Ndejje University Journal Of Interdisciplinary Studies,
Volume 2, Issue 2 (October 2026)
eISSN:3079-7683 **DOI:** https://doi.org/10.64080/ndujis.2026.2.2.Oct010

Evaluating the effect of productive use of energy of optimal mini-grids and sizing in rural areas of Uganda

[1]David Kibirige, Faculty of Engineering and survey, Ndejje University, Kibirigedavid06@gmail.com, dkibirige@ndejjeuniversity.ac.ug, ORCID: 0009-0005-3357-5606
[2]Bob Rich Mwecumi, Faculty of Engineering and survey, Ndejje University abooki2014@gmail.com, ORCID: 0009-0009-44998-9888
[3]Shaban Ronald Onencan, Mbarara University Science and Technology, Faculty of Applied science and Technology, shabanronald9@gmail.com, 2026mbme013@std.must.ac.ug, ORCID: 0009-0006-2000-7893
[4]David Makumbi Faculty of Engineering and survey, Ndejje University makumbidavid92@gmail.com, ORCID: 0009-0002-0129-6096
[5]Ruth Kanyana, Kampala International University, School of Natural and Applied Sciences, kanyanaruth@gmail.com, ORCID: 0000-0002-5353-5047
[6]Isaac kitone kitonei@gmail.com, ikitone@kab.ac.ug, Kabale university, Faculty of Engineering, Technology, Applied Design and fine Art, ORCID: 0000-0003-2856-090X
[7]Hannington Kolokolo, hanningtonkolokolo@gmail.com, Kampala International University, School of Natural and Applied Sciences, ORCID: 0009-0005-2808-2110

Abstract

Access to reliable electricity remains a critical challenge in rural Uganda, where approximately 58% of the population lacks grid connectivity, constraining socio-economic progress. This study evaluates the effect of productive use of energy (PUE) through optimally sized solar mini-grids in rural Uganda, using a case study in Kasanje Sub-County, Entebbe Municipality. Employing a mixed-methods approach underpinned by a cross-sectional design, the study integrated questionnaire surveys of 25 business operators, field observation of 12 energy-consuming enterprises, and simulation using PVsyst v7.4.7. A 720 kWp standalone photovoltaic-battery mini-grid, designed to supply 4,000 kWh per day, was modelled and validated. Results indicate that solar mini-grid power costs approximately UGX 322 per kWh compared to UGX 575 per kWh for utility power over 20 years, a saving of over 44%. The system achieved a Solar Fraction of 95.54% and a Performance Ratio of 77.86%, confirming technical viability. Productive use of energy extended business operating hours by 50%, significantly boosting milling and processing output. The study concludes that optimally designed solar mini-grids can catalyse economic growth, improve access to education, healthcare, and clean water, and contribute to Uganda's national electrification targets, provided they are supported by appropriate policy incentives, financing mechanisms, and community capacity-building programmes.

Keywords: Mini-grids, productive use of energy, rural electrification, solar photovoltaic, Uganda, PVsyst simulation, Kasanje Sub-County

How to cite this article:
Kibirige, D., et. al. (2026). Evaluating the effect of productive use of energy of optimal mini-grids and sizing in rural areas of Uganda. Ndejje University Journal of Interdisciplinary, Vol 2 (2), DOI: https://doi.org/10.64080/ndujis.2026.2.2.Oct010

Introduction and Background

Access to reliable and affordable electricity is a fundamental driver of socio-economic development, and remains one of the most pressing developmental challenges of the 21st century. Globally, over 770 million people are without electricity access, the majority concentrated in Sub-Saharan Africa and South Asia (IEA, 2022). Energy poverty continues to undermine progress on health, education, industrialisation, and poverty alleviation across the African continent (IRENA, 2020).

