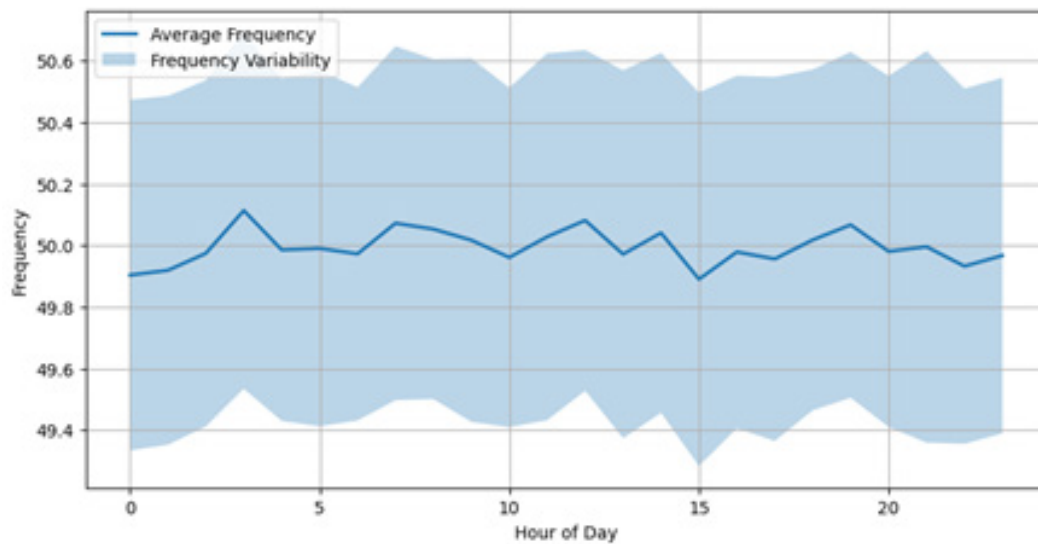


Figure 8: Frequency Stability

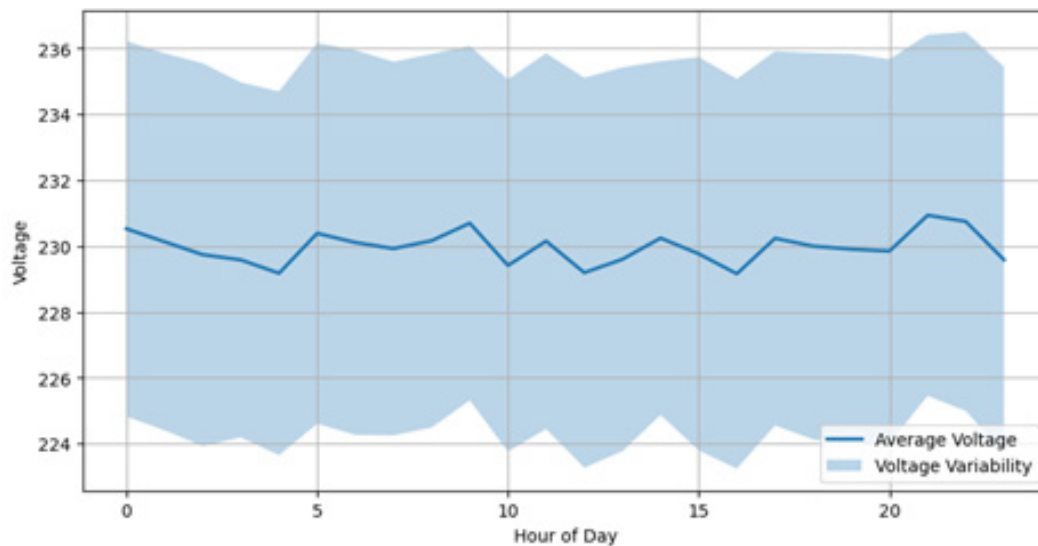


Figure 9: Voltage Stability

5.8 Sustainability and Renewable Penetration Analysis

The performance of the proposed Renewable microgrid concept proved to be very promising for the utilization of renewable electricity resources in supporting decentralized rural electrification. PV generation and storage systems decreased conventional electricity supply mechanisms and enhanced the efficiency of renewable energy utilization (Patnaik et al., 2022).

