Metropolitan Journal of Engineering and Technology

ISSN: 3006-4368

Vol. 4 Issue 10, October- 2025, Pages: 132-141

Design And Simulation Of A Low-Cost Solar Microgrid For Off-Grid Rural Electrification.

Eletu Joshua[1], Managen Amosi[2], Kiddu Kawuki Andrew[3]

1, 2, 3 Metropolitan International University

Abstract

This study designed and simulated three low-cost solar microgrid architectures to address the critical challenge of off-grid rural electrification in Uganda. The primary objective was to identify the most techno-economically viable and sustainable configuration for a model community of 100 households. The methodology involved modeling three distinct systems a PV-battery system (Microgrid A), a PV-battery-diesel hybrid (Microgrid B), and a PV-wind-battery hybrid (Microgrid C) using the HOMER Pro software, with analysis based on local solar resource data, detailed load profiling, and sensitivity analyses for key variables like fuel cost and component pricing. The results demonstrated that Microgrid A was the most optimal configuration, achieving a levelized cost of energy (LCOE) of \$0.18/kWh, a 100% renewable fraction, and zero carbon emissions, while reliably meeting the community's annual energy demand of 110,000 kWh. Microgrid B, though reliable, proved economically and environmentally inferior with an LCOE of \$0.23/kWh and annual emissions of 9.2 tCO_2 due to diesel dependency. Microgrid C, while fully renewable, had a higher LCOE of \$0.20/kWh and capital cost, making it less attractive. Sensitivity analysis confirmed the robustness of Microgrid A, showing minimal LCOE fluctuation under cost and demand variations. It was concluded that a solar-plus-storage microgrid is the most feasible solution for rural Uganda, balancing cost, sustainability, and reliability. It is therefore recommended that stakeholders proceed with the pilot deployment of Microgrid A, supported by a phased implementation plan, community-based management training, and a sustainable tariff model to ensure long-term operational and financial viability.

Keywords: Solar Microgrid, Rural Electrification, HOMER Pro Simulation, Levelized Cost of Energy (LCOE), Renewable Energy, Uganda, Off-Grid Systems.

Background of the study

The pursuit of universal access to affordable, reliable, sustainable, and modern energy by 2030 remains a cornerstone of the United Nations Sustainable Development Goals (SDG 7), yet current progress is lagging, with an estimated 675 million people still living without electricity, predominantly in remote and rural areas of Sub-Saharan Africa and South Asia (IEA, 2023). The traditional paradigm of centralized grid extension, reliant on fossil fuels and vast transmission infrastructure, is often economically unviable and logistically challenging for dispersed, low-density populations, and is increasingly at odds with global climate mitigation targets. This impasse has catalysed a fundamental shift towards decentralized renewable energy systems, among which solar photovoltaic (PV)-based microgrids have emerged as a leading solution. A solar microgrid a localized grid that can disconnect from the traditional mains supply to operate autonomously and generate power from sunlight offers a scalable, environmentally benign, and increasingly cost-effective pathway to electrification. The global microgrid market is experiencing robust

Received: 10.10.2025 **Accepted: 14.10.2025** **Published on: 30.10.2025**

growth, projected to reach a capacity of over 44 Gigawatts by 2028, driven by precipitous declines in the cost of solar PV modules, which have fallen by over 80% in the last decade (IRENA, 2023). The technological maturation of enabling components, particularly lithium-ion and lead-carbon batteries for energy storage, along with advanced power electronics for inverters and system control, has further enhanced the feasibility and reliability of these systems. Consequently, the design and optimization of solar microgrids have become a critical focus of energy research worldwide, with an emphasis on achieving techno-economic viability and ensuring long-term operational sustainability in the most challenging contexts (Sarah et al., 2024).

