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Techno-economic and environmental assessment of hybrid energy configurations for dairy farm electrification using organic waste

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Abstract

This study evaluates the technical, economic, and environmental performance of hybrid renewable energy systems (HRES) for Maizube Dairy Farm, Sabon Daga, Nigeria, using HOMER Pro software. Three configurations were analysed: solar-grid-battery, solar-diesel generator-grid-battery, and solar-biogas generator-grid-battery. These were compared with the existing system, which relies on an unreliable grid supported by a diesel generator. The evaluation considered Net Present Cost (NPC), Levelised Cost of Energy (LCOE), renewable fraction, operating cost, system reliability, and greenhouse gas (GHG) emissions. Results show that the PV-biogas generator-grid-battery configuration achieved the best overall performance. The optimal system comprises a 163 kW solar photovoltaic array, a 30 kW biogas generator, 236 kWh battery storage, and a 96.2 kW converter. It recorded an NPC of $635,258, a LCOE of $0.195/kWh, and a renewable fraction of 79.8%. Compared with the existing system, the proposed configuration reduced NPC by 52.9%, LCOE by 56.0%, operating cost by 76.2%, and CO_2 emissions by about 84%. Sensitivity analysis confirmed its economic viability under varying diesel prices and nominal discount rates. Overall, the proposed system offers a reliable, cost-effective, and sustainable solution for dairy farm electrification in areas with unstable grid supply.

Keywords: Battery storage; biogas generator; dairy farm; greenhouse gas emissions; hybrid renewable energy systems; HOMER Pro; photovoltaic system; unreliable grid supply.

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1. Introduction

Access to reliable and uninterrupted electrical energy remains a central driver of socio-economic development, technological progress, and improved human welfare. Despite sustained global efforts, a significant energy access gap persists. Over 789 million people, largely in Sub-Saharan Africa and rural South Asia, still lack a consistent electricity supply, while earlier estimates place this figure at approximately 1.3 billion people in developing regions with fragile infrastructure and low load density (Ayed et al., 2024). In these regions, the grid is often characterised by instability, frequent outages, and scheduled load shedding. Load shedding, implemented to prevent total grid collapse, introduces periodic disconnections that disrupt economic activities and reduce productivity (Adetoro et al., 2023b).

The agricultural sector, particularly dairy farming, is highly sensitive to such power interruptions. Dairy operations require continuous electricity for milking machines, ventilation, refrigeration, automated feeding systems, and waste management. Even short outages can lead to milk spoilage, animal stress, and financial losses. As a result, many farms rely on self-generation, traditionally through diesel generators (DGs), which provide reliability but at the expense of high fuel costs, operational complexity, and significant GHG emissions (Adetoro et al., 2023a). These challenges create a need for alternative energy solutions that ensure reliability while reducing long-term costs and environmental impact.

HRES have emerged as a practical solution to address these challenges. By integrating renewable energy sources such as solar photovoltaic (PV) and wind turbines with energy storage systems and dispatchable generators, HRES can provide stable and cost-effective electricity in both grid-connected and off-grid environments (Beyene et al., 2023; Ramkumar et al., 2025; Samatar et al., 2025). The declining cost of renewable technologies has accelerated their adoption; however, their intermittent and stochastic nature introduces a mismatch between energy generation and load demand. PV and wind generation depend on weather conditions and time of day, which makes them insufficient as standalone solutions for critical applications like dairy farming. To ensure system reliability, dispatchable generators play a key role in HRES design. These generators can be controlled to supply power on demand, compensating for renewable intermittency and grid outages. DGs have historically dominated this role due to their maturity, reliability, and relatively low initial capital cost. However, their long-term viability is increasingly questioned due to volatile fuel prices, high maintenance requirements, and emissions that can reach as high as 1.27 kg CO_2/kWh (Köprü et al., 2024). These limitations have driven interest in alternative dispatchable technologies that align with sustainability goals.

Biogas-based generators present a viable and sustainable alternative, especially in agricultural environments. Dairy farms create a lot of animal waste, which can be turned into biogas via anaerobic digestion. This biogas is a renewable energy source for electricity generation that also aids in the management of farm waste. Furthermore, biogas systems promote the sustainable economy by converting waste into usable energy and nutrient-rich fertiliser, which helps reduce environmental impacts and improve farm-level income (Emetere et al., 2021; Ferreira et al., 2025). Emissions from biogas systems are significantly lower, estimated at approximately 26g CO_2/kWh, making them a cleaner alternative to diesel (Köprü et al., 2024). However, their performance depends on consistent feedstock availability, proper digester sizing, and effective system integration.

The integration of dispatchable generators in load-shedding environments introduces significant design and operational complexity. The system must strike a balance between cutting costs, boosting reliability, and promoting ecological sustainability. Advanced modelling and optimisation tools are required to evaluate these trade-offs accurately. HOMER Pro is widely recognised as an industry-standard tool for such analyses. It enables detailed simulation of hybrid systems by evaluating thousands of configurations based on technical, economic, and environmental criteria. Key performance indicators include NPC, LCOE, and Loss of Power Supply Probability (LPSP). HOMER Pro also supports sensitivity analysis, allowing researchers to

assess the impact of variables such as fuel price fluctuations, solar radiation variability, and load changes (Adetoro et al., 2022; Aktas, 2024; Samatar et al., 2025; Woldegiyorgis et al., 2025).

The techno-economic optimisation of HRES has received extensive attention in recent years, due to the growing need to expand energy access and reduce dependence on fossil fuels. HOMER Pro has become a widely adopted tool for evaluating HRES configurations due to its ability to simulate system performance under varying technical and economic conditions (Azam et al., 2026). The software identifies optimal system designs by minimising NPC and LCOE while meeting load requirements (Araoye et al., 2024; Nguyen et al., 2024). Studies consistently show that grid-connected hybrid systems outperform standalone systems in terms of cost-effectiveness, as they allow energy exchange with the grid and reduce reliance on expensive storage solutions. HOMER also uses sensitivity analysis to examine how changes in inputs such as solar radiation, wind speed, biomass cost, and diesel consumption affect system performance under different conditions (Chauhan et al., 2022; Odoi-Yorke et al., 2022; Odou et al., 2020). Empirical studies demonstrate the economic potential of optimised HRES. For example, a seaport hybrid system achieved an LCOE as low as $0.03845/kWh (Samatar et al., 2025). Other studies in countries such as Pakistan and Ethiopia report carbon emission reductions of up to 49% when replacing diesel-only systems with PV-BS hybrids (Bakht et al., 2024; Woldegiyorgis et al., 2025). Reliability in these systems is often measured using LPSP, which quantifies the likelihood of unmet demand. However, many of these studies assume stable grid conditions, which limits their applicability to regions experiencing frequent load shedding.

Load-shedding environments introduce additional operational challenges. Hybrid systems must transition between grid-connected and islanded modes, often multiple times per day. This requires robust dispatch strategies and energy management systems. Common strategies include Cycle Charging (CC) and Load Following (LF). In the LF strategy, the generator runs only when needed and produces just enough power to fulfil the load requirement, which makes it more suitable for systems with high renewable fraction. CC, on the other hand, operates generators at full power to charge batteries, which can increase fuel consumption (Fatin Ishraque et al., 2021; Shezan et al., 2022). Advanced approaches, such as predictive dispatch algorithms, use short-term forecasts to improve system efficiency and reduce excess energy production (Ahmed et al., 2024; Osifeko, 2025).

The role of dispatchable generators in HRES is critical for maintaining reliability. DGs are still commonly utilised because of their simplicity and availability. However, their operational costs are heavily influenced by fuel price volatility and logistical challenges, particularly in remote areas (Adetoro et al., 2023b; Mohamed et al., 2025). The comparative performance of DGs and biogas generators (BGs) as dispatchable sources is a critical area of investigation. While DGs are technically mature, they are increasingly found to be financially unfeasible in the long term due to high fuel prices and significant carbon footprints. In contrast, biogas systems are highly efficient for electricity generation, especially in remote areas with grouped livestock operations. Research has demonstrated that replacing diesel with biogas can lead to massive cost savings, with some studies reporting a reduction in NPC of up to 84.5% over the project's lifetime (Araoye et al., 2021).

Biogas systems are particularly suited to agricultural applications. Dairy farms produce large volumes of manure that can be turned into biogas via anaerobic digestion. The process also yields digestate, which serves as an organic fertiliser. Studies on livestock farms in Turkey and India show that BGs can provide reliable load-following support, especially during nighttime or low solar output periods (Avci, 2025; Winsly et al., 2025). Additionally, modified diesel engines can operate on purified biogas, achieving stable performance (Theansuwan & Laohavanich, 2025). Environmental assessments consistently favour biogas over diesel. Biogas systems are considered carbon-neutral because the carbon released during combustion originates from recently absorbed atmospheric CO_2. In contrast, diesel combustion introduces fossil carbon into the atmosphere, contributing to climate change. Research shows that biogas-based systems can reduce total annual CO_2 emissions by a factor of nearly 60 compared to diesel-based systems (Köprü et al., 2024).

Many studies focus on either off-grid electrification or grid-connected cost reduction, without addressing the complexities of systems operating under scheduled load shedding. There is limited research comparing diesel and biogas dispatch strategies within such environments using a unified modelling framework. Most existing work also overlooks the practical integration of agricultural waste resources for energy generation, particularly in dairy farm applications where biogas potential is high. In addition, few studies simultaneously evaluate techno-economic performance, environmental impact, and system reliability under varying fuel price and economic conditions. This creates a gap in understanding the real-world feasibility of hybrid systems in rural areas with unstable grid supply and high dependence on diesel generation.

