Development of a Solar Photovoltaic-Biogas Hybrid Microgrid for Off-Grid Rural Communities in Uganda

Emmanuel Wokulira Miyingo, David Sunday Tusubira, Roseline Nyongarwizi Akol, Sheila N. Mugala, Davis Kayiza Kawooya

Abstract—**Electricity is vital for social-economic growth and development. However, over 80% of rural dwellers in Uganda do not have access to it due to the absence of the national electricity grid. Most rural inhabitants use biomass to meet their energy needs using primitive conversion devices, e.g., the 3-stone stoves. They are mainly agricultural and generate a lot of waste, whose disposal is usually open dumping and burning. Such practices lead to environmental concerns and limited economic opportunities. This research aimed to address energy poverty and waste management in off-grid Ugandan communities. The study focused on solar photovoltaic (PV)-biogas hybrid microgrids as a potential solution, given the abundance of solar and bio-waste, particularly animal dung. Field surveys were conducted in Mubende District to gather data on energy usage, appliances, and demographics. Technical simulations and financial analyses were performed for different energy supply scenarios. The results indicated that the solar PV-biogas hybrid system was financially viable, with positive internal rate of return, net present value, and return on investment, whereas solar PV only was not. A pilot project was successfully implemented in one community with seven end users and has been operating since April 2024. The feedback from the end users is full of praise and excitement, and many more users wish to be connected. The study concluded that solar PV-biogas hybrid microgrids can be a valuable solution for providing energy access to off-grid communities in Uganda. Scaling up such systems is recommended to address the energy needs of such areas.**

Index Terms—**Biomass, energy access, energy systems, environmental, photovoltaic**

I. Introduction

Uganda's off-grid population stood at about 80% in 2022, which accounted for about 33 million people without access to the national electricity grid. Moreover, over 80% of the country's electricity came from hydropower, and only 10% from off-grid solar home systems [1], [2]. The off-grid photovoltaic (PV) installations only serve low energy and vital needs in the households, especially lighting, phone charging, and entertainment. Productive uses of electricity, such as refrigeration and water pumping, are still stagnant due to the high investment required for solar PV solutions [3]–[5].

Traditional biomass (especially firewood and charcoal) remains the most dominant source of energy used in Uganda, accounting for over 85% of the country's total energy consumption, especially for cooking [1], [3]. Moreover, most of the biomass users still use primitive conversion devices such as the 3-stone firewood stoves, which are known to be quite inefficient with several negative environmental and health effects [6]–[8]. Despite biomass being a renewable resource, it still threatens the environment and the health of women and children involved in the cooking through indoor air pollution and the production of particulate matter [1]. In addition to the widespread use of biomass fuel, a large portion of the country is dependent on agriculture, which generates a fair amount of agricultural waste. Agricultural waste poses an even greater risk to the environment due to the release of methane gas into the atmosphere. In fact, only the livestock sector is estimated to contribute 14.5% of global greenhouse gas emissions [9], and such numbers should not be ignored in the effort to reduce emissions.

However, biogas has proved to be a cost-effective and reliable source of energy in Uganda, especially in agricultural communities. It is said to be competitive, viable, and generally a sustainable energy resource due to abundant supply of cheap feedstock and availability of a wide range of biogas applications in heating, power generation, fuel, and raw materials for further processing and production of sustainable chemicals including hydrogen, and carbon dioxide and biofuels [10], [11]. However, it has mostly been used for cooking in Uganda despite its capacity for other applications such as lighting and heating. Similarly, solar PV has scaled widely across the country, especially in rural households for lighting, phone charging, and entertainment in some cases. Nonetheless, there have been many reports of failed components due to poor quality of the

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Emmanuel Wokulira Miyingo, Roseline Nyongarwizi Akol, and Sheila N. Mugala are with the Department of Electrical and Electronics Engineering, College of Engineering, Design, Art and Technology, Makerere University, Kampala, Uganda (e-mails: miyingo@yahoo.com, nrakol@gmail.com, and smugzie@gmail.com).

David Sunday Tushibira is with Dojo Hub (SMC) Ltd, College of Engineering, Design, Art and Technology, Makerere University, Kampala, Uganda (e-mail: tusdavi4@gmail.com).

Davis Kayiza Kawooya is with the KPMG Africa, Kampala, Uganda (e-mail: daviskayiza@gmail.com).

products and the short lifespan of batteries that require full replacement within 5 years of installation. The Uganda National Bureau of Standards (UNBS), the authorized body to enforce standards, has limited capacity to implement the guidelines to regulate the solar market, and mainly relies on third parties outside Uganda for that function [1], [12], [13]. In addition, both solar PV and biogas energy sources have failed to scale for productive uses such as refrigeration, milling, and water pumping, mostly due to the high initial investment requirement [5]. Thus, rural communities are unable to invest in these renewable energy sources for productive use. Additionally, solar PV is only available during the day for less than 10 hours and is quite intermittent. Matching battery storage is therefore required to ensure energy supply at night and during poor weather conditions, yet the batteries are relatively expensive [14] and have to be replaced within 5 years. Moreover, battery storage for off-grid solar PV systems makes the installations more expensive and unaffordable [15], [16]. However, the two energy sources can complement each other in form of a hybrid energy system so that solar PV meets the energy demand whenever available, whereas biogas is applied when solar PV is insufficient or unavailable. A relatively small battery storage can be included, charged by solar PV and biogas for backup. The two are the most applicable renewable energy sources in Uganda since solar is readily available [12], and a lot of biodegradable waste presents a management problem without useful alternative applications.