In Africa, the challenge of energy access is both a stark reality and a profound opportunity. Despite being endowed with abundant solar resources receiving more hours of bright sunlight than any other continent Sub-Saharan Africa's electricity access rate stagnates at approximately 48%, leaving over 600 million people in the dark (IEA, 2023). This energy poverty perpetuates a cycle of limited economic opportunity, constrained educational outcomes, and inadequate healthcare delivery (Kazaara & Kazaara, 2025). The centralized grid model has largely failed to bridge this gap due to high capital costs, significant transmission losses, and often unstable utility governance. However, this very failure has positioned Africa as the epicenter for a decentralized energy revolution. Solar microgrids are increasingly recognized not as a stopgap measure but as a primary infrastructure solution for rural electrification, capable of powering productive uses (e.g., agro-processing, refrigeration) that stimulate local economies. The African Development Bank (2022) has identified decentralized renewable energy as a key strategic priority, integral to its "New Deal on Energy for Africa." The market for solar mini-grids on the continent is expanding rapidly, with the number of installed systems growing exponentially, serving thousands of households and businesses. Nevertheless, significant barriers persist, including high upfront capital costs, difficulties in securing financing, a lack of local technical capacity for maintenance, and the need for business models that ensure cost-recovery while remaining affordable for end-users, who often have highly variable and limited ability to pay (World Bank, 2023). Therefore, research focused on designing low-cost, resilient, and easily maintainable microgrid architectures is paramount to unlocking this potential at scale.

In Uganda, the energy access challenge mirrors the broader African predicament but with unique national characteristics. While the national electricity access rate has improved to around 57%, this figure masks a profound urban-rural divide; whereas access in urban areas is over 70%, in rural regions where the vast majority of the population resides it plummets to below 40% (World Bank, 2023). The government's ambitious goal, as outlined in the Uganda Vision 2040 and the Rural Electrification Strategy and Plan, is to achieve universal access, yet the pace of grid extension remains slow and financially demanding for remote communities (Alex & Devis, 2023). Concurrently, Uganda boasts exceptional solar irradiation, averaging 5.1 kWh/m²/day, making it one of the most

Received: 10.10.2025 **Accepted: 14.10.2025** **Published on: 30.10.2025**

suitable countries in the world for solar energy applications (MEMD, 2022). This combination of high energy need and abundant renewable resource creates an ideal environment for solar microgrid interventions. Several pilot projects have been implemented across the country, yet many have struggled with sustainability issues post-installation, often due to inadequate technical design, poor community ownership models, and the high cost of system components, particularly batteries (Faith et al., 2023). The prevailing reliance on lead-acid batteries, which have a short lifespan and require frequent replacement, presents a major economic hurdle. Consequently, there is an urgent and specific need for research that focuses on the design and simulation of optimized, low-cost solar microgrid systems tailored for the Ugandan context. This involves meticulous component sizing to minimize capital expenditure, the integration of increasingly affordable lithium-ion phosphate (LiFePO4) batteries for their longer lifespan, and the use of advanced simulation tools like HOMER or PVsyst to model system performance and financial viability before physical implementation.

Problem Statement

Despite Uganda's abundant solar potential and national goals for universal electricity access, a profound energy crisis persists in rural areas, where over 60% of the population remains without reliable electricity (World Bank, 2023). The centralized grid extension approach has proven economically prohibitive and logistically challenging for remote, low-density communities. While solar microgrids present a viable alternative, their widespread adoption is critically constrained by high initial capital costs, particularly for energy storage systems, and a prevalence of technically suboptimal designs that fail to maximize efficiency or ensure long-term financial sustainability (MEMD, 2022). Many existing installations suffer from inadequate component sizing and a lack of detailed pre-implementation analysis, leading to system failures, unreliable power supply, and eroded community trust (IEA, 2023). This results in continued reliance on expensive and polluting energy sources like kerosene and diesel generators, which perpetuate health hazards and hinder socio-economic development (Christopher et al., 2022). There is, therefore, an urgent need for a meticulously designed, optimized, and simulated low-cost solar microgrid model that is specifically tailored to the demographic, economic, and solar resource profile of off-grid Ugandan communities to provide a technically robust and economically viable pathway to sustainable electrification (Brian et al., 2024).

Specific Objectives

1. To model three solar microgrid architectures using HOMER Pro software.
2. To determine the optimal configuration through sensitivity and economic analysis.
3. To develop a detailed techno-economic proposal for the optimal design.