In Uganda, the electricity access deficit is particularly acute. According to the Uganda Bureau of Statistics (UBOS, 2021), only approximately 42% of the population has access to electricity, with rural electrification rates lagging significantly behind urban centres. Rural and remote areas, particularly in the northern, north-eastern, and western regions, bear a disproportionate share of this burden. Communities in these regions experience chronic power shortages that stifle economic activity, constrain healthcare and education delivery, and perpetuate cycles of poverty. The magnitude of this gap underscores the urgent need for scalable, community-appropriate energy interventions.

The Uganda Electricity Transmission Company Limited (UETCL), supported by the Government of Uganda, has endeavoured to extend the national grid through substation expansion. However, the capital cost of reaching dispersed, low-density rural settlements estimated at USD 10,000 to USD 22,000 per kilometre in Sub-Saharan Africa (IRENA, 2020) renders conventional grid extension economically impractical for a significant proportion of Ugandan communities. This reality necessitates alternative energy delivery models capable of serving rural populations sustainably and affordably. Solar mini-grids have emerged globally as one of the most promising solutions to the rural electrification challenge. Mini-grids are decentralised energy systems that generate, store, and distribute electricity to localised communities, operating independently from or in conjunction with the national grid (World Bank, 2021). Driven by the dramatic 89% reduction in photovoltaic technology costs between 2010 and 2020 (IRENA, 2020), solar-based mini-grids are increasingly viable for Uganda's high-irradiation regions and are central to the country's Revised Energy Policy 2023 and Vision 2040 framework.

Central to this study is the concept of productive use of energy (PUE) the application of electricity to income-generating activities such as agro-processing, grain milling, refrigeration, welding, and small-scale manufacturing. Research consistently demonstrates that mini-grids which actively promote PUE generate significantly higher social and economic returns than those focused solely on household lighting (SE4ALL, 2021; World Bank, 2021; Ahmed & Khatun, 2018). However, the effectiveness of PUE depends critically on optimal mini-grid sizing, appropriate technology selection, and alignment with the socio-economic context of the target community.

This study investigates these dimensions in the context of Kasanje Sub-County, Entebbe Municipality an 86.5-square-mile area characterised by high solar irradiation, a predominantly agricultural economy, and significant energy access gaps. Approximately four-fifths of the sub-county remains unconnected to the national grid. This paper aims to address three core research imperatives: to evaluate the economic impacts of solar mini-grid PUE on local businesses; to assess the mini-grid's potential to improve access to education, healthcare, and clean water; and to determine the optimal sizing and technical performance of a standalone PV-battery mini-grid using PVsyst simulation.

Despite decades of investment in electricity infrastructure, approximately 58% of Uganda's population remains without grid access (UBOS, 2021), with rural communities disproportionately affected. Households and enterprises relying on kerosene lamps, diesel generators, and firewood face high energy costs while enduring inconsistent, unreliable supply. Agricultural processors, millers, welders, and retailers are unable to extend operating hours or scale production, directly suppressing income and economic resilience. Healthcare facilities without reliable power cannot maintain vaccine cold chains, operate diagnostic equipment, or provide emergency lighting directly compromising patient outcomes.

The dependent variable in this study productive use of energy is constrained by energy poverty. Where electricity is unavailable or unaffordable, productive economic activity is limited to daylight hours, manual processes, and low-value outputs. This limitation perpetuates income inequality, reduces competitiveness, and restricts community development. The national grid alone cannot close this gap within the timeframes demanded by Uganda's development agenda. Solar mini-grids, optimally designed and sized to promote productive energy use, represent a viable and evidence-based solution yet robust assessment of their performance, economic impact, and scalability in the Ugandan context remains limited. This study addresses that evidence gap by systematically evaluating mini-grid design, simulation performance, and productive energy use impact in Kasanje Sub-County.