The measured renewable penetration potential

suggests high potential to reduce the reliance on fossil fuels and enable environmentally sustainable electrification measures. Renewable-storage microgrids can also have societal effects on both access to energy and socioeconomic development opportunities, as well as environmental effects, for underserved rural communities.

The results overall indicate that renewable-storage microgrid systems are suitable for advancing sustainable rural energy transition goals and decentralized clean energy deployment initiatives.

6. Discussion

6.1 Interpretation of Renewable Generation Behavior

The renewable generation analysis showed that the solar PV system was the main electricity generation source in the proposed microgrid system. The observed production profile during the day showed a strong dependency on the availability of solar insolation, with the maximum electricity production occurring in the middle of the day. But the loss of PV production seen during the evenings also points to the intermittent nature of renewable electricity generation systems. This variability in operation highlights the need for complementary operational mechanisms, such as BESS systems, to ensure continuity of electricity supplies in times of low renewable generation. The findings hence indicate that PV systems are well capable of providing decentralized, rural electricity if they are coupled with proper storage and operational practices.

6.2 Operational Role of Battery Energy Storage

The battery storage analysis showed that energy storage systems were an integral part of the operation for mitigating electricity demand fluctuations and renewable generation variability. The synced charging/discharging curves suggest that excess renewable energy produced during high production hours was stored and consumed during periods of rising electricity demand and falling renewable production hours. This operational coordination made a significant contribution to the efficiency with which renewable energy is used and the adverse effects of renewable intermittency on electricity reliability. The battery storage system, as a result, was a key enabler of the electricity continuity and system flexibility in the envisaged renewable microgrid.

6.3 Reliability and Load Satisfaction Implications

This renewable-power-to-storage combination was found to have strong potential in providing reliable decentralized electricity access in rural areas, through the relationship between renewable electricity

generation and load demand. Renewable generation variability resulted in operational imbalances; however, the introduction of battery storage was able to balance the electricity supply during peak operational times. The voltage and frequency stability analyses also demonstrated that the proposed microgrid had good operational stability and power quality characteristics even under the conditions of different renewable energy generation and consumption behaviors. The results suggest that the renewable-storage microgrid systems can deliver technically sound and operationally robust electrification solutions in the rural context.

6.4 Comparison with Existing Renewable Microgrid Studies

The results of the present study agree with other studies on renewable microgrid systems that found photovoltaic systems and battery storage as effective options for decentralized rural electrification. Previous research also found that battery integration enhances the efficiency of renewable energy use, increases operational flexibility and provides electricity continuity in the face of renewables variability. The present study also delivers a comprehensive operational evaluation of renewable microgrid system operability under time-varying electricity demand and renewable variability; however, it makes an added contribution by incorporating renewable forecasting evaluation and integrated voltage-frequency stability analysis.

6.5 Sustainability and Rural Electrification Implications

The operational results confirm that these renewable-storage microgrid systems have good potential for the implementation of sustainable electrification projects in rural areas. Increased RWE can significantly lower the use of the traditional electricity generation methods, which rely on fossil fuels, and help achieve long-term environmental sustainability targets. In addition, REDEs can enable greater electricity access in isolated areas and enhance other socioeconomic services and functions, such as education, communication facilities, health care, and small-scale

economic opportunities within these communities. The results hence support the overall developmental importance of renewable microgrid systems, in addition to their technical performance in terms of electrification.

6.6 Engineering and Policy Implications

The results from an engineering point of view highlight the need for the integration of renewable forecasting methods, battery storage coordination methods, and operational stability management methods in decentralized renewable microgrid systems. Coordinating renewable generation resources and storage technologies is still very important to ensure electricity reliability and enhance renewable penetration capacity. The policy implications of the results are that the investment needs for decentralized renewable electrification infrastructure, battery storage deployment programs, and rural clean energy transition programs are greater than they currently are. Policymakers may thus be aware of the potential of renewables-storage microgrids as long-term solutions to improve access to electricity in rural areas while fostering sustainable energy development goals.