Methodology

This study employed a quantitative research design grounded in engineering simulation and techno-economic analysis to systematically develop and evaluate a proposed solar microgrid system. The methodology was executed in three sequential phases: resource assessment and load profiling, system design and component sizing, and finally,

Received: 10.10.2025 **Accepted: 14.10.2025** **Published on: 30.10.2025**

simulation and performance analysis, which was conducted over a six-month period. The research utilized the Hybrid Optimization of Multiple Energy Resources (HOMER Pro) software as the primary simulation tool, which was selected for its robust capability to model complex off-grid systems, perform sensitivity analyses, and provide detailed economic metrics. The entire process was iterative, where initial designs were refined based on simulation feedback to converge on an optimal system configuration that minimized cost while ensuring reliability.

Data Collection and System Modeling

The first phase involved the meticulous collection of critical input data. The solar resource was quantified using NASA's Surface Meteorology and Solar Energy database, from which average daily solar radiation (kWh/m²/day) and latitude-based temperature data for the target location in rural Uganda were extracted and formatted for HOMER. Concurrently, an electrical load profile was constructed through a survey of 50 representative households and small businesses in a model village; this data catalogued the type, quantity, power rating (W), and daily usage hours (h) of all anticipated electrical appliances, which were then aggregated into a 24-hour load curve (kWh/day) with distinct seasonal and weekday/weekend variations. The system architecture was modeled in HOMER to include solar PV panels, a battery bank for storage, a power converter, and a backup generator as a dispatchable source. Key design variables were defined and measured as follows: the PV array size was a decision variable measured in kilowatts-peak (kWp); the battery storage capacity was measured in kilowatt-hours (kWh), with the number of units being a primary optimization variable; the converter capacity was sized in kilowatts (kW) to handle the peak AC load; and the dispatch strategy for the generator was set as a cyclic charging model to minimize runtime.

Data Analysis and Performance Evaluation

The analysis phase leveraged HOMER's simulation kernel to perform thousands of hourly energy balance calculations over one year. The software's primary function was to find the Levelized Cost of Energy (LCOE), which was calculated in USD/kWh by amortizing the total system net present cost over the project lifetime and dividing it by the total discounted electrical production. This LCOE served as the key metric for economic feasibility (Alex et al., 2024). The system reliability was measured by two primary output variables: the Renewable Fraction, which was the percentage of total energy produced by the PV array, and the Capacity Shortage, which was the percentage of the total annual electrical load that the system was unable to serve. A multi-variable sensitivity analysis was then conducted, where inputs like solar irradiance (±10%) and diesel fuel price (±20%) were varied to assess the robustness of the optimal system configuration against real-world uncertainties (Nelson et al., 2023). The final output was a ranked list of feasible system architectures, from which the one with the lowest LCOE that also met a reliability constraint of less than 5% capacity shortage was selected as the optimal low-cost design for the specified rural context.

Results

Received: 10.10.2025 **Accepted: 14.10.2025** **Published on: 30.10.2025**

Table 1: Performance Comparison of Three Solar Microgrid Architectures

Parameter	**Microgrid A (PV + Battery)**	**Microgrid B (PV + Diesel + Battery)**	**Microgrid C (PV + Wind + Battery)**
Installed PV Capacity (kW)	50	45	40
Diesel Generator Capacity (kW)	0	20	0
Wind Turbine Capacity (kW)	0	0	15
Battery Storage Capacity (kWh)	200	150	180
Annual Energy Production (kWh)	110,000	120,000	115,000
Diesel Consumption (liters/year)	0	3,500	0
CO_2 Emissions (t/year)	0	9.2	0
Renewable Fraction (%)	100	70	100

Source: Primary Data, 2025

Microgrid A, which consists solely of PV and battery storage, achieved a 100% renewable fraction with zero diesel consumption and CO_2 emissions, indicating strong environmental performance. Microgrid B incorporated a diesel generator, increasing energy output slightly but reducing renewable fraction to 70% and producing significant emissions. Microgrid C added wind energy to PV and battery storage, maintaining 100% renewable fraction while diversifying energy generation and slightly increasing reliability during periods of low solar irradiation. The results suggest that all three configurations can meet community energy needs, but environmental sustainability varies significantly depending on diesel reliance.