Table 1. Overview of previous studies on techno-economic analysis of HRES

Reference	Location	Components	Method	Research Objective	Sensitivity Analysis
Azam et al. (2026)	Hatiya Island, Bangladesh	PV, wind, BS, and grid	HOMER Pro and MATLAB	Optimise a hybrid energy system for island electrification considering technical, economic, and environmental performance.	Temperature, solar radiation, wind velocity, electricity tariff, feed-in tariff and inflation rate
Awadh et al. (2025)	Sharurah, Saudi Arabia	PV, wind, DGs, and BS	HOMER Pro linked with MATLAB	Determine the optimal hybrid system configuration for remote power supply	Diesel price and DG capacity
Jean et al. (2025)	University of Douala, Cameroon	PV, Biogas (human faecal biomass), and batteries	HOMER Pro	Assess the feasibility of human waste-based biogas hybrid electrification	Fuel cost, interest rates, and renewable resource availability
Barva et al. (2025)	Western India	PV, wind, and energy storage system (ESS)	HOMER Pro	Optimise renewable energy integration for a reliable electricity supply	Solar radiation, wind speed, and component costs/multipliers
Samatar et al. (2025)	Hobyo Seaport, Somalia	PV, wind, DG, pumped hydro, and BS	HOMER Pro and MATLAB	Develop an optimal hybrid system for seaport electrification	Modelling, optimisation, and simulation variables for generation and storage
Hüner (2025)	Hatay, Turkey	PV modules, biomass, fuel cell, and electrolyser	HOMER Pro	Evaluate biomass-based hydrogen hybrid systems under varying climatic conditions.	Meteorological conditions and power source configurations
El-Maaroufi et al. (2024)	Northern Morocco	PV, wind, biomass, batteries, and PCs	HOMER Pro	Design an economically viable renewable hybrid system for rural electrification.	Scaled average electric load, solar radiation, wind speed, and biomass availability.
Yadav et al. (2024)	Kanur, Maharashtra, India	Wind, PV, fuel cell, electrolyser, HSS, and BS	HOMER Pro	Optimise a renewable hydrogen-based hybrid energy system	Inflation, capital cost, wind/solar resources, project lifetime, and capacity shortage
Patil et al. (2024)	Banka District, Bihar, India	PV, wind, and biomass	HOMER Pro	Evaluate biomass-assisted hybrid systems for sustainable rural electrification.	Load demand fluctuations, resource availability, and technology improvements
Wincy et al. (2025)	South India	PV, wind turbine, biomass gasifier, BS	HOMER Pro	Assess the techno-economic performance of biomass-based hybrid systems	Variations in SPV cost, fuel price, and resource availability
Assouo et al. (2025)	Mayos Village, Cameroon	PV, biomass generator, DG, BS	HOMER	Assess the economic and environmental performance of biomass-based hybrid electrification.	Assessment of economic viability based on solar irradiation levels

Reference	Location	Components	Method	Research Objective	Sensitivity Analysis
Mahmoudi et al. (2025)	Remote communities	Wind, PV, DG	Gravitational Search Algorithm	Optimise hybrid system design considering carbon taxation	Sensitivity analysis of the carbon tax impact on the economic performance of the system
Avci (2025)	Diyarbakır, Turkey	Solar PV, BG, BS, PC	HOMER Pro	Evaluate the techno-economic feasibility of a biogas-based hybrid energy system.	Variations in biomass price, solar radiation, and interest rate
Aktas (2024)	Southampton, UK	Wind turbine, BG, CHP, BS	Quantity optimisation and simulation	Optimise CHP-based hybrid energy systems using biogas resources	Impact of inflation rates and project durations
Khattak et al. (2024)	Khyber Pakhtunkhwa, Pakistan	PV, DG, BS, utility grid	HOMER Pro	Design a reliable and cost-effective grid-connected hybrid energy system	Determination of uncertainties affecting ideal system behaviour
Agajie et al. (2024)	Debre Markos, Ethiopia	Solar PV, Biogas, PHES, SMES	NSWOA and MOPSO	Perform multi-objective optimisation of a renewable hybrid energy system	Identification of key sensitivities for informed decision-making
Hasan et al. (2024)	Kuakata, Bangladesh	PV, DG, BS	HOMER Pro software	Evaluate the techno-economic feasibility and reliability of a hybrid power system.	Fuel price, solar irradiation, temperature, inflation, and demand

This study evaluates a hybrid energy system that combines renewable energy sources with dispatchable generation under load-shedding conditions, addressing key gaps in rural energy planning. The configurations include diesel- and biogas-based systems, analysed using HOMER Pro to compare cost, reliability, and environmental performance. By utilising dairy farm organic waste for biogas production, the study presents a practical approach to reducing energy costs while improving supply reliability. This integration supports improved agricultural productivity and provides a pathway for sustainable rural development in areas with unstable grid electricity.

The primary objectives of this study are as follows:

- Design and simulate HRES configurations for Maizube Dairy Farm with HOMER Pro software.
- Compare and evaluate the technological, economic, and environmental sustainability of PV/grid/BS, PV/DG/grid/BS, and PV/BG/grid/BS systems against the existing grid/DG base case.
- Identify the optimal system configuration based on NPC, LCOE, renewable fraction, system reliability, and GHG emissions.
- Perform sensitivity analysis to assess system performance under differences in diesel fuel price and nominal discount rate.

The rest of this paper is organised as follows. Section 2 goes over the methodology, including the study area, input parameters, load profile, grid characteristics, renewable energy resources, system configuration, and economic and technical inputs used in HOMER Pro. Section 3 describes the mathematical modelling of the system components, including the PV system, biogas and DGs, BS, and bidirectional power converter (PC). It also describes the objective function employed for the techno-economic optimisation of the hybrid energy system. Section 4 discusses the simulation results, including optimisation, operational performance, environmental assessment, and sensitivity analysis. Section 5 concludes the study and highlights the key findings.

2. Methodology

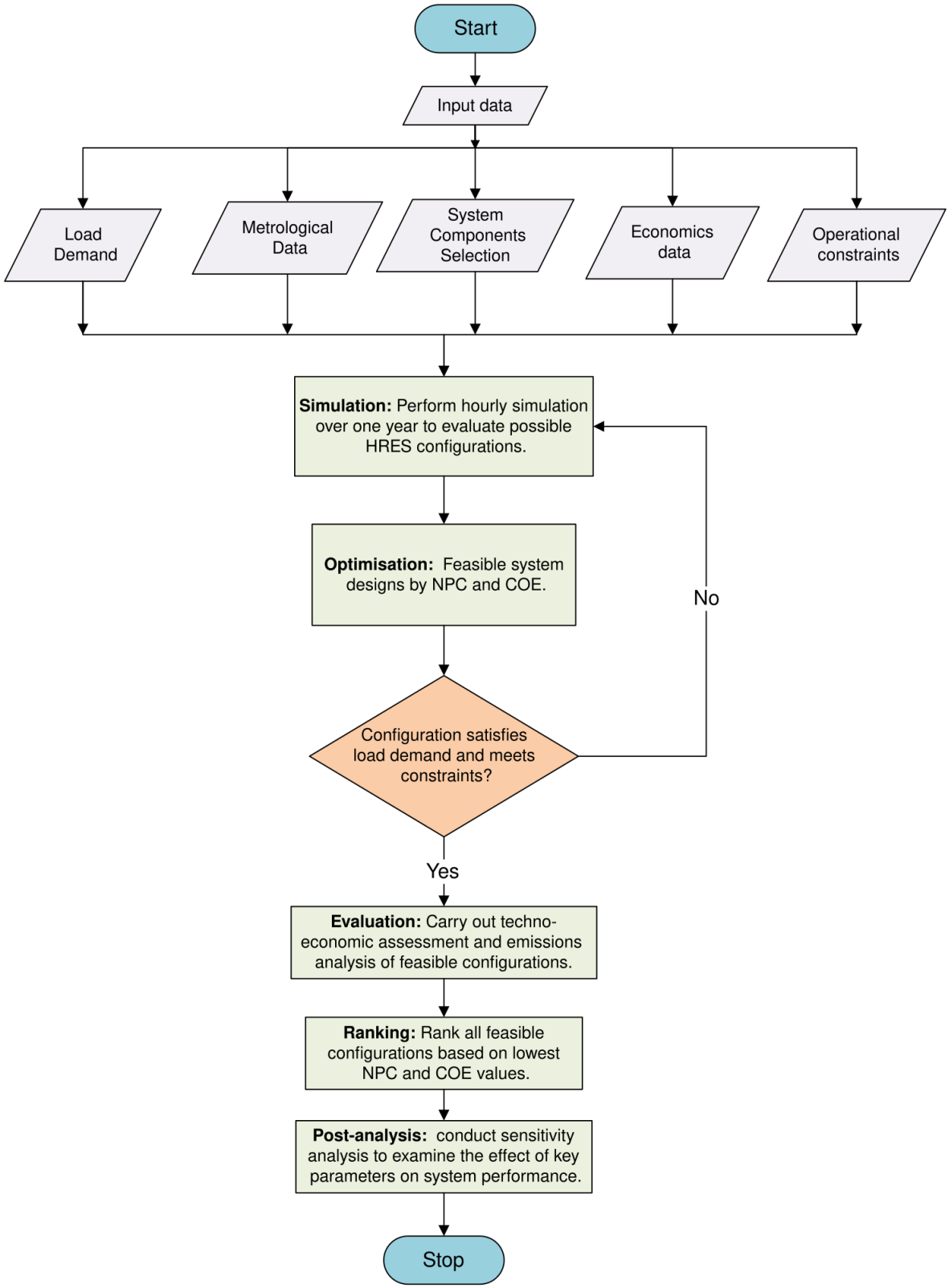


Figure 1. HOMER Pro optimisation procedure for the simulation and evaluation of HRES configurations.

This study employs HOMER Pro to model, simulate, and optimise a hybrid energy system for Maizube Dairy Farm, located in Sabon Daga, Nigeria. The analysis is based on site-specific meteorological data and the estimated electrical load profile of the farm. The electrical load profile, utility grid availability profile, meteorological data, and farm-specific information were obtained from our previous studies of the same Maizube Dairy Farm case study (Adetoro et al., 2023a, 2023b). No new farm surveys, interviews, field measurements, or participant data were collected for the present study. These previously established inputs were reused to support the new system configuration comparison, economic assessment, environmental evaluation, and sensitivity analysis presented herein. Three configurations were assessed: PV/grid/BS, PV/DG/grid/BS, and PV/BG/grid/BS, and their performance was compared with the existing system relying on grid and diesel generation. The novelty of this study lies in the comparative evaluation of these alternative hybrid energy system configurations using updated economic assumptions, together with an environmental assessment and sensitivity analysis. Using HOMER Pro, different system configurations were modelled with combinations of energy sources, storage units, and converters to evaluate their technical performance and economic feasibility under defined load requirements and operating constraints. The overall optimisation procedure implemented in HOMER Pro is presented in Figure 1 as a flowchart of the simulation and decision-making process. The software evaluates system performance using key economic and technical indicators such as NPC, LCOE, renewable fraction, and operating cost while ensuring that the required reliability constraints are satisfied. A sensitivity analysis was also performed on the optimal configuration by varying the diesel fuel price and nominal discount rate to examine the effect of fuel-cost and financing assumptions on system economics. Through this process, the most reliable, sustainable, and cost-effective hybrid energy solution for the study location was identified, thereby providing a structured basis for microgrid design and energy planning (Khan et al., 2021). This study is based on a single dairy farm case, with an estimated electrical load profile and an assumed grid availability profile. Fixed electricity tariffs and uncertainties in biomass availability and biogas conversion may affect the results. In addition, the environmental assessment considers only operational emissions estimated by HOMER Pro.