This research targeted to achieve the following specific objectives: (i) determine the energy needs of a typical off-grid rural community, (ii) model a hybrid microgrid that can fulfill the energy needs of a selected community, (iii) install and operate a pilot hybrid microgrid, (iv) derive a model design, and (v) disseminate the findings in form of a research paper. The team therefore pursued a hybrid of solar PV and biogas so that the two sources would complement each other, due to the facts given in the preceding text in this section. The solar PV is mostly applied during sunny conditions, and biogas is applied at night and during poor weather conditions. This means it is not necessary to match the battery storage with the expected load. The hybrid microgrid was designed to meet the energy needs of a specific off-grid rural community, but can be adopted and modified to meet the energy requirements of any given small community of end users. The model design consists of a bill of materials, schematics, and guidelines for the establishment and maintenance of the energy generation plant.

The designed hybrid microgrid consisted of the following main components or subsystems:

(i) Biogas digester, (ii) PV array, (iii) single phase hybrid inverter, (iv) unmatched battery bank, (v) bio-feedstock feeding system, (vi) biogas filtering system, (vii) filtered gas storage or buffering system, (viii) digestate extraction system, (ix) biogas generator, (x) gas distribution infrastructure (plumbing, metering, and control), (xi) booster pump, and (xii) electricity distribution infrastructure (wiring, metering, and control).

The designed energy system specifies the individual sizes of each of the above main components to meet the energy requirements of a specific community. The design aims to ensure the highest value for money to facilitate the self-financing of the microgrid installed according to the reference design. The design also specifies the maintenance routines for each of the components or subsystems, their respective costs, including the installation and maintenance, and capacity expansion instructions.

The model design can be used by investors, energy solutions providers, and end-user groups to set up hybrid solar PV-biogas microgrids with minimized risk and maximized yield. It will save them from the research and development burden and enable them to reap the rewards immediately after only incurring the cost of establishment.

The users of the model design will only need to carry out a survey and estimate the energy needs of the target community, and adjust the design accordingly to meet the estimated energy needs.

Indeed, the availability of sustainable (reliable, affordable, and clean) energy services is critical for economic growth, poverty reduction, as well as the social and cultural transformation of society. Our proposed solution paves the way for the mass establishment of hybrid solar PV-biogas microgrids in all rural parts of Uganda where sufficient biogas feedstock is available. Additionally, the proposed solution contributes to Sustainable Development Goal (SDG) #7, which entails access to affordable, reliable, sustainable, and modern energy for all [17], [18].

This paper makes the following key contributions:

- It presents a comprehensive methodology for designing and implementing solar PV-biogas hybrid microgrids tailored to the specific energy needs of off-grid rural communities in Uganda.
- It provides a detailed technical and financial model for such systems, enabling stakeholders to assess viability and optimize system design.
- It offers empirical evidence of the feasibility and benefits of hybrid microgrids through the implementation and operation of a pilot project in a rural Ugandan community.
- It demonstrates the potential of hybrid microgrids to promote the use of renewable energy resources, reduce reliance on unsustainable energy sources, and improve waste management practices in rural areas.

The remainder of the paper is organized as follows: Section II details the methods used to determine energy needs, model the hybrid microgrid, and conduct financial analyses. Section III presents the results and discussion of the field surveys, technical simulations, and financial viability assessments. Section IV concludes the paper by summarizing the key findings and highlighting the implications of this research.

II. METHODS

A. Determination of Energy Needs of a Typical Off-grid Rural Community

Field surveys were conducted in two off-grid trading centers in Mubende District, central region, Uganda (communities A and B). The Mubende Environment Officer proposed the two communities based on their district data about the energy and electricity needs and led the research team to the two communities. The local council I chairpersons guided the actual selection on ground by taking the survey team around and introducing it to the potential respondents. Electrical consumers who were available and willing to participate voluntarily were interviewed. Seven respondents were selected from community A to represent the most common business types identified in the community. The main business types identified in community A were milk cooling, primary schools, restaurants, hair salons, drug shops or clinics, retail shops, and bars. Similarly, six business types were selected from community B. They included casinos, retail shops, restaurants, video halls, nursery and primary schools, and maize millers. It was assumed that the same business type would generally have almost the same electrical equipment and use patterns, and from the total number of each business type, the estimated number of equipment and usage were derived. Structured questionnaires were used to collect data from the chairpersons and the selected potential electrical consumers on various aspects of their day-to-day energy-related activities. The respective chairpersons provided general demographics (using a specific questionnaire) about their communities, e.g., the population, economic activities, number of households, number of farms and businesses, to mention a few. Similarly, a specially prepared questionnaire was used to collect data from the individual respondents, who were mainly business persons. Additionally, animal farmers with at least 30 heads of cattle were also interviewed with a view to establishing the potential source(s) of cow dung as a biogas feedstock. The data collected included but was not limited to the population to be served, prospective users (nature of business, scale of operations, ownership, etc.), current energy sources, current and desired electrical appliances, cooking energy consumption by prospective users, space availability for power plant installation, and potential biogas feedstock.