The main Objective of this study is to evaluate the effect of productive use of energy through optimally sized solar mini-grid deployment in rural areas of Uganda, with specific reference to Kasanje Sub-County, Entebbe Municipality.
The specific Objectives include:

- To assess the economic impacts of productive energy use from solar mini-grids on local businesses in Kasanje Sub-County.
- To evaluate the potential of solar mini-grids to improve access to basic services education, healthcare, and clean water in rural Uganda.
- To determine the optimal sizing and technical performance of a standalone PV-battery mini-grid for Kasanje Sub-County using PVsyst simulation software.

Literature review

Productive Use of Energy and Mini-Grid Economic Impacts

The productive use of energy (PUE) is the applying electricity to income-generating activities that is widely identified in the literature as the primary mechanism through which electrification translates into sustained economic development. Ahmed and Khatun (2018) conducted a rigorous comparative study of mini-grid impacts on small enterprises in rural Bangladesh, documenting revenue increases of up to 35% and daily operating hour extensions of four to six hours following reliable electrification. These findings are consistent with broader evidence from Sub-Saharan Africa: SE4ALL (2021) and the World Bank (2021) both conclude that mini-grids explicitly designed to promote PUE yield substantially higher social and economic returns than systems focused solely on household lighting.

Gartland (2019) introduces an important cautionary note, however, highlighting that technical challenges that include poor maintenance, equipment failures, and inadequate operator training that can erode the productive use potential of even well-designed mini-grids. This underscores the necessity of robust system design, community engagement, and ongoing technical support frameworks, particularly in low-income rural contexts such as Uganda where maintenance capacity may be limited. The study by Ahlborg (2014) in Tanzania and Uganda identified weak institutional frameworks and limited access to capital as compounding barriers, slowing the translation of PUE potential into measurable economic outcomes. From the perspective of the present study, this confirms the theoretical and empirical basis for the PUE hypothesis and yet it also reveals a critical gap: most existing evidence derives from South Asian or East African contexts other than Uganda. This study contributes uniquely Ugandan empirical evidence to the global PUE debate.

Mini-Grids and Access to Basic Services

Access to reliable electricity is foundational to the delivery of quality public services. The World Bank (2021) and IEA (2022) both document strong correlations between electrification and improvements in healthcare outcomes, educational attainment, and access to safe water. In the health sector, electrification enables vaccine cold chains, diagnostic equipment operation, and emergency lighting are the services that are critically absent in a large proportion of Uganda's rural health facilities (UBOS, 2021). In education, reliable electricity extends effective study hours, supports digital learning tools, and improves teacher recruitment and retention in rural postings.

Akpan (2021) demonstrates that hybrid mini-grids incorporating solar PV with battery storage can provide the reliability of supply necessary to power community institutions continuously, unlike diesel-only systems subject to fuel cost volatility and supply disruptions. For water systems, solar-powered pumps and purification units represent a transformative upgrade over manual or diesel alternatives, reducing both cost and service interruption. Eberhard (2021) argues that realising these service-sector gains requires coordinated public-private investment frameworks, with clear regulatory support for mini-grid operators who serve community institutions at subsidised rates. This literature directly informs Objective 2 of the present study, which examines these potential service-sector outcomes in the Kasanje Sub-County context. A notable gap in the existing literature is the absence of integrated quantitative and qualitative assessments that capture both technical mini-grid performance and community service access impacts simultaneously.

Mini-Grid Sizing, Technical Performance, and Policy Environment

Optimal mini-grid sizing is a technically demanding task that requires accurate load assessment, appropriate technology selection, and simulation-based performance validation. PVsyst is widely regarded as the industry-standard simulation tool for standalone PV systems, endorsed by IEEE standards 1562-2021 and 1013 (Creswell & Creswell, 2018). Comparative analyses of solar panel technologies consistently favour monocrystalline silicon panels (efficiency 18–22%) for high-irradiation environments with constrained installation areas such as those characteristics of Kasanje Sub-County over polycrystalline (15–18%) or thin-film alternatives (10–12%) (IRENA, 2020). For battery storage, lithium-ion technology's superior depth of discharge (80–90%), cycle life (10–15 years), and round-trip efficiency (85–95%) make it the preferred option despite higher upfront costs relative to lead-acid alternatives (Zander & Fu, 2020).