2.1. HOMER-Pro input parameters

The technical and economic assessment of the proposed hybrid energy system is carried out using HOMER Pro software. The model requires detailed input data describing the study location, electrical load demand, resource availability, and existing grid conditions. These inputs are structured to reflect the real operating environment of the Maizube farm, ensuring accurate simulation and optimisation of system configurations. The key input parameters include the geographical and operational characteristics of the farm, its load profile, grid supply reliability, and the availability of solar and biogas resources.

2.1.1. Load profile of the case study farm

This study is carried out at Maizube Dairy Farm, selected because of its strong suitability for integrating solar and biomass energy systems. The farm is located in Sabon Dagah, near Minna in Niger State, Nigeria, at approximately 9°24′36″N, 6°23′44″E, and it spans about 500 hectares. The location and satellite image of the farm are presented in *Figure 2*. Maizube Dairy Farm is a large agricultural facility made up of several operational units. It includes a milk production and processing section with a milking parlour and a processing plant capable of handling about 1,000 litres of milk per day. The farm also has supporting infrastructure such as a feed preparation centre, administrative offices, and an orchard. The livestock section consists of cattle housing units accommodating different breeds, including White Fulani, Sokoto Gudali, Holstein Friesian, and Red Friesian. Although the farm is connected to the grid, the electricity supply is unreliable. This has led to frequent reliance on diesel generators to maintain continuous operations across the facility.

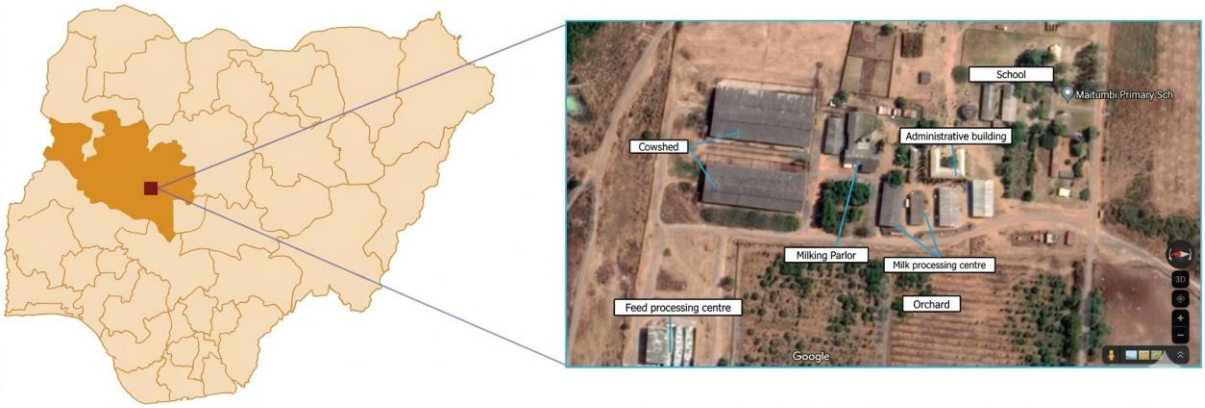


Figure 2. Geographic location and satellite image of Maizube Dairy Farm (Adetoro et al., 2023a).

The electrical demand at Maizube Dairy Farm follows a structured daily operation pattern, as shown in *Figure 3*, which presents the average weekly load profile. Routine farm activities take place from 08:00 to 17:00 on weekdays. Milking operations are carried out twice daily at 04:30 and 16:30, including weekends. The load data were collected through field surveys, questionnaires, and semi-structured interviews with farm staff. Only operational energy information was collected, participation was voluntary with informed verbal consent, no personal or identifiable information was recorded, and formal ethics approval was therefore not required. The main electrical consumers include pumps, compressors, ventilation fans, and lighting systems used across different sections of the farm. The farm records an average daily energy consumption of 917.57 kWh, with an average daily demand of 38.23 kW. Given a peak demand of 83 kW, the resulting annual load factor is approximately 46.1%. Seasonal conditions also affect electricity demand. Higher consumption is observed during the dry season (February to April) due to increased use of cooling equipment and water pumping systems. In contrast, lower demand is recorded during the harmattan period (December to January), when cooler weather reduces the need for cooling loads.

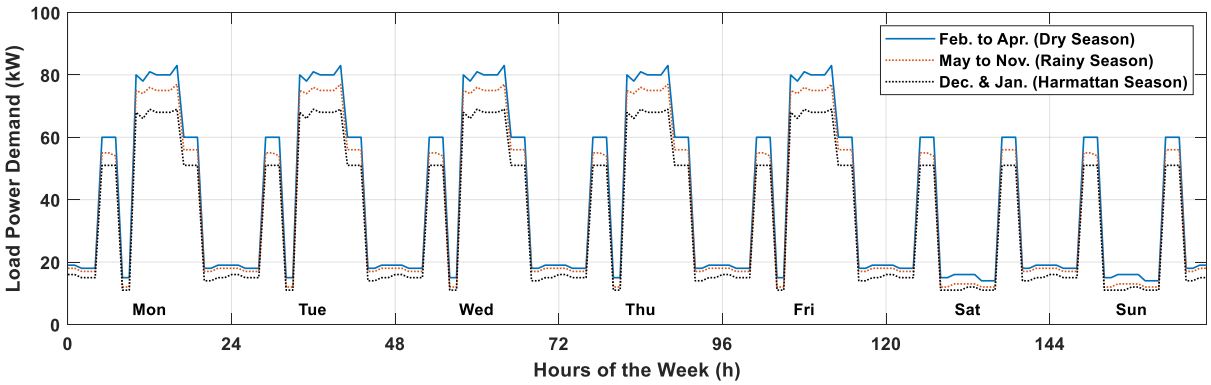


Figure 3. Weekly average load profile of Maizube Dairy Farm showing daily electricity demand pattern (Adetoro et al., 2023a).

2.1.2. Grid power supply characteristics

The farm is connected to the grid, but the electricity supply is unreliable and inconsistent. As illustrated in *Figure 4*, grid electricity is available for only about 6 hours per day on average, with outage occurrences exceeding 70%. This unstable power supply negatively affects farm operations and increases reliance on

alternative energy sources such as biogas and DGs to maintain uninterrupted operation of farm activities. In this study, a fixed grid electricity tariff of 0.12 $/kWh is adopted for imported electricity.

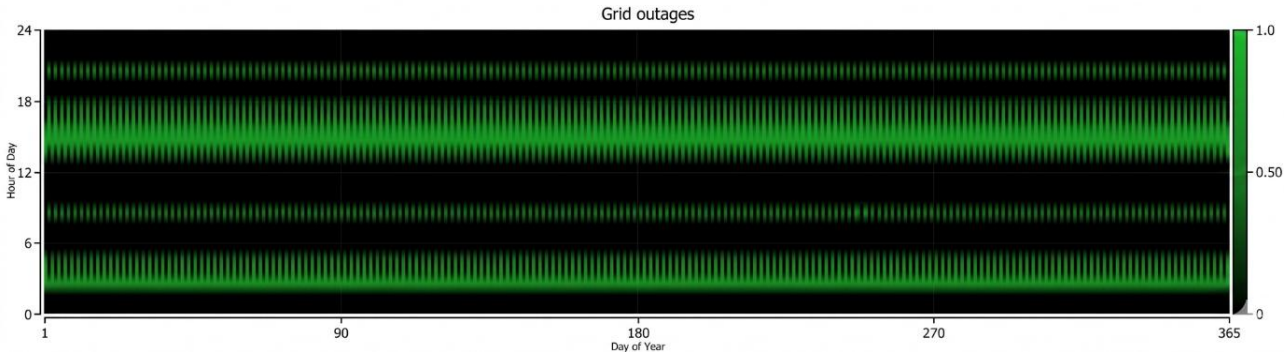


Figure 4. Grid electricity availability profile showing high outage frequency at Maizube Dairy Farm.

2.1.3. Solar energy resources

The study area has strong solar energy potential due to its location in the tropical region. Ambient temperature and solar irradiance data used in this study were obtained from the HOMER Pro database. The temperature data are derived from NASA, while the solar radiation data are sourced from the National Renewable Energy Laboratory (NREL). These datasets are developed from long-term satellite observations and validated ground measurements, providing reliable site-specific weather information. The data are available at hourly intervals over one year, resulting in 8,760 data points. Solar resource data, particularly global horizontal irradiance (GHI), are used in HOMER to calculate and predict the power output of the PV system. Ambient temperature data are used to account for temperature effects on system performance, particularly the efficiency of PV modules. This approach improves the accuracy of the simulation by reflecting actual environmental conditions at the study location. As illustrated in *Figure 5*, the solar resource is characterised by an average annual GHI of 5.59 kWh/m^2/day, with a peak in April (6.31 kWh/m^2/day) and a minimum in August (4.58 kWh/m^2/day). The clearness index ranges from 0.44 to 0.64, indicating moderate atmospheric conditions. The estimated annual solar energy potential is about 2040 kWh/m^2/year, confirming good solar availability for PV applications. As presented in *Figure 6*, the average ambient temperature is 26.27°C, varying from 24.34°C in January to 28.72°C in April. These temperature levels can slightly reduce PV efficiency, but the effect remains small. Overall, the high solar irradiance and stable temperatures support reliable PV system deployment at the site.