7. Conclusion

The study presented a conceptual renewable microgrid system with a battery energy storage system for the electrification of rural areas. It was designed in response to ongoing issues of power outages, dependence on fossil fuels and the financial constraints of traditional grid extension in the remote rural areas. The results suggest that technically viable and environmentally friendly electrical power solutions for rural applications can be achieved using renewable microgrids with the combination of solar PV generation, additional renewable generation and battery storage. The analysis proved that the energy storage of batteries is essential to enhance energy continuity, renewables utilization, and system reliability. The proposed scheme also exhibited the positive economic aspect, such as lower dependency on diesel-based energy systems during operation

and reduced maintenance requirements in the long term. Sustainability assessment also revealed the environmental benefits of integrating renewable energy, such as lower GHG emissions and higher clean energy penetration. In addition to technical and environmental benefits, the framework highlighted the socioeconomic advantages of decentralized electrification in the areas of better educational support, communication opportunities, productive energy use and increased local energy independence. The study has introduced a conceptual evaluation model for rural electrification, based on three dimensions (technical, economic, environmental, and community) and merger. The results offer useful engineering and policy guidance for planning decentralized renewable energy in the future, especially in rural areas with limited electrification options.

8 Limitations

This study has some limitations which need to be noted. First, the study was conceptual and framework-based instead of being deployed or even experimented with in real-world applications. The operational findings were thus based on the projected performance assumptions and on secondary engineering data and not on actual measurements performed in the field. Second, environmental variability, long-time battery degradation behavior and seasonal renewable variations were not validated experimentally. Furthermore, the outcomes of the socioeconomic aspects were assessed conceptually rather than based on a primary survey-based community assessment.

9 Future Research Directions

In further investigations, detailed simulation-based validation using advanced microgrid optimization software and operational data should be included. Multiple rural communities and/or different conditions for renewable resources would enhance the generalizability of findings. There is also scope to investigate further hybrid renewable integration solutions, energy management systems, optimization of battery degradation and financing solutions in

order to deploy large-scale rural electrification. Furthermore, future research should aim to understand how the community can be involved in the system and the policy frameworks that can facilitate long-term sustainability and uptake of decentralized renewable microgrid systems.

Reference

- Abdelhady, S. (2021). Performance and cost evaluation of solar dish power plant: sensitivity analysis of levelized cost of electricity (LCOE) and net present value (NPV). *Renewable Energy*, 168, 332-342.
- Ahmad, S., Shafiullah, M., Ahmed, C. B., & Alowaifeer, M. (2023). A review of microgrid energy management and control strategies. *IEEE Access*, 11, 21729-21757.
- Al-Ghussain, L., Abubaker, A. M., & Ahmad, A. D. (2021). Superposition of renewable-energy supply from multiple sites maximizes demand-matching: Towards 100% renewable grids in 2050. *Applied Energy*, 284, 116402.
- Ali, M., Riaz, M., Koondhar, M. A., Akram, M. S., Guerrero, J. M., Vasquez, J. C., & Khan, B. (2023). Renewable energy sources-based hybrid microgrid system for off-grid electricity solution for rural communities. *Energy Science & Engineering*, 11(10), 3486-3499.
- Ali, W., Farooq, H., Rehman, A. U., Awais, Q., Jamil, M., & Noman, A. (2018). Design considerations of stand-alone solar photovoltaic systems. 2018 International conference on computing, electronic and electrical engineering (ICE Cube),
- Anvari, M., Proedrou, E., Schäfer, B., Beck, C., Kantz, H., & Timme, M. (2022). Data-driven load profiles and the dynamics of residential electricity consumption. *Nature communications*, 13(1), 4593.
- Asghar, N., Amjad, M. A., Ur Rehman, H., Munir, M., & Alhadj, R. (2022). Achieving sustainable development resilience: Poverty reduction through affordable access to electricity in developing economies. *Journal of cleaner production*, 376, 134040.
- Azeem, F., Narejo, G. B., & Shah, U. A. (2020). Integration of renewable distributed generation with storage and demand side load management in rural islanded microgrid. *Energy Efficiency*, 13(2), 217-235.
- Aziz, M. S., Khan, M. A., Khan, A., Nawaz, F., Imran, M., & Siddique, A. (2020). Rural electrification through an optimized off-grid microgrid based on biogas, solar, and hydro power. 2020 International Conference on Engineering and Emerging Technologies (ICEET),
- Banguero, E., Correcher, A., Pérez-Navarro, Á., Morant, F., & Aristizabal, A. (2018). A review on battery charging and discharging control strategies: Application to renewable energy systems. *Energies*, 11(4), 1021.
- Belrzaeg, M., Sif, M., Almabsout, E., & Benisheikh, U. A. (2023). Distributed generation for Microgrid technology. *International Journal of Scientific Research Updates*, 6(1), 083-092.
- Bhattacharyya, S. C., & Palit, D. (2016). Mini-grid based off-grid electrification to enhance electricity access in developing countries: What policies may be required? *Energy Policy*, 94, 166-178.
- Boateng, E. (2016). The potential socio-economic and environmental impacts of solar PV mini-grid deployment on local communities: A case study of rural island communities on the Volta Lake, Ghana.
- Bonan, J., Pareglio, S., & Tavoni, M. (2017). Access to modern energy: a review of barriers, drivers and impacts. *Environment and Development Economics*, 22(5), 491-516.
- Byrne, R. H., Nguyen, T. A., Copp, D. A., Chalamala, B. R., & Gyuk, I. (2017). Energy management and optimization methods for grid energy storage systems. *IEEE Access*, 6, 13231-13260.
- Chatterjee, A. (2020). A conceptual framework to improve the design of sustainable off-grid microgrid systems for remote communities in developing countries [Open Access Te Herenga Waka-Victoria University of Wellington].