The financing and policy environment are equally critical. Zander and Fu (2020) identify high upfront capital costs, limited access to concessional finance, and weak revenue collection as major constraints to mini-grid scale-up. Pay-as-you-go (PAYG) and results-based financing (RBF) models have demonstrated effectiveness in bridging the financing gap while preserving affordability for low-income consumers. Uganda's Revised Energy Policy 2023 commits to increasing national electricity access from 19% to 80% by 2040, designating mini-grids as a key instrument. The Rural Electrification Agency (REA) and the World Bank have supported several pilot programmes, establishing a nascent enabling environment for expanded deployment (Eberhard, 2021). However, standardised licensing frameworks and tariff regulation for mini-grid operators remain underdeveloped, creating uncertainty that deters private investment. This study's findings contribute directly to this policy debate by providing evidence-based technical benchmarks and economic assessments from a representative Ugandan mini-grid case study.

Methodology

Research Design

This study employed a cross-sectional research design where the design that collects data from a defined population at a single point in time to examine the current state of phenomena and relationships between variables (Creswell & Creswell, 2018). The cross-sectional design was appropriate for this study because it enables concurrent assessment of the technical performance characteristics of the mini-grid system and the socio-economic conditions of businesses and service facilities in Kasanje Sub-County, without requiring longitudinal tracking. Within this design, a mixed-methods approach was applied in a methodological strategy that integrates quantitative data (survey measurements, simulation outputs) with qualitative insights (stakeholder observations, contextual reporting) to achieve triangulated, rigorous findings (Creswell & Creswell, 2018). The mixed-methods approach, rather than being the design itself, served as the analytical framework through which data from multiple sources were collected, analysed, and interpreted in a complementary manner.

Study Area and Target Population

The study was conducted in Kasanje Sub-County, Entebbe Municipality, located in the south-western region of Uganda at latitude -0.13° South and longitude 30.50° East, at an altitude of 1,432 metres above sea level. The sub-county covers approximately 86.5 square miles and receives high solar irradiation throughout the year, making it well-suited for solar PV generation. Approximately 80% of the sub-county's area remains unconnected to the national electricity grid (UBOS, 2021).

The target population comprised all households, small and medium enterprises (SMEs), and community service institutions including schools, health centres, and water supply facilities located within Kasanje Sub-County. According to UBOS (2021), Kasanje Sub-County has an estimated adult population of approximately 18,500 persons, with approximately 2,400 registered business entities across agricultural processing, retail, services, and trades. The decision to focus on SMEs and community institutions was deliberate: these categories are the primary drivers of productive energy use and the principal beneficiaries of enhanced service delivery, making them the most relevant population for assessing PUE impacts.

Sample Size and Sampling Procedure

A purposive sampling approach was employed to select 25 business operators representing the principal energy-consuming enterprise categories in Kasanje Sub-County: grain millers (n = 8), welders and metal fabricators (n = 5), restaurant and food processing operators (n = 7), and retail traders (n = 5). Purposive sampling was selected because it enabled the deliberate targeting of respondents with direct, verifiable experience of energy access challenges and productive energy use the core phenomena under investigation (Creswell & Creswell, 2018). The sample of 25 respondents was determined by applying the Slovin formula [$n = N/(1+Ne^2)$] to the sub-population of approximately 120 identified energy-intensive SMEs operating within the study area at a 95% confidence level and a 5% margin of error, yielding a minimum required sample of 24 respondents, rounded to 25 for practical completeness. Additionally, six key informant interviews were conducted with community leaders and local government officials from the Kasanje Sub-County administration to contextualise findings within the local governance and infrastructure landscape.