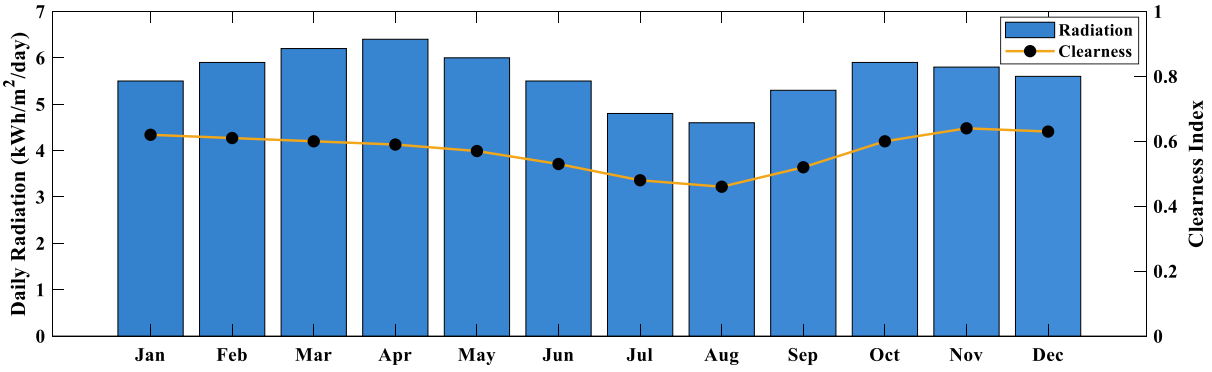


Figure 5. Monthly average GHI profile for Maizube Dairy Farm showing solar resource variation.

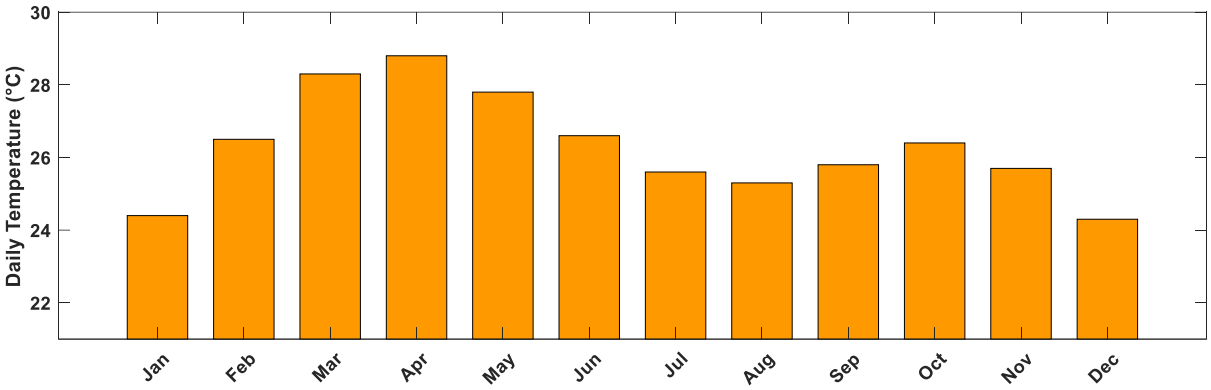


Figure 6. Monthly average ambient temperature profile for Maizube Dairy Farm.

2.1.4. Biogas energy potential

The farm has significant potential for biogas production due to the large quantity of organic waste generated daily. The farm houses over 300 cattle, although the quantity of manure produced varies seasonally depending on factors such as cattle population, feed availability, and management practices. Based on these variations, the farm generates a daily average of approximately 4.11 tonnes of organic waste per day, representing an ample feedstock source for biogas generation. This organic waste can be converted into biogas through anaerobic digestion, a biochemical process in which microorganisms break down organic matter in the absence of oxygen to produce methane-rich biogas (Alao et al., 2020; Lee et al., 2023).

Typically, biogas derived from such waste contains 55% to 75% methane (CH_4) and 25% to 45% carbon dioxide (CO_2) by volume (Ayodele et al., 2017; Diyoke et al., 2025). The mixture also includes trace amounts of other gases such as hydrogen sulphide (H_2S), nitrogen (N_2), hydrogen (H_2), carbon monoxide (CO) and ammonia (NH_3) (Ayodele et al., 2017; Diyoke et al., 2025). Leveraging this resource provides the farm with a dependable and cost-effective supplementary energy source for electricity generation, while simultaneously enhancing waste management practices and environmental sustainability. *Figure 7* illustrates the average daily organic waste availability (in tonnes/day) for each month of the year used in this study.

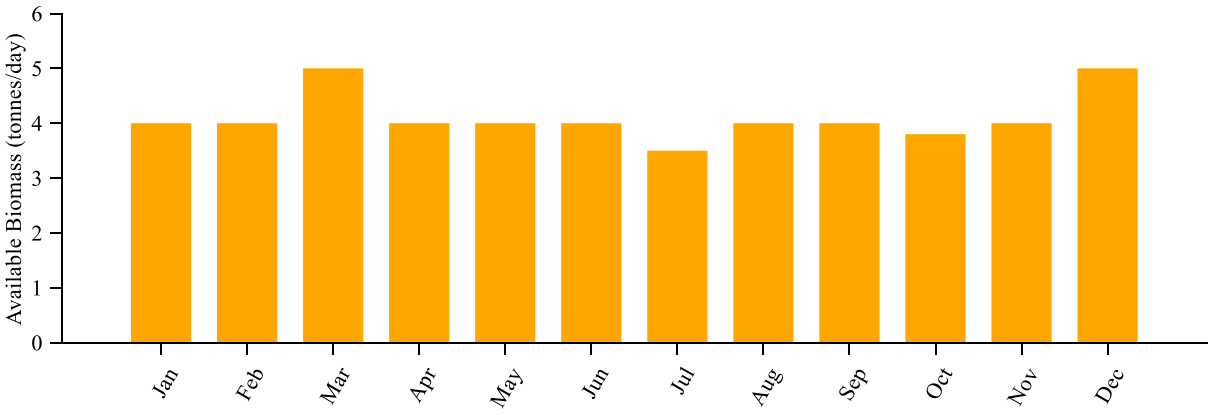


Figure 7. Monthly organic waste availability for biogas production at the farm.

2.2. System configuration

Figure 8 presents the proposed renewable energy systems for the farm. The system is designed to improve power reliability and reduce energy cost by incorporating renewable energy sources with the existing grid

supply. However, the grid at the study location is unreliable due to frequent load shedding. As a result, additional backup energy sources are required to maintain continuous operation. To identify the most suitable option, three system configurations are evaluated.

The first configuration, shown in *Figure 8(a)*, consists of a PV array, battery storage (BS), biogas generator (BG), and grid connection. In this configuration, the PV system supplies daytime electricity demand, while excess solar energy is stored in the battery for later use. The biogas generator provides additional renewable backup power during periods of low solar generation or grid outage. Organic wastes generated on the farm, including cow dung, leftover feed, and other biodegradable materials, are processed in an anaerobic digester to produce biogas. The produced biogas is then used to fuel the generator for electricity generation. This configuration improves energy reliability while promoting waste-to-energy utilisation and reducing dependence on the grid.

The second configuration, presented in *Figure 8(b)*, includes PV, BS, grid supply, and a diesel generator (DG). Similar to the first configuration, the PV system and battery storage meet a significant portion of the load demand. The DG operates as a backup source during periods of insufficient solar generation, low battery charge, or grid outage. Although this configuration improves supply reliability, it depends on diesel fuel, which increases operating costs and environmental emissions.

The third configuration shown in *Figure 8(c)* consists of PV, BS, and the utility grid without any additional backup generator. In this system, the PV array serves as the primary daytime energy source, while the battery stores excess energy for use during low solar periods. Due to the unstable nature of the grid supply, grid electricity is used only when the combined output from the PV system and battery storage is unable to satisfy the load demand.

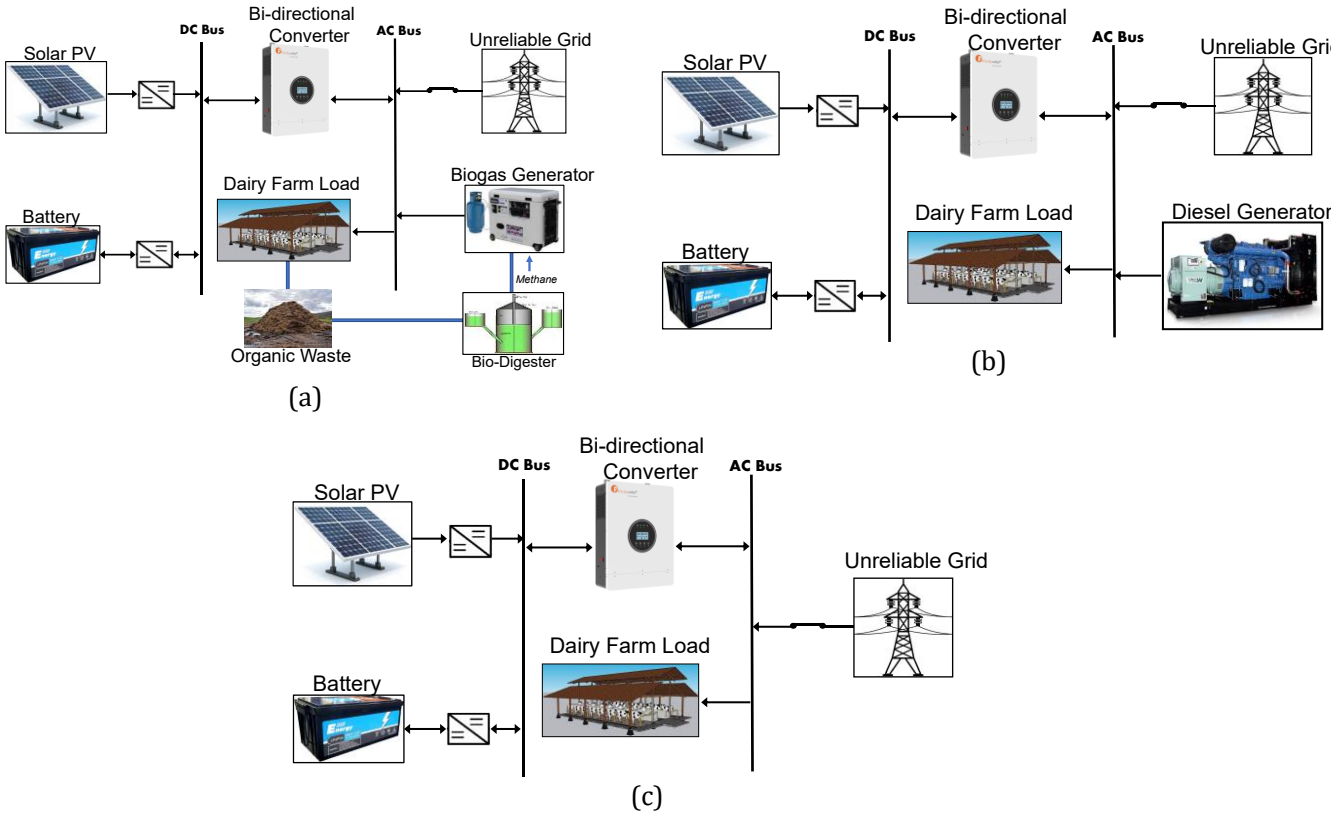


Figure 8. Proposed power system configurations for the farm: (a) PV-Battery-Biogas-grid system, (b) PV-Battery-Diesel Generator-grid system, and (c) PV-Battery-grid system.