A preliminary evaluation of the data collected from the two communities was done, and community B was found to have more population and 20 more businesses in the trading center, which meant higher utilization of the energy generated by the intended microgrid. Additionally, the businesses were located close to each other (not more than 7 m), making electrical distribution straightforward, unlike the ones found in community A. Therefore, community B was selected for detailed analysis and design. Consequently, the collected data for community B was digitized and analyzed together with the desk research findings to derive a load profile in a Microsoft Excel spreadsheet. The load profile was based on a list of appliances with their respective power ratings, the respective quantities of each type of appliance for each business type, and the respective individual usage patterns for each appliance. Appliances whose ratings could not be established from the field data were assigned power ratings based on other common appliances on the Ugandan market. The load profile was therefore a summation of the load profiles of individual businesses, which were derived from the load profiles of individual appliances. The load profile spreadsheet developed can be applied to any community, given the number of businesses for each type in a given community.

B. Modelling of the Hybrid Microgrid

Based on the analysis, a hybrid microgrid was specifically designed to fully satisfy the energy needs of community B. The microgrid was sized and modeled using Microsoft Excel based on the demand profile. A financial model was developed in Microsoft Excel to determine the financial viability of the microgrid design. Fig. 1 shows the layout of the solar PV-biogas hybrid energy generation system that was modelled.

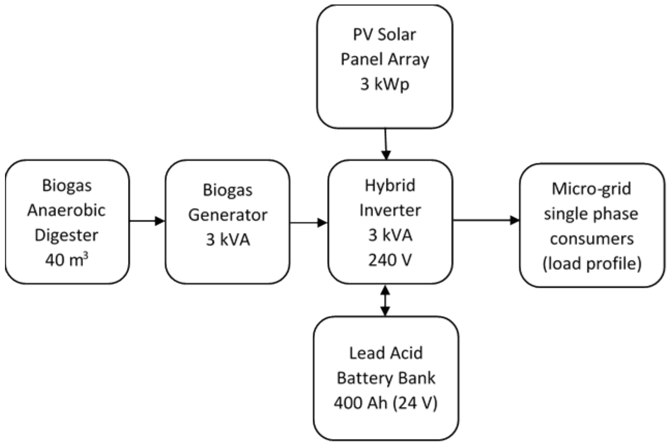


Fig. 1. Hybrid Microgrid Energy Generation System Block Diagram

The specifications for the various components used for the modeling of the hybrid microgrid energy system are shown in Table I. Some of the numbers used, e.g., biogas generation rate from cow dung, were obtained from the literature [19].

TABLE I
SPECIFICATIONS FOR THE VARIOUS MICROGRID COMPONENTS OF THE MODEL

Solar PV subsystem	
Solar panel array (Wp)	3,000
Battery bank (Ah)	400
Battery bank nominal voltage (V)	24
Battery charging maximum current (A)	20
Battery bank maximum charging energy (W)	480
Battery bank depth of discharge (DoD)	0.5
Inverter (W)	3,000
Biogas subsystem	
Anaerobic digester (m^3)	40
Biogas generator (kVA)	3,000
Cow dung feedstock rating (kg/day)	350
Cow dung gas generation rate (m^3/kg)	0.04
Maximum gas generation capacity (m^3)	14
Biogas generator conversion rate (kWh/m^3)	1.2
Inverter Energy Source Prioritization	
Solar PV	1
Biogas	2
Battery	3

Using the system design (layout and specifications) and the load profile, a model depicting the behavior of the energy generation system was developed and simulated to demonstrate the technical feasibility of the system design and the performance of each of the energy sources over 24 hours. The simulation has three inputs that include a single-day hourly solar irradiation profile, a single-day hourly biogas generator operation profile, and a single-day hourly load profile. The simulation outputs the hourly solar irradiation, hourly demand, hourly energy supply from each of the energy sources, hourly battery state of charge (SoC), and hourly energy deficiency as line graphs. The system specifications of the model can be adjusted to meet any given load profile. The model is designed to integrate a load profile sheet, a system specifications sheet, and a simulation sheet in the same Microsoft Excel document to provide flexibility to potential users that enables them to model a wide range of scenarios.

The model was designed to behave according to the intended hybrid inverter configuration in which solar PV is prioritized as the primary source of energy, followed by biogas, and lastly, the battery bank. It was also configured to charge the battery bank using both solar PV and biogas at a maximum current of 20 A. If solar PV is unavailable, and the biogas and battery storage are exhausted, the system shuts down automatically. The battery bank is considered empty at 50% SoC, and the 0% in the simulation results is equivalent to 50% in reality.

Two technical scenarios were simulated under the following conditions:

C. Scenario 1: Moderately Sunny Day

In scenario 1, the irradiation profile of a moderately sunny day (data from Photovoltaic Geographical Information System (PVGIS) [20] was used where the peak irradiation of the day was 841 W/m^2 at 1300 hours (1 PM), which is 159 W/m^2 shy of the ideal PV cells testing irradiance of 1,000 W/m^2.