Data Collection Methods and Instruments

Survey Method: A structured questionnaire survey was the primary quantitative data collection method, selected because it enables systematic measurement of standardised variables across multiple respondents and is widely recommended for socio-economic impact assessments in energy research (Ahmed & Khatun, 2018; Creswell & Creswell, 2018). The survey instruments a researcher-administered questionnaire that comprised 32 items structured in four sections:

i. respondent business profile and energy access history (8 items, closed-ended nominal and ordinal scales);
ii. (ii) daily energy consumption patterns and equipment ratings (10 items, interval and ratio scale measurements);
iii. (iii) business productivity and income impact of current energy access arrangements (8 items, Likert-scale and open-ended items); and
iv. (iv) willingness to pay and perceptions of solar mini-grid viability (6 items, ordinal scale). Closed-ended questions ensured quantitative comparability across respondents, while open-ended items captured qualitative contextual data not amenable to pre-coded categories.

Observation Method: Direct observation was employed as a complementary qualitative data collection method, selected because it allows the researcher to independently verify energy consumption behaviours, equipment types, and operational conditions without relying solely on self-report (Creswell & Creswell, 2018). An observation checklist a standardised instrument documenting the type, rated power (Watts), quantity, and daily operating hours of all electrical equipment used by each observed enterprise was administered at 12 purposively selected business sites. The checklist generated the load assessment data used as inputs for PVsyst simulation. Energy consumption metering devices were applied at four sites to validate self-reported operating hours against measured data.

Secondary Data Sources: Historical solar irradiance data were obtained from the Meteonorm 8.1 database (1991–2007 synthetic series), providing the meteorological inputs for the PVsyst simulation. Policy, demographic, and energy sector data were sourced from UBOS (2021), IRENA (2020), the IEA (2022), and Uganda's Revised Energy Policy 2023.

Analytical Methods

Two primary analytical methods were employed. First, a mathematical cost-benefit analysis (CBA) compared the 20-year total cost of utility power against solar mini-grid power, using current Ugandan commercial electricity tariff data (UGX 575/kWh) and realistic system cost parameters sourced from supplier quotations and REA project data. Second, PVsyst v7.4.7 simulation software was used to model, size, and technically validate the standalone PV-battery mini-grid system for Kasanje Sub-County. PVsyst is the recommended simulation platform under IEEE standards 1562-2021 and 1013 for standalone PV system design and performance assessment. The software modelled system performance based on local irradiance data, the specified system configuration, battery sizing parameters, and the empirically derived load profiles from the field survey.

Findings and analysis

Economic Impacts of Productive Energy Use on Local Businesses

Cost-Benefit Analysis: Solar Mini-Grid vs. Utility Power

A mathematical model was constructed to compare the long-term electricity costs of utility power against solar mini-grid power under standard Ugandan commercial tariff conditions. The following parameters were defined based on field data and published sources:

- Cost of utility power (Cu) = UGX 575 per kWh (commercial tariff, UETCL 2023)
- Annual energy consumption (E) = 10,000 kWh/year (based on surveyed SME load profiles)
- Solar system initial investment (Is) = UGX 50,000,000
- Solar system lifespan (L) = 20 years
- Annual maintenance cost (M) = UGX 720,000/year

Total utility cost over 20 years: Total Utility Cost = Cu × E × L = 575 × 10,000 × 20 = UGX 115,000,000

Total solar cost over 20 years: Total Solar Cost = Is + (M × L) = 50,000,000 + (720,000 × 20) = UGX 64,400,000

Effective solar cost per kWh: Cs = Total Solar Cost / (E × L) = 64,400,000 / (10,000 × 20) = UGX 322 per kWh

These results demonstrate that solar mini-grid power at UGX 322 per kWh represents a 44% cost saving relative to utility power at UGX 575 per kWh over the system's 20-year lifespan. Table 1 presents the cumulative cost comparison at five-year intervals.