2.3. Economic and technical parameters of the proposed hybrid energy system

Table 2 summarises the economic and technical parameters of the proposed hybrid energy system, including key components such as the grid, solar PV, BS, PC, BG, and DG. For each component, cost data and performance characteristics are specified. The project lifetime is set at 25 years to align with the operational lifespan of the solar PV system. These parameters support accurate modelling and optimisation in HOMER Pro.

Table 2. Cost and technical inputs for the proposed HRES

S/N	Component	Parameter	Value	Reference
1	Grid	Grid installation cost	0$	Bills (2025)
		Electricity purchase tariff	0.12$/kWh	
		Electricity export to the grid	0.07$/kWh	
		Grid Availability	30%	
2	Solar PV	Initial capital cost per unit	650$/kW	Nemouchi et al. (2024)
		Component replacement cost	500$/kW	
		Annual O&M cost	15$/yr	
		Service life	25years	
		Energy conversion efficiency	21%	
		Performance derating factor	80%	
		Temperature coefficient	−0.40%/°C	
3	Battery Storage	Battery technology	Lithium-ion	Khattak et al. (2024)
		Energy storage capacity	1kWh	
		Initial capital cost	1800$	
		Battery replacement expense	1400$	
		Annual O&M cost	20$/yr	
		Maximum discharge level	80%	
		Annual energy throughput	4500kWh/yr	
4	Power Converter	Initial capital cost per unit	300$/kW	Nemouchi et al. (2024)
		PC replacement cost	250$/kW	
		Annual O&M cost	5$/yr	
		Expected operating duration	15years	
		DC-AC conversion efficiency	95%	
		AC-DC conversion efficiency	94%	
5	Biogas Generator	Nominal power rating	10kW	Ali et al. (2023)
		Energy conversion rate	30%	
		Initial capital cost per unit *(including biodigester and biogas filtration system)*	3000$/kW	

S/N	Component	Parameter	Value	Reference
		Replacement cost	1200$/kW	
		Annual O&M cost	$100/kW/yr	
		Expected working hours	15,000hours	
6	DG	Initial capital cost per unit	450$/kW	Khattak et al. (2024)
		Generator replacement cost	350$/kW	
		Generator servicing cost	0.05$/hr	
		Useful operating life	15,000hours	
		Fuel-to-electricity efficiency	30%	
		Cost of diesel fuel	1.2$/L	
		Fuel consumption gradient	0.25L/kWh	
7	Control parameters	Project duration	25years	
		Simulation interval	1hour	
		Permissible yearly unmet load	1%	
		Nominal discount rate	10%	
		Energy management strategy	Cycle Charging	

3. Mathematical modelling of system components

The proposed energy systems comprise solar PV, PC, grid, BS, a BG, and a DG, as shown in *Figure 8*. The power output from renewable sources is assumed to remain constant within each one-hour simulation interval. This section describes the mathematical models used to represent each component for system performance evaluation.

3.1. Solar PV model

The power output of a PV system depends mainly on the level of solar radiation and the surrounding temperature at each time interval. In HOMER, the PV output is calculated using a built-in mathematical model based on standard photovoltaic performance equations.

$$P_{PV}(t) = P_{\mathrm{PV_r}} \times \delta \times \frac{I(t)}{I_{STC}}\left[1 + \gamma_T\left(\left(T_a + (0.0256 \times I(t))\right) - T_{STC}\right)\right] \quad (1)$$

In this expression, $P_{PV}(t)$ denotes the photovoltaic output power at time *(t)* in watts. $P_{\mathrm{PV_r}}$ is the rated or peak capacity of the PV system under Standard Test Conditions (*STC*). The derating factor δ accounts for real-world losses such as dust accumulation, wiring losses, and module mismatch effects. $I(t)$ represents the solar irradiance incident on the PV surface at time (t), measured in W/m^2, while I_{STC} is the reference irradiance under STC, fixed at 1000 W/m^2. The temperature coefficient of power, γ_T, reflects the sensitivity of PV output to temperature changes and is typically taken as -3.7×10^{-3} °C^{-1}. T_a is the ambient temperature in degrees Celsius, and T_{STC} is the standard reference cell temperature, which is 25°C.

3.2. Biogas generator model

The dairy farm generates cattle manure, which provides a continuous feedstock source for biogas production. In this study, the biogas potential was estimated based on the available manure resource and the fraction that can be practically collected and used for anaerobic digestion. The usable manure fraction was assumed to be 80% of the total available manure to account for collection limitations and handling losses (Oladigbolu et al., 2020).

The biogas generator was modelled as a dispatchable generation unit in HOMER Pro, supplying electricity when renewable resources such as solar PV were insufficient (Babalola et al., 2022). The BG capacity was varied from 0 to 100 kW during the optimisation process. The annual electrical energy produced by the BG is expressed as:

$$E_{BG} = P_{BG} \cdot T_{BG}^{yr} \tag{2}$$

where E_{BG} is the energy output (kWh), P_{BG} is the generator power (kW), and T_{BG}^{yr} is the operating time (hours/year). The generator size (P_{BG}^{max}) is determined from the biomass resource (Babalola et al., 2022):

$$P_{BG}^{max} = \frac{M_{ORG} \times \mathrm{F}_{usable} \times DM \times OF \times \Upsilon_{BG} \times CV_{BG} \times \eta_{BG} \times 1000}{T_{BG}^{yr} \times 860} \tag{3}$$

Where M_{ORG} is the available biomass (ton/year), F_{usable} is the usable manure fraction, DM is the dry matter fraction of manure, OF is the organic fraction of dry matter, Υ_{BG} is the biogas yield (m^3/kg ODM), CV_{BG} is the calorific value (kcal/m^3), η_{BG} is the electrical conversion efficiency of the BG, assumed as 30% (Gomez et al., 2010), and T_{BG}^{yr} is the annual operating time of the biogas generator (h/year).

In this study, the average manure availability was estimated at 4.11 tonnes/day (1,500.15 tonnes/year), of which 80% was assumed to be usable. The manure was assumed to contain 23% dry matter, with 85% of the dry matter considered organic, resulting in an estimated 234.62 tonnes/year of Organic Dry Matter (ODM). Based on a biogas yield of 0.30 m^3/kg ODM, the annual biogas production was calculated as approximately 70,387 m^3/year. With a methane content of 60%, the biogas calorific value was estimated at 5.97 kWh/m^3 (approximately 5,117 kcal/m^3). Assuming an electrical conversion efficiency of 30%, the corresponding theoretical electricity potential was calculated as approximately 126,063 kWh/year (126.06 MWh/year). The electrical conversion efficiency of the BG was assumed to be 30% (Ayodele et al., 2017; Diyoke et al., 2025).

3.3. Diesel generator operational model

The DG also serves as a dispatchable power source within the HRES. Fuel consumption depends on the DG's rated capacity and the actual load demand at each time step. For better efficiency, the generator is usually operated at moderate to high load levels.

The hourly fuel consumption is given by:

$$D_{fuel}(t) = AP_o(t) + BP_r \tag{4}$$

where $D_{fuel}(t)$ is the diesel fuel consumption rate (L/h), $P_o(t)$ is the generated power (kW) at time *t,* and P_r is the rated power capacity (kW). A represents the rate at which fuel use increases with load, while B represents fuel consumption when the system operates at no load or very low load. In this study, A is taken as 0.25 L/kWh, and B is 0.084 L/kWh. These parameters represent the generator's fuel consumption behaviour under varying load conditions and support accurate modelling of performance at partial load.

Within the HRES, the DG provides backup power during periods of low renewable generation or high demand, ensuring a continuous and reliable electricity supply.

3.4. Battery energy storage model

In HOMER Pro, the BS is modelled as an energy storage unit that balances supply and demand by storing excess energy and releasing it when generation is insufficient. The model updates the battery state of charge (SOC) at every time step based on the balance between charging and discharging activities, while also considering system losses. The stored energy in the battery at time *(t)* is computed as follows:

$$E_{BT}(t) = E_{BT}(t-1) + \eta_{ch} \cdot P_{ch}(t)\Delta t - \frac{P_{dis}(t)\Delta t}{\eta_{dis}} \quad (5)$$

where $E_{BT}(t)$ is the stored energy (kWh), $P_{ch}(t)$ is the charging power (kW), and $P_{dis}(t)$ is the discharging power (kW). The terms η_{ch} and η_{dis} represent charging and discharging efficiencies, and Δt is the simulation time step (1 hour). The state of charge is defined as:

$$SOC(t) = \frac{E_{BT}(t)}{E_{BT,max}} \times 100 \quad (6)$$

where $E_{BT,max}$ is the maximum BS capacity (kWh). The SOC is constrained within allowable limits to prevent overcharging and deep discharge:

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad (7)$$

In operation, the BS charges when excess energy is available from renewable sources and discharges when there is a deficit. This helps reduce reliance on dispatchable generators and improves overall system stability and efficiency.

3.5. Bidirectional power converter model

In a hybrid energy system with both AC and DC components, a bidirectional power converter connects the two sides and allows power to flow in either direction. It performs two main functions. It converts AC power to DC through the rectifier and converts DC power to AC through the inverter. This setup ensures that all components, regardless of their native form, can operate together in a single system.

The rectifier handles the conversion of AC power from sources such as the utility grid, DG, or BG into DC power. This DC output is mainly used to charge the BS system, especially during charging periods. The relationship between the input and output power depends on the rectifier efficiency:

$$P_{\text{Rec_out}}(t) = P_{\text{Rec_in}}(t) \times \eta_{Rec} \quad (8)$$

Here, $P_{\text{Rec_out}}(t)$ is the AC power supplied to the rectifier, $P_{\text{Rec_in}}(t)$ is the DC power delivered to the BS, and η_{Rec} represents the rectifier efficiency.