D. Scenario 2: Rainy Day

In scenario 2, the irradiation profile of a day with a rainy morning and moderately sunny late afternoon, where the peak irradiation of the day was 593 W/m^2 at around 1600 hours (4 PM), was simulated. This was 407 W/m^2 less than the ideal testing irradiance of 1,000 W/m^2.

Both scenarios 1 and 2 were simulated under the assumption that the biogas digester is regularly fed so that sufficient biogas is available and the battery bank is fully charged at the start of the day at 0000 hours (midnight).

E. The Financial Model

A dynamic three-statement financial model (consisting of an income statement, balance sheet, and cash flow statement) was built to evaluate the financial viability of the Hybrid Solar PV-Biogas Microgrid. The viability was assessed using the Internal Rate of Return (IRR), Net Present Value (NPV), Return on Investment (ROI), and simple payback period (SPP) [21], [22]. These metrics are widely used to assess financial viability due to their ease of interpretation. A positive IRR and NPV indicate that the investment is financially viable, whereas negative values indicate that it is not viable. The higher the IRR and NPV are, the more financially viable the investment is, and vice versa. A positive ROI indicates that the investment has generated a profit, whereas a negative ROI means that the investment has resulted in a loss [21], [22]. The SPP is a straightforward metric that estimates the time it takes for an investment to recover its initial cost from the cash flows it generates. These four metrics were applied to the hybrid microgrid and were based on the future cash flows that the microgrid would be expected to generate during its useful life.

The cash flows of the microgrid included the initial capital expenditure (CAPEX) to purchase the equipment needed; the operating expenditure (OPEX) for the periodic expenses needed to run and maintain the microgrid after installation; and the revenues derived from the sale of electricity to the target community. The revenue was based on the expected units of electricity sold (as per the demand profile of the target community) and the price per unit of electricity sold. The OPEX for the microgrid included labor costs, water costs, and service fees for the premises that house the equipment for the microgrid. The labor cost drivers are the number of casual workers needed and their monthly salary. The water cost drivers are the quantity of water used and the cost per unit of water used. The service fees for the premises are based on the agreement with the landlord.

The IRR, NPV, ROI, and SPP were automatically computed by the financial model, and the model users can fill in the specific inputs or drivers for each target community to assess the viability of the proposed microgrid in each community.

The viability of the microgrid is heavily dependent on the funding structure used to finance the investment. The funding structure used in this research was 70% debt and 30% equity. As such, the financial model allows its users to test the viability under different funding structures. The key financing cost drivers are the percentage of investment financed with debt, the interest rate on loans, and the cost of equity to the investor. The financial model has been built in a dynamic way that allows users to change inputs to enable analysis of the viability of a microgrid in different communities.

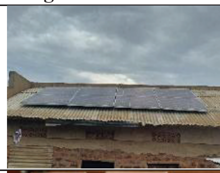
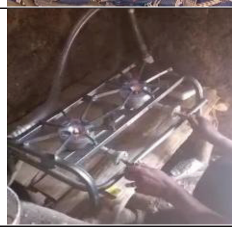
Two cases were catered for in the financial model to determine the impact of biogas as an alternative to a large solar-powered battery bank. Case 1 was a hybrid solar PV and biogas system like the one that was modeled in the technical model. Case 2 was a solar PV system with a battery bank designed to meet the daily energy demand with only one day of autonomy. Case 2 differs from Case 1 in the following major ways:

- 7 kWp panel array instead of 3 kWp
- 6,000 Ah battery bank instead of 400 Ah battery bank
- No biogas digester, no biogas generator, and no biogas accessories

F. Pilot Installation and Operation of the Microgrid

The hybrid microgrid design derived from the modeling was implemented at the pilot site (Kalungi B Village, Mubende District) with a few modifications. Due to budget constraints, the panel array installed is only 2.2 kWp as opposed to the intended 3 kWp. Similarly, only 7 out of the 20 businesses in the Kalungi B village were connected to the microgrid. Analog energy sub-meters and basic electrical fittings, typically consisting of two lamp holders, 2 Light Emitting Diode (LED) lights, and a double wall socket, were installed at the premises of each of the connected consumers. Table II provides detailed specifications of the major components installed.

TABLE II
DETAILED SPECIFICATIONS FOR THE COMPONENTS OF THE PILOT

No.	Item	Specifications	Image
1	Solar PV array	Type: Monocrystalline Module rating: 550 Wp Nominal voltage: 24 V Brand: Jinko No. of modules: 4	
2	Inverter	Type: Hybrid (direct PV) Brand: Felicity Rating: 3 kVA Voltage: 12/24/48 V Power factor: 90	
3	Battery bank	Type: Lead Acid (Gel) Brand: Gaston No. of cycles: 1,500 Nominal voltage: 12 V Rating: 200 Ah No. of units: 2	
4	Digester	Type: PVC Brand: Sistema Size: 40 m^3 Feedstock: Cow dung	
5	Generator	Type: Dual Petrol/biogas Model: TYMG3500E Rating: 3 kVA Output voltage: 240 V AC Power factor: 1	
6	Electrical energy meter	Type: Postpaid (Rotary) Brand: DDS Honey Rating: 60 A Display: LCD Voltage: 220 V AC	
7	Biogas cooker	Type: Double burner	
8	Electric poles	Type: Metallic (Steel) Diameter: 60 mm Thickness: 2 mm Height: 4.5 m	
9	Distribution cable	Type: Aluminum Size: 10 mm^2 No. of cores: 2 Total length: 200 m	