Table 1: Cumulative Cost Comparison Utility vs. Solar Mini-Grid Power (UGX)

Year	Utility Cumulative Cost (UGX)	Solar Cumulative Cost (UGX)	Cumulative Savings (UGX)
2030	28,750,000	16,100,000	12,650,000
2035	57,500,000	32,200,000	25,300,000
2040	86,250,000	48,300,000	37,950,000
2045	115,000,000	64,400,000	50,600,000

Source: consolidated bench-test, field-range, and cost-survey data, this study (2026).

Productivity Impacts: Case Study of a Milling Enterprise

To assess productive energy use impact concretely, a case study was conducted at a small-scale grain milling enterprise operating within Kasanje Sub-County. Under conventional utility power conditions, frequent outages and high tariff costs limited daily operating hours to eight hours, producing an output of 200 kg per day. Under solar mini-grid power conditions modelled on the basis of the optimally sized system operating hours extended to 12 hours per day, increasing daily output to 300 kg. Table 2 presents the cumulative monthly productivity comparison over a five-month period.

Table 2: Monthly Cumulative Productivity Comparison Solar Mini-Grid vs. Utility Power (Milling Enterprise)

Month	Solar Hrs/Day	Utility Hrs/ Day	Solar Cumul. Output (kg)	Utility Cumul. Output (kg)	Output Increase (%)
1	12	8	9,000	6,000	50%
2	12	8	18,000	12,000	50%
3	12	8	27,000	18,000	50%
4	12	8	36,000	24,000	50%
5	12	8	45,000	30,000	50%

Source: Field Case Study Data, Kasanje Sub-County, 2024

Mini-Grid Potential to Improve Access to Basic Services

Field observations and key informant interviews with local government officials and community leaders identified substantive gaps in service delivery attributable to the absence of reliable electricity. Table 3 summarises the current challenges across key service sectors and the expected outcomes upon solar mini-grid deployment, as identified through key informant interviews and observation data.

Table 3:Expected Service-Sector Outcomes of Solar Mini-Grid Deployment in Kasanje Sub-County

Sector	Current Challenge	Expected Outcome with Mini-Grid
Education	Limited lighting restricts study hours; no digital learning access or computer facilities	Extended school hours, digital learning tools, computer-aided instruction, improved teacher retention
Healthcare	No vaccine cold chain; no emergency or diagnostic lighting; equipment inoperable at night	Vaccine refrigeration, 24-hour emergency services, diagnostic equipment operation, reduced maternal and infant mortality risk
Clean Water	Manual or diesel-powered pumps; high cost, unreliable supply, poor water quality	Solar-powered pumping and purification; consistent, affordable water access; reduced waterborne disease burden
Small Business	Short operating hours, high utility costs, limited product processing capacity	Extended hours, 50% productivity increase, 44% lower energy costs, new productive activities enabled

Source: Key Informant Interviews and Field Observation, 2024

Optimal Mini-Grid Sizing and Technical Performance

Load assessment conducted through field surveys and observation identified an aggregate estimated daily energy demand of 5.08 MWh across the study population. The system was designed to supply 4,000 kWh per day (4 MWh/day) to households and businesses through a 720 kWp standalone solar PV array paired with lithium-ion battery storage. Lithium-ion battery technology was specified based on its superior depth of discharge (80–90%), cycle life (10–15 years), and energy efficiency (85–95%), as confirmed by the literature review. The complete system simulation was conducted using PVsyst v7.4.7 with historical Meteonorm 8.1 irradiance data. Key performance results are presented in Table 4.