The inverter performs the reverse process. It converts DC power from sources such as solar PV, wind turbines, and the BS into AC power to supply load demand. This conversion is necessary because most appliances and grid systems operate on AC power. The inverter output is given by:

$$P_{\text{Inv_out}}(t) = P_{\text{Inv_in}}(t) \times \eta_{Inv} \quad (9)$$

In this case, $P_{\text{Inv_in}}(t)$ is the DC power entering the inverter, $P_{\text{Inv_out}}(t)$ is the AC power supplied to the load, and η_{Inv} is the inverter efficiency.

3.6. Objective function

In HOMER Pro, the techno-economic performance of a hybrid energy system is evaluated by minimising the NPC while also considering the LCOE and unmet load. The NPC represents the total lifetime cost of the system expressed in present value terms and is derived from the total annualised cost of the system.

The total annualised cost, $C_{\text{ann,tot}}$, represents the overall yearly cost of owning and operating the system. It aggregates all cost components converted into equivalent annual values, including capital investment ($C^j_{ann,cap}$), operation and maintenance expenses ($C^j_{ann,O\&M}$), replacement costs ($C^j_{ann,rep}$) and the salvage value, denoted as ($C^j_{ann,sal}$), which represents the remaining economic worth of component *j* at the end of the project lifetime.

$$C^j_{ann,tot} = C^j_{ann,cap} + C^j_{ann,O\&M} + C^j_{ann,rep} - C^j_{ann,sal} \tag{10}$$

Using this total annualised cost, the NPC is calculated by dividing it by the capital recovery factor (CRF), which accounts for the time value of money over the project lifetime.

$$NPC(\$) = \frac{\sum C^j_{ann,tot}}{CRF(i,n)} \tag{11}$$

The capital recovery factor converts present value into an equivalent annual cost and depends on the real discount rate *i* and project duration L_p.

$$CRF = \frac{i(1+i)^{L_p}}{(1+i)^{L_p} - 1} \tag{12}$$

The LCOE is then determined as the ratio of the total annualised cost to the total electrical energy supplied to the load annually, providing a measure of the average cost per kilowatt-hour.

$$LCOE(\$/kWh) = \frac{\sum C^j_{ann,tot}}{E_{served}} \tag{13}$$

Through this formulation, HOMER identifies the optimal system configuration by minimising NPC while ensuring that system constraints such as load demand and allowable unmet load are satisfied.

4. Results and discussion

This section presents the simulation, optimisation, and sensitivity analysis results obtained from the HOMER Pro analysis for the proposed hybrid energy systems at Maizube Dairy Farm, Sabon Daga, Nigeria. Three hybrid configurations, namely PV/grid/BS, PV/DG/grid/BS, and PV/BG/grid/BS, were evaluated and compared with the existing base case system consisting of an unreliable grid supply supported by a DG. The analysis focuses on key performance indicators such as NPC, LCOE, operating cost, renewable fraction, and system reliability. The operational performance of the PV array, BS, BG, DG, and grid supply in meeting the farm load demand is also discussed. In addition, a sensitivity analysis was conducted on the optimal

configuration to examine the effects of variations in diesel fuel price and nominal discount rate on the overall system economics and feasibility under changing economic conditions in Nigeria.

4.1. Optimised configuration results

The optimisation results of the different hybrid energy system configurations obtained from HOMER Pro are presented in *Figure 9*. Three proposed hybrid configurations were evaluated and compared with the existing base case system currently used at the study location, which consists of an unreliable grid supply supported by a DG. The results show significant differences in economic performance, operating cost, and renewable energy contribution among the configurations. Although the base case system has the lowest initial capital cost of $41,400, it recorded the poorest economic performance with the highest NPC of $1.35 million and the highest LCOE of $0.443/kWh. The high lifecycle cost is mainly due to continuous diesel fuel consumption, frequent operation of the DG during grid outages, and high operation and maintenance expenses. In addition, the base case system has a 0% renewable fraction, making it economically and environmentally unsustainable over the project lifetime.

Architecture												Cost				System
						PV (kW)	BiogasGen (kW)	Diesel Gen (kW)	Battery	Grid (kW)	Converter (kW)	Dis	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)
						163	30.0		236	999,999	96.2	CC	$635,258	$0.195	$34,243	$324,430	79.8
						212		92.0	582	999,999	107	CC	$720,556	$0.216	$33,008	$420,945	69.0
						266			645	999,999	257	CC	$774,389	$0.211	$32,224	$481,892	68.4
							40.0		311	999,999	96.4	CC	$828,079	$0.272	$60,285	$280,866	50.6
								92.0	158	999,999	54.7	CC	$1.11M	$0.365	$109,485	$114,682	0
									1,147	999,999	184	CC	$1.11M	$0.365	$70,565	$467,908	0
						203		92.0		999,999	74.1	LF	$1.20M	$0.369	$110,800	$195,705	39.2
								92.0		999,999		LF	$1.35M	$0.443	$143,729	$41,400	0

Figure 9. HOMER Pro optimisation results comparing the proposed hybrid energy system configurations with the existing base case system.

Among the proposed systems, the first configuration, which consists of PV/BG/grid/BS, achieved the best overall performance. The system comprises a 163 kW PV array, 30 kW BG, 236 kWh battery storage capacity, and a 96.2 kW PC. This configuration recorded the lowest NPC of $635,258 and the lowest LCOE of $0.195/kWh while achieving a renewable fraction of 79.8%. Compared with the base case system, the configuration achieved approximately a 52.9% reduction in NPC, a 56.0% reduction in LCOE, and a 76.2% reduction in annual operating cost. The improved performance is mainly attributed to the integration of biogas energy generated from farm organic waste, which significantly reduces diesel fuel consumption and dependence on the unreliable grid supply. Despite its relatively higher initial capital investment of $324,430, the configuration demonstrated strong economic viability.

The second configuration, consisting of PV/DG/grid/BS, recorded an NPC of $720,556 and a LCOE of $0.216/kWh with a renewable fraction of 69.0%. Relative to the base case system, this configuration reduced the NPC by 46.6% and the LCOE by 51.2%. However, the continued dependence on diesel generation increased fuel and maintenance costs compared to the biogas-based configuration. The third configuration, consisting of PV/grid/BS, achieved an NPC of $774,389 and an LCOE of $0.211/kWh with a renewable fraction of 68.4%. Although this system recorded a higher NPC than the PV/DG/grid/BS configuration, it achieved a slightly lower LCOE because eliminating the diesel generator removed fuel consumption and reduced routine operation and maintenance costs over the project lifetime. However, maintaining system

reliability without dispatchable generation required a substantially larger PV array and battery storage system, resulting in a higher initial investment and replacement costs, which increased the overall NPC.

4.2. Energy production and reliability performance of the evaluated hybrid energy systems

Table 3 compares the energy production and reliability of the three hybrid system configurations. The PV/BG/Grid/BS system supplied 334,869 kWh/yr of the load, with PV, biogas, and the grid contributing 269,417, 107,925, and 72,333 kWh/yr, respectively. The selected 30 kW BG generated 107,925 kWh/year over 3,647 operating hours, corresponding to 3,597.5 equivalent full-load hours. Its average operating output was approximately 29.59 kW. It maintained high reliability, with only 44 kWh/yr of unmet load and 326 kWh/yr of capacity shortage. The PV/DG/Grid/BS configuration achieved the highest reliability, with zero unmet load and capacity shortage, but relied on 72,485 kWh/yr of diesel generation and 80,059 kWh/yr of grid electricity. In contrast, the PV/Grid/BS system produced the highest PV output (440,324 kWh/yr) but also recorded the highest grid purchases (127,503 kWh/yr), excess electricity (123,076 kWh/yr), unmet load (246 kWh/yr), and capacity shortage (313 kWh/yr). Overall, the results indicate that the PV/BG/Grid/BS configuration offers the best compromise between high reliability and reduced dependence on fossil fuels. The selected configuration also exported 23,194 kWh/yr to the grid at the assumed tariff of $0.07/kWh.

Table 3. Energy production and reliability performance of the evaluated configurations

Configuration	Load Served (kWh/yr)	PV (kWh/yr)	BG (kWh/yr)	DG (kWh/yr)	Grid Purchase (kWh/yr)	Excess Electricity (kWh/yr)	Unmet Load (kWh/yr)
PV/BG/Grid/BS	334,869	269,417	107,925	–	72,333	67,516	44
PV/DG/Grid/BS	334,913	305,276	–	72,485	80,059	63,399	0
PV/Grid/BS	334,667	440,324	–	–	127,503	123,076	246

4.3. Peak load performance

The performance of the HRES under peak load conditions was evaluated using the first week of February, which represents a period of high energy demand. *Figure 10(a)* presents the time-series response of the system components, including the PV array, BG, BS, and grid, in meeting the electrical load throughout the week. The first five sections correspond to weekdays, while the last two represent the weekend. During weekdays, the load demand is higher and more variable due to increased farm activities. The PV system supplies a significant portion of the daytime demand, with peak generation occurring around midday. Surplus PV energy is used to charge the BS, while the BS discharges during evening and early morning hours when solar generation is unavailable.

The BG provides additional support during nighttime operation and periods of grid outage. It works together with the BS to meet evening peak demand, thereby reducing excessive BS discharge and maintaining a reliable power supply. Grid energy is intermittently purchased to support the system during sudden load increases or periods of low renewable generation. During the weekend, the load profile becomes lower and more stable, allowing the PV system and BS to satisfy a larger portion of the demand with reduced reliance on the grid and BG. *Figure 10(b)* shows the battery SOC profile over the same period. The SOC increases during periods of high PV generation and decreases when the battery supplies the load, particularly at night and during outages. Throughout the week, the SOC remains above the minimum allowable limit of 20%, indicating effective energy management and adequate protection against deep battery discharge.