The power from the hybrid was distributed using metallic poles and aluminum cables. A total of about 200 meters of cable and 5 metallic poles were used. The end users that were connected include 2 saloons, 2 retail shops, 1 motorcycle repair shop, 1 fast food joint, and 1 drug shop. The double biogas burner was installed in one nearby kitchen for domestic use. The biogas digester was placed in a 2-meter-deep pit that was excavated next to the powerhouse. The digester was initially fed with about 350 kg of cow dung and 700 liters of water. The pilot has been in operation since April 2024, and various attributes have so far been recorded. These include revenue, expenses, energy generated, energy consumed, faults, downtime, and end-user feedback. Fig. 2 shows a cable connected to one of the shops (a) and the biogas digester (b).

(a) Cable connection from the metallic pole to the shop (b) Biogas digester

Fig. 2. Cable Connection and Biogas Digester

III. RESULTS AND DISCUSSIONS

G. General Findings

The estimated number of households was 300 in community A and 3,000 in community B, with respective populations of 900 and 2,000. The main economic activities in the two communities are crop and animal farming, trading, and small-scale agro-processing. The primary sources of energy are firewood, charcoal, and solar energy. Firewood and charcoal are mainly used for cooking, whereas solar energy is used for open sun drying, and solar photovoltaic (PV) is only utilized for lighting and entertainment. In both communities, the main sources of water are the public dams (about 2 km from the center) and rainwater from residential roofs. Some of the electrical appliances currently being used on solar and gasoline are maize mills, lighting bulbs, hair shaving machines, to mention a few. The desired electrical equipment and appliances, in case sufficient, affordable, and reliable electrical energy becomes available, are fridges or refrigerators, fuel pumps, lights, hoofers or sound systems, and maize millers.

H. Energy Needs of Community B

The energy needs of community B are summarized in form of an energy load profile shown in Fig. 3. Power consumption starts at about 20 Watts for the first few hours of the day and increases drastically between 0800 hours (8 AM) and 1000 hours (10 AM) to about 2,200 Watts, which is maintained for most of the day. The power consumption peaks from 2000 hours (8 PM) to 2200 hours (10 PM) and then reduces drastically to about 800 Watts at midnight.

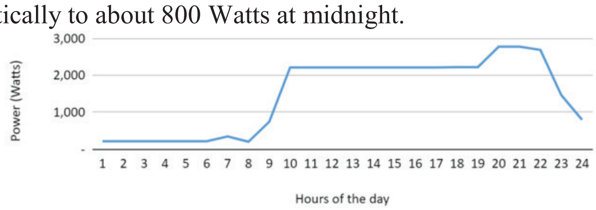


Fig. 3. Load Profile of Community B

The derived load profile in Fig. 3 revealed that the community's existing daily electrical energy demand was a total of about 35 kWh with a peak power of about 2.8 kW between 2000 hours (8 PM) and 2200 hours (10 PM).

I. Scenario 1-Moderately Sunny Day – Solar Irradiance

Fig. 4 shows a graph of the scenario 1 hourly irradiation profile. Solar irradiation starts to increase gradually at 0700 hours (7 AM) and peaks to 850 W/m^2 at 1300 hours (1 PM) and reduces gradually to zero at about 1900 hours (7 PM).

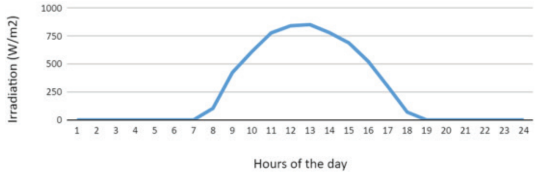


Fig. 4. Hourly Solar Irradiation for Scenario 1

J. Scenario 1-Moderately Sunny Day – Power Supply by Source

The power supplied by each of the sources under scenario 1 is shown in Fig. 5. In this scenario, the biogas generator is turned on at 1700 hours (5 PM) and turned off at midnight. The energy demand of the day before the sun starts shining, between midnight and 0800 hours (8 AM), is met by the battery bank. The power demand between 0800 hours (8 AM) and 1600 hours (4 PM) is predominantly met by solar PV except for short periods like 0900 hours (9 AM) to 1100 hours (11 AM) and 1400 hours (2 PM) to 1700 hours (5 PM), where the battery bank supplements it. The biogas generator starts to supplement the solar PV from 1700 hours (5 PM) to 1800 hours (6 PM). Between 1700 hours (5 PM) and midnight, the biogas generator supplies most of the demand as shown in Fig. 5.