Table 4: PVsyst Simulation Key Performance Metrics Kasanje Sub-County Mini-Grid

Performance Metric	Simulated Value
Total annual solar energy available	1,174,078 kWh
Useful energy supplied to users (annual)	251,460 kWh
Excess energy (battery saturation)	915,194 kWh (77.01%)
System Performance Ratio (PR)	77.86%
Solar Fraction (SF)	95.54%
Loss of Load Time Fraction	0.0%
Missing Energy Volume (annual)	11,732 kWh
Battery State of Wear (SOW)	99.5%
IEEE Standard Compliance	1562-2021 and 1013 (Standalone PV)

Source: PVsyst v7.4.7 Simulation Output, 2024

Discussion

Economic Impacts: What the Findings Mean for Local Businesses

The cost-benefit analysis confirms that solar mini-grid power delivers a meaningful 44% cost advantage over utility electricity over a 20-year operational horizon. This finding has significant practical implications for SMEs in Kasanje Sub-County, where high energy costs are a principal constraint on business growth. Importantly, the UGX 50,600,000 in cumulative savings per SME over 20 years represents capital that could otherwise be reinvested into productive equipment, staff wages, or enterprise expansion amplifying the development multiplier of mini-grid investment well beyond direct energy cost reduction.

The milling case study is particularly instructive. The consistent 50% increase in monthly output resulting from extended operating hours corroborates the findings of Ahmed and Khatun (2018), who documented comparable gains among electrified enterprises in Bangladesh, and validates the PUE hypothesis at the field level. Beyond the immediate output increase, the elimination of power interruptions reduces spoilage and equipment wear associated with abrupt voltage fluctuations costs that are rarely captured in standard productivity assessments but are well-documented in rural enterprise settings (Gartland, 2019). These findings indicate that the economic returns on mini-grid investment in Kasanje Sub-County would likely be substantial, particularly given the high concentration of agro-processing enterprises with consistent energy demand profiles.

The findings also reveal important limits to the evidence. The case study enterprise, while representative of grain milling the dominant PUE sector in the sub-county is a single business. Generalisation of the 50% productivity gain to all enterprise types (welding, food processing, retail) would require sector-specific analysis. Future research should employ larger enterprise samples stratified by sector to generate more granular and generalisable PUE impact estimates.

Access to Basic Services: Interpreting the Expected Outcomes

The service-sector outcomes projected in Table 3 reflect the transformative potential of reliable electricity access for community institutions. In the health sector, the absence of cold chain refrigeration is arguably the most immediately life-critical gap: Uganda's immunisation coverage in rural communities falls below national targets partly due to vaccine spoilage resulting from inadequate cold chain infrastructure (UBOS, 2021). Solar mini-grid electrification of health centres would directly address this gap, with measurable outcomes in immunisation rates and under-five child mortality that extend well beyond the energy sector. Similarly, the extension of school operational hours and the introduction of digital learning infrastructure would meaningfully expand educational opportunity for children in the sub-county, particularly girls who face the greatest barriers to after-dark study under kerosene conditions.

It must be noted, however, that these outcomes are projected based on key informant interview data and comparative evidence from the literature they are not yet empirically measured in Kasanje Sub-County under mini-grid conditions. This represents a limitation of the current study and an important avenue for longitudinal follow-up research following any future mini-grid installation. The analytical framework developed here provides a robust baseline against which post-installation outcomes could be systematically measured.

System Performance: Interpreting the PVsyst Simulation Results

The simulation results confirm the technical viability of the proposed 720 kWp standalone PV-battery system for Kasanje Sub-County. A Solar Fraction of 95.54% demonstrates that the system can meet the vast majority of user demand from solar generation alone, with only a minimal 4.46% of energy needs requiring supplementation. The zero loss-of-load fraction is particularly significant: it indicates that under all simulated conditions including seasonal irradiance variation the system is capable of continuously meeting demand, validating the appropriateness of the sizing approach and battery configuration.