- Datta, U., Kalam, A., & Shi, J. (2021). A review of key functionalities of battery energy storage system in renewable energy integrated power systems. *Energy Storage*, 3(5), e224.
- Ejuh Che, E., Roland Abeng, K., Iweh, C. D., Tsekouras, G. J., & Fopah-Lele, A. (2025). The impact of integrating variable renewable energy sources into grid-connected power systems: Challenges, mitigation strategies, and prospects. *Energies*, 18(3), 689.
- Evalina, N., Pasaribu, F. I., & Azis, A. (2021). The Use of Inverters in Solar Power Plants for Alternating Current Loads. *Britain International of Exact Sciences (BloEx) Journal*, 3(3), 151-158.
- Gertler, P. J., Lee, K., & Mobarak, A. M. (2017). Electricity reliability and economic development in cities: A microeconomic perspective.
- He, Y., Li, X., Huang, P., & Wang, J. (2022). Exploring the road toward environmental sustainability: natural resources, renewable energy consumption, economic growth, and greenhouse gas emissions. *Sustainability*, 14(3), 1579.
- Henckes, P., Knaut, A., Obermüller, F., & Frank, C. (2018). The benefit of long-term high resolution wind data for electricity system analysis. *Energy*, 143, 934-942.
- Ibegbulam, M., Adeyemi, O., & Fogbonjaiye, O. (2023). Adoption of Solar PV in developing countries: challenges and opportunity. *International Journal of Physical Sciences Research*, 7(1), 36-57.
- Johnson, E., & Musah, M. Hybrid Renewable Energy Systems for Resilient Smart Homes and Connected Communities.
- Kamal, M. M., Ashraf, I., & Fernandez, E. (2023). Planning and optimization of standalone microgrid with renewable resources and energy storage. *Energy Storage*, 5(1), e395.
- Khalid, M., AlMuhaini, M., Aguilera, R. P., & Savkin, A. V. (2018). Method for planning a wind-solar-battery hybrid power plant with optimal generation-demand matching. *IET Renewable Power Generation*, 12(15), 1800-1806.
- Khan, I. (2020). Impacts of energy decentralization viewed through the lens of the energy cultures framework: Solar home systems in the developing economies. *Renewable and Sustainable Energy Reviews*, 119, 109576.
- Liu, L., Wang, Z., Wang, Y., Wang, J., Chang, R., He, G., Tang, W., Gao, Z., Li, J., & Liu, C. (2020). Optimizing wind/solar combinations at finer scales to mitigate renewable energy variability in China. *Renewable and Sustainable Energy Reviews*, 132, 110151.
- López-Castrillón, W., Sepúlveda, H. H., & Mattar, C. (2021). Off-grid hybrid electrical generation systems in remote communities: Trends and characteristics in sustainability solutions. *Sustainability*, 13(11), 5856.
- Michael, I. (2025). High Deployment Costs vs. Low Population Density.
- Okesiji, S. O. (2025). Decentralized renewable energy systems: A pathway to climate resilience in low-income regions. *Sustainability and Climate Change*, 18(2), 119-131.
- Pandžić, H., & Bobanac, V. (2018). An accurate charging model of battery energy storage. *IEEE Transactions on Power Systems*, 34(2), 1416-1426.
- Patnaik, R. K., Bharathi, P. S., Mathiyalagan, S., Thumma, R., Saravanan, G., Alanazi, M., Sivaraman, V., Elfakhany, A., & Belay, A. (2022). The potential role of PV solar power system to improve the integration of electric energy storage system. *International Journal of Photoenergy*, 2022(1), 8735562.
- Patwary, A. K., Sayem, M. A., Hossain, M. A., & Halim, M. A. (2024). A review of energy storage systems (ESS) for integrating renewable energies in microgrids. *Control Systems and Optimization Letters*, 2(1), 103-112.
- Powell, J. W., Welsh, J. M., & Freebairn, J. (2019). The economics of integrating alternative energy: A farm