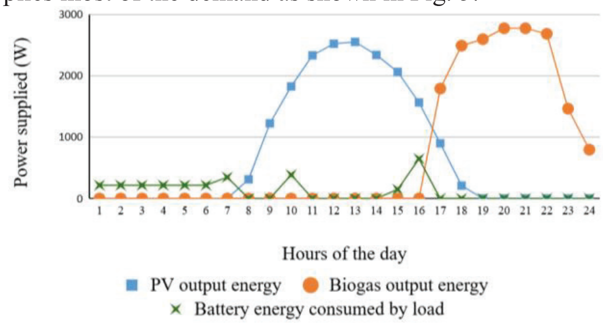


Fig. 5. Power Supply by Source

K. Scenario 1-Moderately Sunny Day – Battery Bank State of Charge (SoC)

Fig. 6 shows a plot of the battery bank's SoC throughout the day. The battery SoC starts at 100% at midnight and reduces gradually to 65% at about 0800 hours (8 AM), increases to 78% at 1000 hours (10 AM), reduces briefly and then increases to 88% at 1500 hours (3 PM) before reducing and then increasing to 100% at 2000 hours (8 PM), which is maintained until midnight.

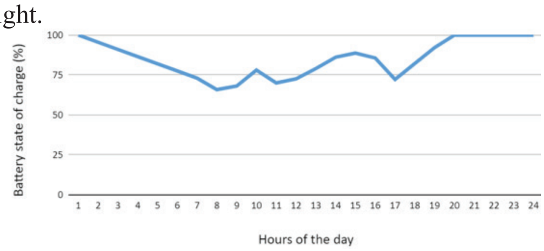


Fig. 6. Battery Bank State of Charge Throughout the Day

L. Scenario 1-Moderately Sunny Day – Energy Deficiency

Fig. 7 shows that there is no occurrence of energy deficiency throughout the day. This is because the energy sources are appropriately sized to meet the load requirement.

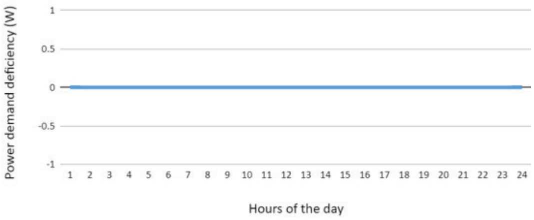


Fig. 7. Energy Deficit Graph

M. Scenario 2-Rainy Day – Solar Irradiance

Fig. 8 shows a graph of scenario 2 hourly irradiation profile. The plot indicates that the sun begins to shine at approximately 0800 hours (8:00 AM). The irradiation increases steadily until 1000 hours (10 AM) when it suddenly starts to drop to 80 W/m^2 at 1100 hours (11 AM) due to rain. The irradiation starts to increase at 1300 hours (1 PM) and peaks to 600 W/m^2 at 1600 hours (4 PM) and reduces to zero at 1900 hours (7 PM).

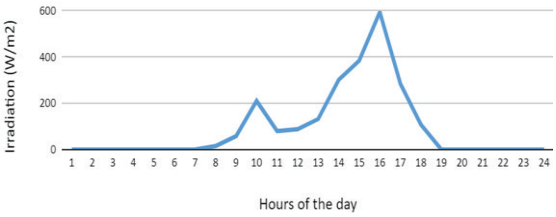


Fig. 8. Hourly Solar Irradiation for Scenario 2

N. Scenario 2-Rainy Day – Power Supply by Source

In this scenario, the biogas generator was turned on at 1100 hours (11 AM) and turned off at 2100 hours (9 PM) as shown in Fig. 9. The power demand of the day between midnight and 1100 hours (11 AM) is mostly met by the battery bank with a supplement of solar PV that starts at 0900 hours (9 AM). Between 1100 hours (11 AM) and 2000 hours (8 PM), the energy demand is mostly met by the biogas generator, with a significant contribution from solar PV. Between 1300 hours (1 PM) and 1900 hours (7 PM), it can be observed that an increase in solar PV availability causes a reduction in biogas energy consumption due to solar PV being prioritized by the hybrid inverter. The biogas energy runs out at 2100 hours (9 PM), and the battery bank takes over all supply until the battery bank energy runs out at 2300 hours (11 PM). That means the energy system shuts down.

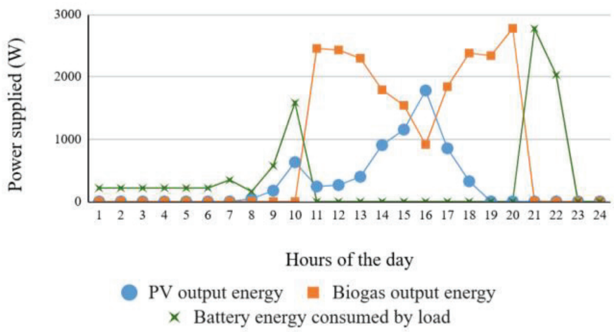


Fig. 9. Power Supply by Source

O. Scenario 2-Rainy Day – Battery Bank State of Charge

Fig. 10 shows the state of charge of the battery bank throughout the day for scenario 2. The battery bank starts at 100% at midnight and reduces to a minimum of 17% at 1100 hours (11 AM) and gradually increases to 100% at 2000 hours (8 PM), maintains full capacity for 1 hour, and then reduces drastically to 0% (50% in reality) at 1100 hours (11 AM).