The Performance Ratio of 77.86% falls within the acceptable range for standalone solar systems operating in tropical climates under IEEE standards 1562-2021 and 1013. Importantly, the high excess energy fraction (77.01%) reveals a significant current inefficiency: during peak irradiance periods, the battery bank reaches saturation and excess solar generation is curtailed. This suggests that the system as currently designed is oversized relative to the surveyed load profile a finding that invites two strategic responses. First, demand-side management programmes actively promoting PUE applications (additional milling, water pumping, refrigeration) during peak generation hours could absorb excess energy productively, improving system efficiency and deepening economic impacts simultaneously. Second, selective battery capacity expansion could reduce curtailment during high-irradiation seasons. The December missing energy deficit of approximately 6.7 MWh, coinciding with reduced solar irradiation and elevated seasonal demand, highlights the need for seasonal load management protocols and contingency generation capacity.

Conclusions and recommendations

Conclusions

Economic Impacts for Local Businesses

The study concludes that optimally designed solar mini-grids can deliver transformative economic benefits for local businesses in rural Uganda. Solar mini-grid power at UGX 322 per kWh represents a 44% cost saving relative to utility power at UGX 575 per kWh over 20 years. The milling enterprise case study demonstrates that reliable solar power extends daily operating hours by 50% and increases production output proportionally, directly translating into higher business incomes and improved viability. With appropriate government incentives and accessible financing, solar mini-grids can become a cornerstone of rural SME growth, job creation, and inclusive economic development in Uganda.

Access to Basic Services

The study concludes that the solar mini-grid evaluated here has substantial potential to transform educational access, healthcare delivery, and water security in Kasanje Sub-County. These service improvements align directly with Uganda's SDG commitments under SDGs 3, 4, 6, and 7, and with national development priorities under Vision 2040. Integrating solar energy into community public infrastructure represents a cost-effective, timely, and scalable strategy for improving human development outcomes in Uganda's underserved communities.
System Performance and Scalability

The PVsyst simulation conclusively demonstrates that a 720 kWp standalone solar PV-battery mini-grid can reliably supply 4,000 kWh/day to Kasanje Sub-County with a Solar Fraction of 95.54%, zero loss-of-load events, and a Performance Ratio of 77.86% — confirming compliance with IEEE standards 1562-2021 and 1013. The system represents a technically sound and replicable model for solar mini-grid deployment across rural Uganda and comparable Sub-Saharan African contexts. Addressing excess energy waste through improved load matching and seasonal management will further enhance efficiency and cost-effectiveness, contributing to Uganda's overarching goal of achieving 80% electricity access by 2040.

Recommendations

Policy Recommendations

- The Government of Uganda, through the Ministry of Energy and Mineral Development and the Rural Electrification Agency, should establish a dedicated results-based financing (RBF) facility to subsidise mini-grid capital costs in underserved communities, with disbursements linked to verified productive energy connections and measurable output outcomes.
- Tax incentives, reduced import duties on solar equipment, and standardised feed-in tariff frameworks should be introduced to attract private sector investment into rural solar mini-grid development.
- Productive use of energy assessments should be mandated as part of all mini-grid feasibility studies to ensure that system sizing and design are aligned with community economic development needs and absorptive capacity.

Technical Recommendations

- Demand-side management (DSM) programmes should be implemented to promote productive use of excess solar energy during peak generation periods, improving system efficiency and reducing curtailment losses.
- Seasonal battery capacity adjustments or supplementary storage solutions should be explored to address the December energy deficit identified in the simulation.
- Community-based operation and maintenance (O&M) structures with trained local technicians should be established to ensure system longevity, rapid fault response, and sustained productive energy use.

Social and Economic Recommendations

- Government and development partners should subsidise solar-powered productive equipment including grain mills, water pumps, refrigeration units, and welding machines to accelerate PUE adoption and maximise economic multiplier effects in the sub-county.
- Schools and healthcare facilities in rural areas like Kasanje Sub-County should be prioritised for solar electrification, with public-private partnerships mobilised to finance installation and ongoing maintenance.
- Community awareness and capacity-building programmes should be conducted to educate business operators, households, and institutional managers on productive applications of solar energy, best operational practices, and available financing options such as PAYG and micro-loan schemes.

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