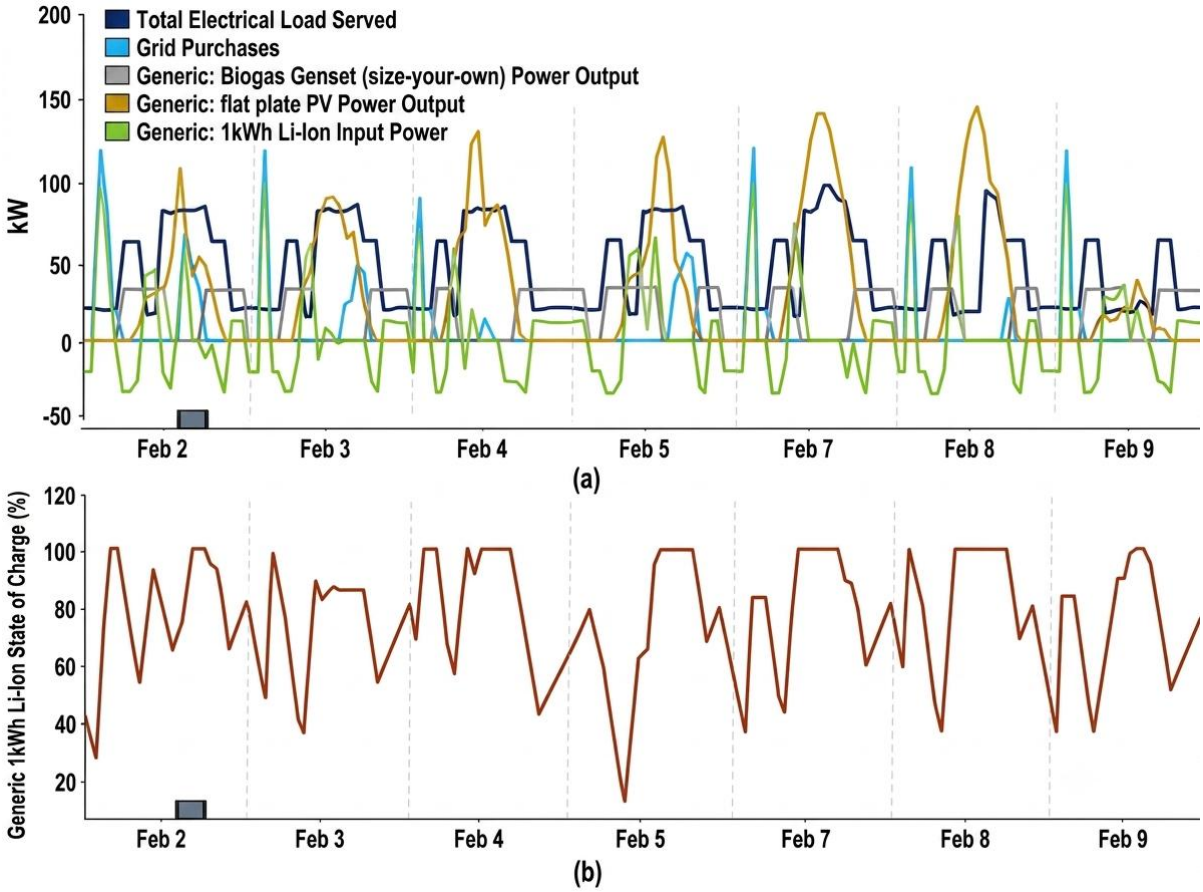


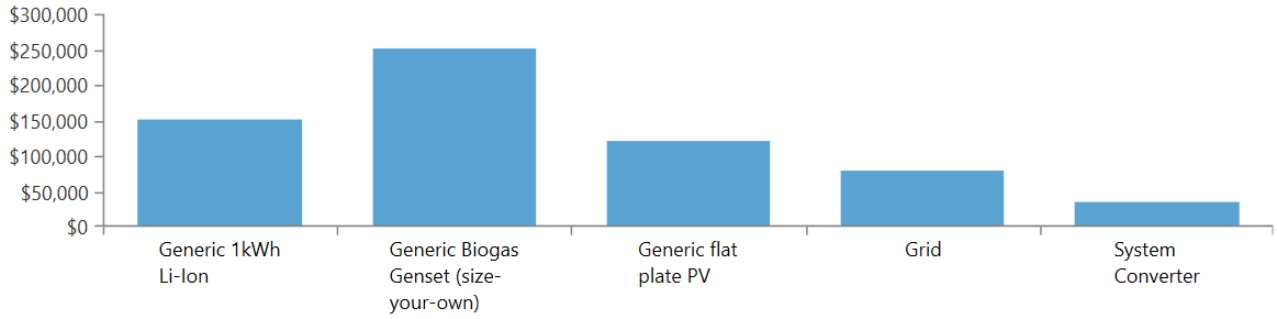
Figure 10. Peak load performance of the HRES (a) Time-series power contribution of system components. (b) Battery SOC profile.

The BG plays a significant role in maintaining the battery SOC by supporting evening loads during grid outages. This coordinated operation between the BG and BS improves system reliability, reduces grid dependence, and ensures stable operation under peak load conditions.

4.4. Component-wise lifetime cost breakdown of the proposed HRES

Figure 11 illustrates the total lifetime cost contribution of the major components of the proposed HRES, including the Generic 1 kWh Li-ion BS, Generic Biogas Genset, Generic flat plate PV, grid, and PC. The costs are categorised into capital, replacement, operation and maintenance (O&M), fuel, and salvage values. The Generic Biogas Genset has the highest total lifetime cost of approximately $250,655.42, mainly due to its high O&M expenses throughout the project lifetime. This shows that continuous generator operation significantly affects the overall system economics. The Generic 1 kWh Li-ion BS is the second-largest contributor, with a total cost of about $151,578.95, largely resulting from replacement and maintenance costs associated with BS degradation over time.

The generic flat-plate PV system contributes about $120,375.19, with most of the expense coming from the initial capital investment, while operating and replacement costs remain low. The grid contributes approximately $78,787.83 entirely from operating costs, indicating recurring electricity purchase expenses. The PC has the lowest contribution, around $33,860.32, showing a smaller economic impact compared to generation and storage components.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Generic 1kWh Li-Ion	$84,960.00	$45,558.02	$21,421.81	$0.00	-$360.87	$151,578.96
Generic Biogas Genset (size-your-own)	$105,000.00	$47,870.73	$99,311.89	$0.00	-$1,527.21	$250,655.42
Generic flat plate PV	$105,625.00	$0.00	$14,750.19	$0.00	$0.00	$120,375.19
Grid	$0.00	$0.00	$78,787.83	$0.00	$0.00	$78,787.83
System Converter	$28,845.39	$5,754.46	$0.00	$0.00	-$739.53	$33,860.32
System	$324,430.39	$99,183.21	$214,271.73	$0.00	-$2,627.61	$635,257.73

Figure 11. Lifetime component-wise cost breakdown of the proposed HRES obtained from HOMER analysis.

4.5. Annualised cost distribution over the project lifetime

Figure 12 presents the cost distribution over the 25-year project lifetime. The system experiences a high initial capital investment of about $320,000 at year 0 due to the installation of PV panels, BS, PC, and the BG. Operating costs remain relatively low and stable throughout the project, reflecting reduced fuel consumption and low maintenance requirements associated with renewable energy integration.

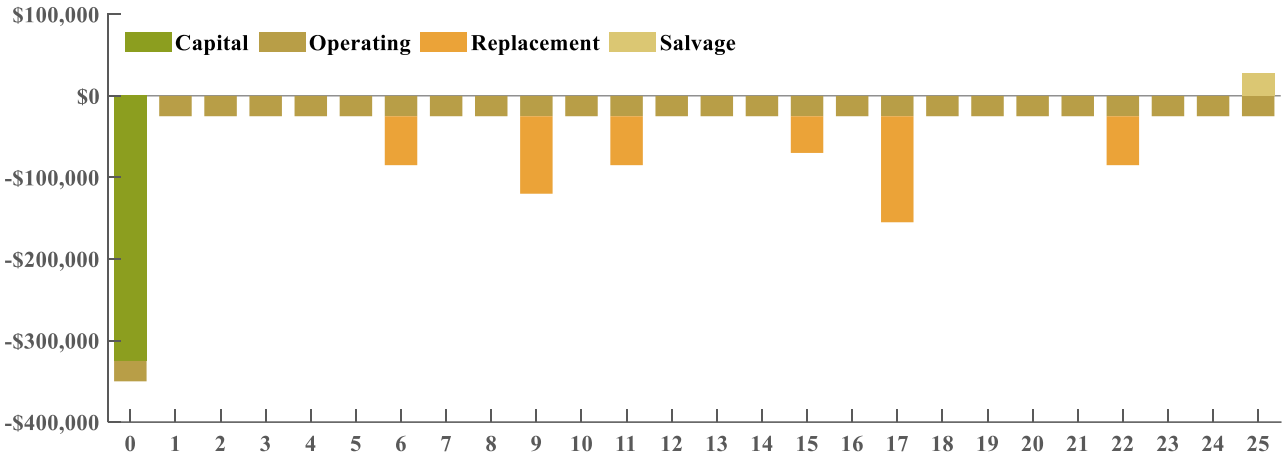


Figure 12. Lifecycle cost distribution of the proposed HRES over the 25-year project period.

Replacement costs occur at specific periods, mainly around years 6, 9, 11, 15, 17, and 22, primarily due to BS and PC replacements. The highest replacement cost occurs around year 17. At the end of the project lifetime, a positive salvage value is observed at year 25, indicating that some components still retain residual value. The HOMER results show that the proposed HRES requires a high initial investment but achieves lower operating costs and improved long-term economic performance over the project lifetime.

4.6. Monthly electricity production profile of the proposed HRES across seasons

Figure 13 shows the monthly electricity production profile of the proposed HRES, where total generation remains stable throughout the year, ranging between about 35 and 41 MWh. This confirms consistent system performance under seasonal variations. PV is the dominant energy source, contributing more than half of the total monthly generation. Peak output occurs in March, October, and November, when total production approaches 40 MWh. This reflects strong solar resource availability and confirms PV as the main supply source. The BG provides a steady contribution across all months, typically between 8 and 11 MWh. This stable output supports reliability, especially during periods of reduced solar generation, ensuring continuous baseload supply. Grid electricity is the least utilised source, with slight increases between July and September when PV output declines. During these months, the grid mainly acts as backup to maintain supply balance while overall dependence remains low. Seasonal variation is clear, with higher solar months reducing grid use and lower solar periods supported by biogas and limited grid imports. This interaction maintains a stable total energy output throughout the year.