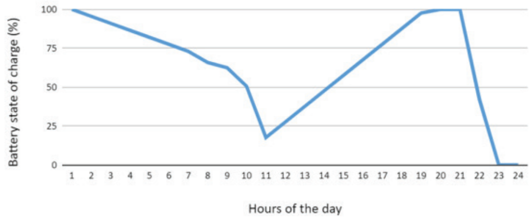


Fig. 10. Battery Bank State of Charge Throughout the Day

P. Scenario 2-Rainy Day – Energy Deficiency

Fig. 11 shows the energy deficiency throughout the day. The power demand of 1,500 Watts at 2300 hours (11 PM) and about 800 Watts at midnight is unmet.

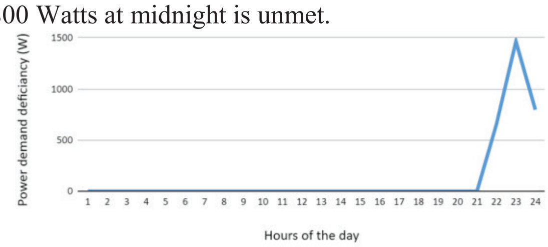


Fig. 11. Energy Deficit Graph

In both scenarios, the early morning energy demand is solely met by the battery bank until around 0800 hours (8 AM) when the sun starts shining and the panels start generating electricity. In scenario 1, most of the demand is met by the solar PV power, except for the moments at 1000 hours (10 AM) and 1600 hours (4 PM), where the battery bank contributes a bit of energy. In scenario 2, the daytime demand is met by a combination of all sources, starting with the battery bank, which gets almost depleted (25% SoC) at around 1100 hours (11 AM) when the biogas generator is turned on. The demand is mostly met by biogas between 1100 hours (11 AM) and 2100 hours (9 PM), with a significant contribution from the solar PV, especially in the late afternoon. The biogas energy is depleted at around 2100 hours (9 PM) and the battery bank takes over until it is also depleted at 2300 hours (11 PM). An energy deficit of 2,917 Wh occurs in scenario 2 due to the unavailability of solar energy and depletion of the battery bank and biogas energy. This means that the morning energy demand of the subsequent day in scenario 2 is not met until the sun starts shining. Scenario 1 shows no energy deficit, and the battery gets fully charged by 2000 hours (8 PM), and the battery is not used until the next day's morning demand.

The results show that there is no energy deficiency at any point throughout the day under scenario 1. The battery state of charge output shows that no more than 35% of the battery's charge is used throughout the day, which implies that the system is sufficiently sized under scenario 1. The simulation under the same conditions reveals that the biogas energy from the digester is almost completely utilized between 1700 hours (5 PM) and midnight, which suggests that the biogas energy is only enough for electricity conversion and not cooking at that time. Use of biogas for cooking in this scenario 1 would cause an energy deficit in the late evening hours. In general, the use of biogas for cooking on moderately sunny days does not significantly affect the electrical energy services since cooking is mostly done during the day when the PV and the battery bank sufficiently supply the electrical load. However, cooking reduces the biogas pressure, and this was addressed by introducing a booster pump to regulate the pressure.

Table III shows the financial model outputs for Case 1 (hybrid solar PV-biogas) that include SPP (7 years), ROI (82%), NPV (USD 1,335), and IRR (13%). It indicates that Case 1 (hybrid solar PV-biogas system) is financially viable because it returned positive IRR, NPV, and ROI.

TABLE III
FINANCIAL MODEL OUTPUT FOR THE HYBRID SOLAR PV AND BIOGAS SYSTEM

Active case	Solar & Biogas	
	Unit	Input
2 Outputs		
Payback Period	Years	7
Return on Investment (ROI)	$	82%
Project Net Present Value (NPV)	$	1,335
Project Internal Rate of Return (IRR)	% p.a.	13%

Table IV shows the financial model outputs for Case 2 (solar PV system with a big battery bank and no biogas) that include SPP (not specified), ROI (-302%), NPV (USD -24,719), and IRR (-13%). This means, Case 2 (only solar PV) is not viable, since the obtained IRR, NPV, and ROI values are negative.

TABLE IV
FINANCIAL MODEL OUTPUT FOR ONLY SOLAR PV

Active case	Solar Only	
	Unit	Input
2 Outputs		
Payback Period	Years	-
Return on Investment (ROI)	$	-302%
Project Net Present Value (NPV)	$	(24,917)
Project Internal Rate of Return (IRR)	% p.a.	-13%

The SPP in Case 1 is 7 years, which is within the life of the project of over 15 years, whereas the SPP in Case 2 is not specified. This means the investment cost can be recovered within a realistic time in Case 1, but cannot be recovered in Case 2, which can be attributed to the regular cost of replacing the battery within the first 5 years of installation.

