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Design, Techno-Economic evaluation and Environmental Sustainability Analyses of a Hybrid Solar–Biogas Electricity Generation System for Small Scale Agricultural Production in Sub-Saharan Africa

Izu godstime* 

Master of Engineering-Thermofluidic Engineering, Nigeria

Corresponding Author:

Izu godstime, Master of Engineering-Thermofluidic Engineering, Nigeria.

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Abstract

Access to reliable and sustainable electricity remains a major challenge for agricultural production in many developing countries, particularly in rural communities where dependence on fossil fuel generators results in high operating costs and significant environmental impacts. This study presents the design, optimization, techno-economic evaluation, and environmental sustainability assessment of a hybrid solar–biogas power system for decentralized agricultural electrification in Warri, Delta State, Nigeria. The hybrid system comprises a 37.62KWp photovoltaic array, a 33m³ anaerobic biogas digester, a 7.5kW biogas generator, a 96.8 kWh battery energy storage system, and a 25kW bidirectional converter. System optimization was performed using HOMER Pro, while Aspen Plus was employed to simulate the anaerobic digestion process and biogas production. The environmental performance of the optimized system was evaluated using Life Cycle Assessment LCA in SimaPro with the ReCiPe 2016 Midpoint H method and the ecoinvent v3.9 database.

The optimized configuration generated 66,428.0kWh year⁻¹, satisfying an annual electrical demand of 66,312.8kWh with a 100% renewable energy fraction, zero unmet load, zero capacity shortage, and only 0.17% excess electricity, demonstrating effective component sizing and energy management. The economic analysis indicated that the system is financially viable, with an Initial Capital Cost of USD 72,845,116.55 million, Net Present Cost of USD 91,624,146.60 million, a Levelized Cost of Energy of USD 0.078kWh⁻¹ ₦124.80 kWh⁻¹, and a Simple Payback Period of 5.8 years. The Life Cycle Assessment further revealed a Global Warming Potential of 0.142kg CO₂-eq kWh⁻¹, together with relatively low impacts in ecotoxicity, resource depletion, acidification, eutrophication, and water consumption compared with conventional fossil-fuel-based electricity generation. Environmental hotspot analysis identified photovoltaic module manufacturing and battery production as the dominant contributors to life-cycle impacts, while the utilization of cattle manure for biogas production significantly reduced methane emissions and improved waste management.

Overall, the integrated technical, economic, and environmental assessments demonstrate that the proposed hybrid solar–biogas energy system is a reliable, economically competitive, and environmentally sustainable solution for decentralized agricultural electrification. The findings provide a practical framework for the deployment of hybrid renewable energy systems in Nigeria and other developing countries with similar climatic conditions and agricultural resources.

Abbreviations

AC: Alternating Current

AOC: Annual Operating Cost

BESS: Battery Energy Storage System

CAPEX: Capital Expenditure

CO₂: Carbon Dioxide
 CO₂-eq: Carbon Dioxide Equivalent
 DC: Direct Current
 EF: Environmental Footprint
 GHG: Greenhouse Gas
 GWP: Global Warming Potential
 HOMER: Hybrid Optimization of Multiple Energy Resources
 ICC: Initial Capital Cost
 ISO: International Organization for Standardization
 LCA: Life Cycle Assessment
 LCC: Life Cycle Cost
 LCI: Life Cycle Inventory
 LCIA: Life Cycle Impact Assessment
 LCOE: Levelized Cost of Energy
 MPPT : Maximum Power Point Tracking
 NPC: Net Present Cost
 O&M: Operation and Maintenance
 OPEX: Operating Expenditure
 PV: Photovoltaic
 RC: Replacement Cost
 REF: Renewable Energy Fraction
 ReCiPe: Reference Life Cycle Impact Assessment
 SPP: Simple Payback Period
 SV: Salvage Value
 VS: Volatile Solids

Keywords: Hybrid renewable energy system, Solar photovoltaic, Biogas, HOMER Pro, Aspen Plus, Life Cycle Assessment, SimaPro, Techno-economic analysis, Agricultural electrification, Sustainable energy

Introduction

Energy production and utilization has remained major challenges in many developing regions, especially in Sub-Saharan Africa. Many small and medium scale businesses and as households depended on diesel generators and crude energy sources respectively since stable and affordable electricity is not available. Erratic power supply poor grid infrastructure or facilities hinder productive activities, hampers effective educational activities, and limit quality healthcare services delivery. Rural dwellers experience much lower access to electricity supply, leading to the dependence on traditional biomass such as burning of wood and coal, which emit carbon and other toxic substances that damage the ecological set-up. These challenges have however, triggered the need for renewable hybrid energy systems such as solar and biogas. Hybrid system is a technology that integrates two or more energy sources to ensure energy reliability and sustainability as well as the reduction fossil-based fuels consumption. Hybrid systems synchronizes the benefits of different energy resources to solve the problem of irregular power supply. Hybrid energy is not only good for reliable energy but also essential for off-grid and rural electricity supply [1,2].

Solar energy and biogas are renewable energy sources that complement each other by making up for the individual weaknesses. During the daytime, solar energy from the sun supplies the required electrical power, which can be affected by atmospheric conditions such as rainfall. However, biogas can be generated from animal dung and other biomass for continuous power production. Combining these two technologies ensures power stability at night or low solar radiation situations. Standalone renewable energy systems are systems that rely on a single source of energy generation. Such system is associated with energy generation bottlenecks, which pose serious limitation to electrical power reliability and consistency. Solar energy availability depends on weather conditions while biogas systems depend on degradable organic materials for continuous power supply. These individual limitations make standalone energy system (single-energy source) not suitable when energy reliability is considered. Therefore, an energy hybrid technology that adopts energy resource mix is essential for energy sustainability and reliability [3,4].