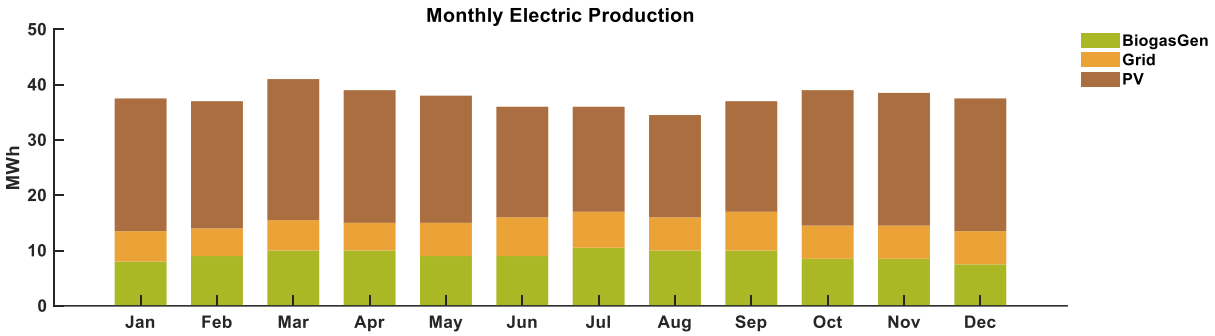


Figure 13. Monthly electricity production profile of the proposed HRES across seasonal conditions.

4.7. Comparison of GHG emissions for different hybrid configurations

The HOMER emission results compare the environmental performance of three hybrid energy system configurations, namely PV/BG/grid/BS (Conf. 1), PV/DG/grid/BS (Conf. 2), and PV/grid/BS (Conf. 3), with the existing base case system consisting of an unreliable grid supply supported by a DG (Conf. 4), as shown in *Figure 14*. The assessment considered modelled operational emissions of carbon dioxide (CO_2) separately from other air pollutants, including nitrogen oxides (NO_x), sulfur dioxide (SO_2), particulate matter (PM), carbon monoxide (CO), and unburned hydrocarbons (UHC). HOMER Pro estimates these emissions using the emission factors assigned to grid electricity, diesel generators, and biogas generators. Under the model assumptions, biogenic CO_2 released during biogas combustion is treated as carbon-neutral. Emissions associated with digester leakage, methane losses, manure management, construction activities, and component manufacturing are not included in the analysis.

Figure 14a compares the annual operational CO_2 emissions of the four configurations. Conf. 1 produces the lowest operational CO_2 emissions at approximately 45,000 kg/yr, followed by Conf. 3 and Conf. 2, with emissions of about 82,000 kg/yr and 105,000 kg/yr, respectively. The base case system (Conf. 4) records the highest operational CO_2 emissions at approximately 280,000 kg/yr because it relies heavily on diesel generation and grid electricity. Although Conf. 3 does not include a diesel generator, it still produces operational CO_2 emissions through electricity imported from the grid. In HOMER Pro, these emissions are calculated using the specified grid emission factor of 0.5346 $kgCO_2e/kWh$ for this study (Climatiq, 2012).

Compared with the base case, Conf. 1 achieves an estimated 84% reduction in modelled operational CO_2 emissions, while Conf. 3 and Conf. 2 reduce operational CO_2 emissions by approximately 71% and 63%,

respectively. In addition, Conf. 1 emits approximately 57% less CO_2 than Conf. 2 and about 45% less CO_2 than Conf. 3. These results indicate that the PV/BG/grid/BS configuration offers the lowest environmental impact and provides the most sustainable performance among the evaluated systems. On the other hand, Configuration 4 records the highest emissions for all pollutant types, mainly due to its strong reliance on diesel generators and an unstable grid supply. Although Conf. 2 and Conf. 3 perform better than the base case system, they still generate higher emissions than Conf. 1 because of their continued reliance on diesel generation or grid electricity.

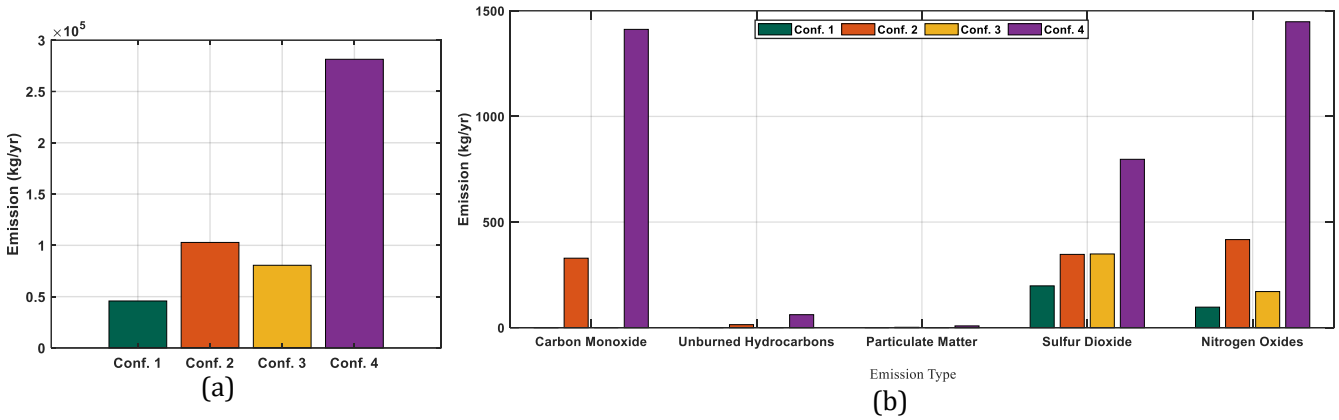


Figure 14. GHG emission comparison of the hybrid energy system configurations: (a) CO2 emissions and (b) other air pollutants (NO_x, SO_2, PM, CO, and UHC)

4.8. Sensitivity analysis

The sensitivity analysis presented in Figure 15 illustrates the operational and economic stability of the optimal PV/BG/grid/BS microgrid configuration under varying nominal discount rates (5% to 20%) and diesel fuel prices ($0.80/L to $1.40/L). The same hybrid configuration remains optimal across the assessed sensitivity space, indicating that the selected configuration is robust within these parameter ranges. LCOE increases from $0.157/kWh at a 5% nominal discount rate to $0.195/kWh at 10%, $0.232/kWh at 15%, and $0.276/kWh at 20%.

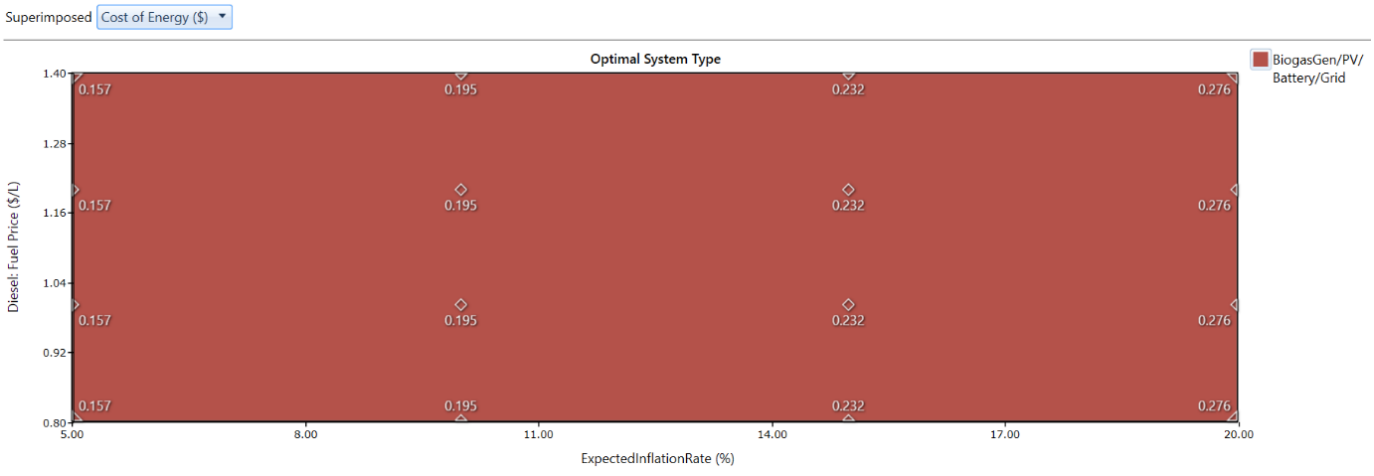


Figure 15. LCOE sensitivity analysis under varying diesel prices and nominal discount rates.

Conversely, variations in the diesel fuel price have virtually no effect on the LCOE of this optimal configuration because the selected system does not incorporate diesel generation. Although the optimal HRES is diesel-free, the diesel price sensitivity was explicitly evaluated to assess whether conventional DG-based configurations could become economically superior at lower fuel costs. The results demonstrate that the proposed PV/BG/grid/BS system remains the most cost-effective and optimal configuration even at the lowest diesel fuel price of $0.8/L, solidifying its economic dominance over conventional fossil-fuel-dependent alternatives.

5. Conclusion

This study evaluated the technical, economic, and environmental performance of hybrid renewable energy systems for Maizube Dairy Farm, Sabon Daga, Nigeria, using HOMER Pro. Three proposed configurations, namely PV/grid/BS, PV/DG/grid/BS, and PV/BG/grid/BS, were assessed and compared with the existing DG-supported grid system under the assumed farm load profile, grid availability, resource conditions, tariff structure, and cost assumptions. The assessment considered economic indicators, renewable fraction, reliability, electricity generation profile, emissions performance, and sensitivity to selected economic parameters. The results showed that the existing DG-supported grid system has poor economic and environmental performance due to its dependence on diesel generation and unreliable grid supply. Although it required the lowest initial investment, it recorded the highest NPC and LCOE over the project lifetime. Among the evaluated configurations, the PV/BG/grid/BS system provided the best performance under the study conditions.

The optimal system consisted of a 163 kW PV array, 30 kW BG, 236 kWh BS, and a 96.2 kW PC, achieving an NPC of $635,258, an LCOE of $0.195/kWh, and a renewable fraction of 79.8%. Compared with the base case, the system reduced NPC, LCOE, and annual operating costs by approximately 52.9%, 56.0%, and 76.2%, respectively. The PV/BG/grid/BS configuration also achieved the lowest operational emissions among the assessed systems, reducing annual CO_2 emissions by approximately 84% compared with the base case under the adopted modelling assumptions. Sensitivity analysis showed that the system remained economically competitive under variations in diesel fuel prices and nominal discount rates. The findings indicate that integrating solar PV, biogas generation, and battery storage can improve the energy, economic, and environmental performance of agricultural facilities with unreliable grid access. However, the results are specific to the considered farm conditions and depend on factors such as electricity demand, biomass availability, grid characteristics, tariffs, and component costs. Therefore, further studies involving different farm sizes, locations, resource conditions, and operational scenarios are required before applying the results to other energy-limited regions. Future work should also consider uncertainties in biomass supply, long-term component degradation, and real-time operational data to improve the assessment of system performance.

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