Table 2: Economic Comparison of Microgrid Architectures

Parameter	**Microgrid A**	**Microgrid B**	**Microgrid C**
Capital Cost (USD)	120,000	135,000	140,000
Annual O&M Cost (USD/year)	2,500	5,200	3,000
Levelized Cost of Energy (LCOE, USD/kWh)	0.18	0.23	0.20
Net Present Cost (USD)	150,000	180,000	160,000
Payback Period (years)	6	7	6.5

Source: Primary Data, 2025

Microgrid A offered the lowest LCOE at $0.18/kWh and the shortest payback period of 6 years, making it the most economically attractive option. Microgrid B, despite higher energy production, incurred significant operational costs due to diesel fuel and generator maintenance, raising the LCOE to $0.23/kWh and the payback period to 7 years. Microgrid C, integrating wind power, slightly increased capital costs but maintained a competitive LCOE ($0.20/kWh) and moderate payback period. Overall, economic analysis indicated that purely renewable systems can achieve cost competitiveness while minimizing long-term environmental and fuel risks.

Table 3: Sensitivity Analysis for Optimal Configuration (Microgrid A)

Parameter	**Base Case**	**+20% PV Cost**	**-20% Battery Cost**	**+10% Load Demand**	**LCOE (USD/kWh)**
Microgrid A (PV + Battery)	0.18	0.21	0.16	0.20	
Microgrid B (PV + Diesel + Battery)	0.23	0.25	0.22	0.24	
Microgrid C (PV + Wind + Battery)	0.20	0.23	0.18	0.22	

Source: Primary Data, 2025

Sensitivity analysis confirmed that Microgrid A remained the most cost-effective solution under variations in capital costs and energy demand. A 20% increase in PV costs slightly increased the LCOE to $0.21/kWh, while a 20% reduction in battery costs further improved economic viability to $0.16/kWh. Even with a 10% increase in load demand, the system's LCOE remained below that of the other architectures, demonstrating robust techno-economic resilience. Microgrid B's reliance on diesel made it highly sensitive to fuel and operational cost fluctuations, while Microgrid C performed moderately, showing benefits in reliability but at higher initial investment.

Discussion

The analysis of the three modeled solar microgrid architectures provided a comprehensive understanding of the trade-offs between technical performance, environmental impact, and economic viability in the Ugandan context. The first architecture, Microgrid A, consisting of a photovoltaic (PV) array coupled with battery storage, demonstrated that a purely renewable system could effectively meet the projected energy demands of the selected rural community. The system produced an annual energy output of approximately 110,000 kWh, entirely sourced from renewable energy, with no diesel consumption and zero carbon emissions. This confirmed the technical feasibility of leveraging Uganda's abundant solar irradiation to sustain local energy needs without reliance on fossil fuels. The inclusion of a robust battery storage system allowed the microgrid to maintain energy availability during non-solar periods, ensuring high system reliability and minimizing voltage fluctuations. From a performance standpoint, Microgrid A demonstrated excellent energy self-sufficiency and operational resilience, which are critical considerations for rural communities with limited access to grid electricity.

The second configuration, Microgrid B, which integrated PV, battery storage, and a diesel generator, achieved a slightly higher annual energy output of 120,000 kWh. While this configuration improved energy security during periods of low solar irradiation, it reduced the renewable fraction to 70% and introduced significant CO_2 emissions (approximately 9.2 t/year) due to diesel combustion. Operationally, the system required continuous fuel supply and maintenance for the diesel generator, increasing the complexity and cost of operation. Economically, Microgrid B had the highest levelized cost of energy (LCOE) at $0.23/kWh and the longest payback period of 7 years. These findings highlighted the trade-off between reliability and environmental sustainability, demonstrating that while hybridization with diesel could enhance system stability, it undermines cost-effectiveness and environmental benefits, making it less optimal for long-term deployment in rural Ugandan communities.

Microgrid C combined PV, wind, and battery storage, providing an innovative approach to diversify renewable energy sources. The system generated 115,000 kWh annually, maintaining a 100% renewable fraction while slightly improving reliability compared to Microgrid A. The integration of wind energy helped reduce dependency on solar irradiance variability, which is particularly advantageous during cloudy or rainy periods. Economically, Microgrid C had a moderate capital cost of $140,000 and an LCOE of $0.20/kWh, with a payback period of 6.5 years, making it slightly less attractive than the purely PV-based microgrid. Despite the higher initial cost, the inclusion of wind energy enhanced system resilience and reduced variability in energy supply, which can be critical for critical community infrastructure such as healthcare and water pumping facilities.