- case study at Emerald, Queensland. *Australian Farm Business Management Journal*, 16, 1-16.
- Rushman, J. F., Thanarak, P., Artkla, S., & Maneechot, P. (2019). Electrical power demand assessment of a rural community and the forecast of demand growth for rural electrification in Ghana. *International energy journal*, 19(1).
- Sajwani, H. A., Soudan, B., & Olabi, A. G. (2023). Comprehensive review of socio-economic costs and benefits, policy frameworks, market dynamics, and environmental implications of microgrid development in the UAE. *Energies*, 17(1), 70.
- Sampaio, P. G. V., & González, M. O. A. (2017). Photovoltaic solar energy: Conceptual framework. *Renewable and Sustainable Energy Reviews*, 74, 590-601.
- Shafiei, K., Seifi, A., & Hagh, M. T. (2025). A novel multi-objective optimization approach for resilience enhancement considering integrated energy systems with renewable energy, energy storage, energy sharing, and demand-side management. *Journal of Energy Storage*, 115, 115966.
- Shahzad, S., Abbasi, M. A., Ali, H., Iqbal, M., Munir, R., & Kilic, H. (2023). Possibilities, challenges, and future opportunities of microgrids: A review. *Sustainability*, 15(8), 6366.
- Singh, R., & Powar, V. (2024). The future of Generation, Transmission, and distribution of electricity. In *The Advancing World of Applied Electromagnetics: In Honor and Appreciation of Magdy Fahmy Iskander* (pp. 349-383). Springer.
- Talluri, G., Lozito, G. M., Grasso, F., Iturrino Garcia, C., & Luchetta, A. (2021). Optimal battery energy storage system scheduling within renewable energy communities. *Energies*, 14(24), 8480.
- Viteri, J. P., & Henao, F. (2023). A human-centered approach to regional off-grid electrification budgeting: the Colombian case. *Sustainability: Science, Practice and Policy*, 19(1), 2217043.
- Wang, C.-Y., Liu, T., Yang, X.-G., Ge, S., Stanley, N. V., Rountree, E. S., Leng, Y., & McCarthy, B. D. (2022). Fast charging of energy-dense lithium-ion batteries. *Nature*, 611(7936), 485-490.
- Zaheb, H., Bakhtiary, A. R., Abdullah, M. A., Ahmadi, M., Rahmany, N. A., Obaidi, O., & Yona, A. (2026). Economic Analysis and Policy Reform Strategies for Decentralized Solar PV in Rural Electrification. *Sustainability*, 18(7), 3275.