IV. CONCLUSION

This research demonstrates the potential of hybrid solar PV-biogas microgrids as a viable solution to address energy poverty and waste management challenges in off-grid rural communities in Uganda. Field surveys in Mubende District provided critical data for the design and modeling of a hybrid system tailored to the energy needs of a typical community, with a daily electrical energy demand of approximately 35 kWh and a peak power of 2.8 kW. Technical simulations revealed that the hybrid system effectively integrates solar PV, biogas, and battery storage to ensure a consistent power supply, even under variable solar irradiation conditions. Notably, financial analysis indicated that the hybrid system is financially viable, boasting a positive internal rate of return (IRR) of 13%, a net present value (NPV) of USD 1,335, and a return on investment (ROI) of 82%, in contrast to a solar-only system, which showed negative financial indicators. The successful implementation and operation of a pilot project further validates these findings, with positive feedback from end-users and high demand for expansion. These results strongly suggest that hybrid microgrids can significantly contribute to achieving Sustainable Development Goal (SDG) #7 by providing access to affordable, reliable, sustainable, and modern energy for all.

Universal access to modern energy, especially electricity, can be quickly achieved if various appropriate approaches are employed. A national electricity grid extension may not be feasible in many rural areas in Uganda, but community-shared energy systems are a cornerstone of energy poverty alleviation in developing countries. The concept of hybrids involving solar PV and biogas is quite captivating in Uganda since solar is abundant, given that the country lies at the equator, and the farming waste, especially animal waste, is readily available with limited or no alternative uses. The energy sources can complement each other such that when one of them is not available, the other can take on the load. The simulation results and the financial analysis in this study provide further motivation to pursue the concept. Moreover, the pilot implemented so far adds value to the already promising idea. The sequencing of the energy supply tested in this research leads to realistic performance and results. A similar idea can be tested on larger coverage areas and an increased number of users, and the testing of other scenarios and cases can be informative.

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Emmanuel Wokulira Miyingo was born in Wobulenzi village, Luweero, Uganda in 1983. He received his Bachelor of Science in Electrical Engineering and Master of Science in Renewable Energy from Makerere University in 2009 and 2013, respectively. He holds a PhD in Agricultural Sciences from the University of Kassel Witzenhausen, Germany awarded in 2020.

From Nov 2013 to June 2021, he was an Assistant Lecturer at Makerere University in the Department of Electrical and Computer Engineering. Since July 2021, he has been a Lecturer in the Department of Electrical and Computer Engineering (currently, Department of Electrical and Electronics Engineering) at Makerere University. He authored various articles and his research interests include design, installation, and maintenance of stand-alone solar systems, biogas-based systems, renewable energy-based microgrids, renewable energy systems for agricultural off-grid communities, small-scale irrigation systems, hybrid renewable energy systems, and sustainable living.

Dr. Miyingo was a visiting Scholar at University of Michigan, Ann Arbor, USA, during the 2015-2016 University of Michigan African Presidential Scholars Program (UMAPS), where he worked for six months under mentorship of Prof. Roy Clarke and made a presentation on the design, development, and deployment of energy systems based on renewable energies. He has also attended several international conferences such as the launch of the University of Michigan's STEM-Africa Initiative 2010, Tropentag 2016 and 2017, STEM-V Conference on Appropriate Technology in Africa 2019 at University of Michigan.

David Sunday Tusubira was born in Kampala, Uganda on the 21st of March 1993. He received his Bachelor of Science degree in Electrical Engineering from Makerere University, Kampala Uganda in 2017. From 2017 to 2025, he was the Chief Technology Officer of Innovex Uganda Limited. Since 2021, he has been the Chief Executive Officer of Dojo Hub SMC Limited based in Kampala, Uganda. His research interests include renewable energy, climate change, and Internet of Things.

Roseline Nyongarwizi Akol obtained Bachelor of Science in Electrical Engineering, from Makerere University, Kampala, Uganda, in 1997. She received a Master of Science and Doctor of Philosophy in Engineering (Electronics), from University of KwaZulu-Natal, South Africa, in 2001 and 2008 respectively.

Since 1996, she has been involved in human capital development of Electrical, Computer, and Telecommunications Engineers in Uganda. She has carried out research in East and Southern Africa. She has published various articles. Her research interests include machine-to-machine type of communication, Artificial Intelligence (IT), Internet of Things (IoT), and Sensor networks.

Sheila N. Mugala was born in Mbale, Uganda in 1982. She received her Bachelor of Science and Master of Science degrees in Electrical Engineering from Makerere University, Kampala, Uganda in 2006 and 2013, respectively. She is currently pursuing a Ph.D. in Electrical Engineering at Makerere University.

Since 2006, she has been an assistant lecturer at Makerere University in the Department of Electrical and Computer Engineering. Her research interests include aerial assisted wireless communications, green communications, electronics for low-cost humanitarian products, instrumentation and control systems.

Davis Kawooya Kayiza was born in Kampala, Uganda on the 16th of June 1992. He received a Bachelor of Commerce from Makerere University, Kampala Uganda in 2016, an Advanced Diploma in Accounting & Business from the Association of Chartered Certified Accountants (ACCA), UK in 2021, and a Master of Business Administration from Edinburgh Business School of Heriot-Watt University, United Kingdom in 2024. He is also a certified member of the Association of Chartered Certified Accountants, United Kingdom. He began his career as an external auditor at KPMG East Africa in 2015, and he currently works as an assistant manager in the Strategy and Deal Advisory department at KPMG Africa where he is involved in market studies and research in several sectors in Africa, including energy, in order to inform investment decisions.

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