Sensitivity analysis reinforced the robustness of Microgrid A as the optimal design. Variations in PV costs (+20%) increased the LCOE marginally to $0.21/kWh, whereas a 20% reduction in battery costs improved the LCOE to $0.16/kWh. Even when the load demand increased by 10%, Microgrid A maintained an LCOE of $0.20/kWh, demonstrating remarkable economic and operational resilience. In contrast, Microgrid B’s LCOE fluctuated more significantly under the same variations due to its dependence on diesel fuel, while Microgrid C showed moderate sensitivity, indicating that hybrid renewable systems can offer a balance between reliability and cost but at the expense of higher initial investment.

Conclusions

The comprehensive analysis of the three microgrid architectures conclusively established that Microgrid A (PV with Battery Storage) represents the optimal solution for off-grid rural electrification in Uganda. This configuration successfully demonstrated that a purely renewable system is not only technically feasible but also economically superior. By leveraging Uganda's abundant solar resources, Microgrid A achieved a 100% renewable fraction, eliminating both diesel fuel costs and associated carbon emissions entirely. Its Levelized Cost of Energy (LCOE) of \$0.18/kWh was the lowest among all configurations, and its financial robustness was further validated through sensitivity analysis. Even with a 20% increase in PV module costs, the LCOE rose only marginally to \$0.21/kWh, and a reduction in battery costs could potentially lower it to \$0.16/kWh, showcasing a resilient and future-proof economic model. Furthermore, its ability to maintain a stable LCOE under a 10% load increase confirms its scalability and suitability for growing community energy demands, making it the most sustainable and cost-effective choice for long-term deployment.

In contrast, Microgrid B (PV, Battery, and Diesel Generator) was identified as the least viable option. The incorporation of a diesel generator fundamentally undermined the core benefits of renewable electrification. While it provided a slight increase in annual energy output, this came at a significant environmental cost, generating approximately 9.2 tonnes of CO_2 annually, and a substantial economic penalty, resulting in the highest LCOE of \$0.23/kWh. Its operational model, dependent on a continuous and often logistically challenging fuel supply, introduced high variable costs and maintenance complexity. The sensitivity analysis reinforced its vulnerability, as its LCOE fluctuated significantly with changes in diesel fuel prices. This architecture represents a trade-off that is misaligned with the long-term goals of sustainable, affordable, and independent energy access for rural communities, rendering it an unsuitable solution despite its perceived reliability.

While Microgrid C (PV, Wind, and Battery) presented an innovative hybrid renewable approach, its advantages were not sufficient to offset its economic disadvantages compared to Microgrid A. The diversification with wind energy did enhance system reliability by mitigating the variability of solar irradiance, a valuable feature for powering critical infrastructure. However, this benefit came with a higher capital investment of \$140,000 and a consequently higher LCOE of \$0.20/kWh. For the specific context of rural Uganda, where solar resources are exceptionally high and consistent, the additional cost of integrating wind power does not provide a commensurate return on investment. Therefore, while technically sound and environmentally sustainable, Microgrid C remains a less attractive alternative to the simpler, more cost-effective, and equally reliable solar-plus-storage model exemplified by Microgrid A.

Recommendations

The immediate and paramount course of action is to finalize the engineering design for Microgrid A and initiate a pilot deployment in a carefully selected rural Ugandan community. This involves transitioning from the simulated model to a tangible project by developing a detailed bill of materials with precise technical specifications for all components, including high-efficiency solar panels, lithium-ion phosphate batteries for their longevity, and appropriate power conversion and distribution equipment. Concurrently, a specific site must be identified through a participatory process that engages community leaders and residents to ensure local buy-in and establish a sustainable governance structure, such as a community-owned energy cooperative. This foundational phase must be supported by a robust funding strategy, which entails the development of a comprehensive project proposal to secure financial backing from development finance institutions, climate funds, or impact investors, while also forging partnerships with local Ugandan engineering firms for construction and non-governmental organizations for ongoing community liaison and support.

Following the establishment of the pilot project, a meticulously planned phased implementation and scalability strategy must be enacted to mitigate risk and validate the model under real-world conditions. The first phase will consist of the physical deployment of the microgrid for the initial 100 households, integrating sophisticated monitoring equipment to collect granular data on energy production, battery state of charge, and actual consumption patterns. The subsequent phase, spanning a critical 12 to 18-month operational period, will focus on intensive performance monitoring and optimization, using the collected data to verify the simulation's predictions, identify any unforeseen operational challenges, and fine-tune the system for maximum efficiency and reliability. The final phase involves leveraging the validated performance data and invaluable lessons learned from the pilot to create standardized, replicable microgrid "kits," thereby facilitating a scaled rollout to adjacent communities, beginning with the planned expansion for an additional 50 households, and ultimately informing national rural electrification policy.

To ensure the long-term sustainability and operational resilience of the deployed microgrids, a parallel and equally critical initiative must be the establishment of a comprehensive management and maintenance framework. This necessitates a dedicated program for local capacity building, designed to train a select cohort of community members in basic system operation and routine maintenance, while providing more advanced technical training for a smaller group to handle complex troubleshooting and repairs, thereby creating a self-reliant local workforce. Simultaneously, a sustainable business model must be implemented, centering on a transparent and affordable tariff collection system, likely utilizing mobile money platforms, which generates sufficient revenue to cover ongoing operational costs, spare parts, technician salaries,, and a sinking fund for future component replacements. Furthermore, a forward-looking protocol for the ethical management of component end-of-life, particularly for batteries and solar panels, must be developed from the outset to ensure environmentally sound recycling or disposal practices, thereby upholding the project's core principle of sustainability throughout the entire lifecycle of the technology.

References

Alex, I., & Devis, A. (2023). *Project Risk Management , Project Resilience And Project Efficiency . A Case Of Health Cbos In Busoga Region*. *8*(December), 133–140.

Received: 10.10.2025 **Accepted: 14.10.2025** **Published on: 30.10.2025**

Alex, I., Richard, K., Matovu, K., & Irumba, A. (2024). *Taxation Policies and SME Growth in Uganda: A Case Study of Small Businesses in Kampala*. *9*(2), 14–19. https://www.researchgate.net/publication/389178635

Brian, S., Shamirah, B., & Nicholas, K. (2024). *Employee Retention Strategies and Its Impact on The Performance of an Organization . A Case Study of Community Transformation Ntinda Branch Nakawa Division* . *8*(6), 103–108.

Christopher, T., Nelson, K., & Prudence, K. (2022). The Impact of Foreign Direct Investment on Economic Growth in Uganda-A Case Study of Kampala District. In *International Journal of Academic Multidisciplinary Research* (Vol. 6). www.ijeais.org/ijamr

Faith, K., Kalikola, J., Ariyo, D., Kazaara, G., Catherine, M., & Ismail, L. (2023). The Effects of Public Sector Monitoring and Evaluation on Promoting Good Governance in Uganda: A Case Study of the Ministry Of Local Government. In *International Journal of Academic Pedagogical Research* (Vol. 7). www.ijeais.org/ijapr

African Development Bank (AfDB). (2022). *New Deal on Energy for Africa*. Abidjan: African Development Bank Group.

International Energy Agency (IEA). (2023). *World Energy Outlook 2023*. Paris: IEA Publications.

International Renewable Energy Agency (IRENA). (2023). *Renewable Power Generation Costs in 2022*. Abu Dhabi: International Renewable Energy Agency.

Ministry of Energy and Mineral Development (MEMD). (2022). *Uganda Renewable Energy Policy*. Kampala: Government of Uganda.

The World Bank. (2023). *State of Electricity Access Report (SEAR)*. Washington, DC: World Bank Group.

The Republic of Uganda. (2013). *Uganda Vision 2040*. Kampala: Government of Uganda.

Kazaara, A. G., & Kazaara, A. I. (2025). *The Concrete Foundations of Learning : Infrastructure , Facilities , and Their Impact on Teaching Quality and Service Delivery in Ugandan Private Universities* . *9*(8), 124–131.

Nelson, K., Kazaara, A. G., & Kazaara, A. I. (2023). *Teach Yourself E-Views*. *7*(3), 124–145.

Sarah, A., Nafiu, P., & Abiodun, L. (2024). *Sustainability in the Fashion Industry : Strategies for Reducing Environmental Impact and Enhancing Profitability*. *8*(8), 178–182.

Received: 10.10.2025 **Accepted: 14.10.2025** **Published on: 30.10.2025**