This study focuses on the design and evaluate a hybrid solar–biogas electricity generation system for sustainable power supply. The specific objectives include determining the optimal system design, estimating energy output from both solar and biogas sources, and assessing the sustainability performance of the system. The study also aims to evaluate the environmental and operational benefits of combining both technologies. It focuses on the design and sustainability analysis of a hybridized system that incorporate solar and biogas energy resources mix for electricity generation. The research will consider the sizing, energy assessment, and basic environmental assessment. Large scale or industrial energy generation will not be considered. The scope is limited to conceptual, design, economics, sustainability and other analytical assessment appropriate for rural energy applications [5,6].

The Review of Related Literature

Hybrid renewable energy refers to a system that integrates two or more energy resources for ensuring reliable energy supply. Such integration may involve the mix of solar, wind, biomass, or hydro to avoid epileptic or intermittent power supply. The design configuration of such energy mix is to ensure continuous power supply in which one energy source is used to complement or compensate for the weaknesses of other energy resources. In rural communities, hybrid systems are reliable energy generation process that can guarantee consistent electrical power supply. Furthermore, hybrid systems are important as they create the possibility of combining different energy production technologies that improve the overall energy output. Thus, hybridized energy system encourages energy security, reliability that ultimately decreases the reliance on fossil-based fuels, which are environmentally challenging. Additionally, hybrid system reduces system failure and bottlenecks since one source can redeem the weaknesses of the other. This makes it possible for changing climate and weather conditions to be managed [7,8].

Hybridized renewable systems may be solar-biogas, solar-diesel, solar wind, or multi-source systems that incorporate several sources of energy. Resource availability and energy requirement are the factors that determine the design configuration of each hybrid system. In recent years, solar-biogas systems have gained more attention because of the availability of organic waste especially in rural areas. Ecological preservation, cost, and efficiency are the fundamental factors considered in the selection of hybrid system. Biomass-based hybrids are considered in agricultural-based communities due to the relatively easy access to organic wastes from domestic and agricultural activities. By means of semiconductor materials, solar photovoltaic (PV) systems convert sunlight directly to electricity. Solar PV system's efficiency depends on solar radiation intensity, temperature, and design. PV systems have low operating cost and are suitable for both small household and systems that require large amount of energy. However, energy from solar PV is sunlight dependent [9,10].

Solar PV efficiency has a percentage range of 15% to 22%, which depends on the type of technology adopted. Losses due to heat, dust and shading can reduce the efficiency of solar PV system. However, good design and routine maintenance such as regular cleaning and ensuring optimal tilt angle can significantly increase the system's output. In addition, using technologically improved solar panels bifacial panels can enhance the overall efficiency. More so, solar panel orientation, location, and weather condition are crucial factors that influence the energy output of solar PV system. A geographical area with high solar radiation leads to greater output. The accumulation of dirt or dust particles on the solar panel's surface and high temperature lead to losses that ultimately reduce the efficiency. Variations in seasons such as cloudy or rainy periods are also serious challenges of solar PV system's efficiency. Dust accumulation and high temperatures can also reduce panel efficiency. Therefore, a good geographical location and proper maintenance are critical factors in the design of solar PV systems [11,12].

Food wastes, animal manure and other organic materials or biomasses can be converted to biogas by means of a digester in which anaerobic reaction takes place. During this reaction, biogas that is methane-rich is produced and can be used for cooking, heating and as feed fuel for biogas generator that produce electricity. The conversion of biomass to biogas helps in the management of wastes, which reduces pollution in rural communities. The four basic stages of biogas production process are hydrolysis, acidogenesis, acetogenesis, and methanogenesis. In these biological reactions, biodegradable substances or complex organic matter is converted into methane and carbon dioxide in the absence of air (anaerobic). The various stage depends on pH, microbial activity and temperature. Ultimately, a proper control of these crucial factors translates to efficient gas production. Digester design, retention time, temperature and feedstock type also have critical influence of the efficiency of biogas system. Optimal methane production is often obtained at mesophilic condition, which occurs at a temperature of about 35°C. With increased energy input, higher amount of gas can be obtained at thermophilic condition. Gas quality and the rate of production can be significantly reduced because of poor management of feedstock. Appropriate feedstock management and system's stability are essential for optimal biogas production [13-15].

By means of generators, biogas can be converted into electricity for various applications. It can also be used for cooking via combustion. As a clean energy source, it captures methane thereby reducing its emission from the decomposition of wastes or organic matters. As a substitute for firewood and charcoal in rural communities, it reduces deforestation. Upgraded biogas serves as bio-methane for grid injection. By capturing the methane gas that would have been released into the atmosphere during the decomposition of organic matters, biogas systems reduce greenhouse gas emission. In rural communities, biogas production helps in the management of waste thereby improving sanitary level of such areas. The digestate from biogas production serves as byproduct used as organic fertilizer, which reduces the demand for expensive chemical fertilizer. Ultimately, biogas contributes significantly to the quest for ecological preservation [16,17].

The hybrid solar-biogas system incorporates solar PV and biogas generation to provide constant supply of electricity energy. During the daytime, solar energy is used while biogas complements energy supply during nighttime or conditions of low solar radiation such as cloudy weather. This balancing process guarantees energy supply stability. This energy mix supports effective use of local renewable resources and adequate energy supply. Thus, hybridized system is more reliable than separate or standalone renewable systems. Solar and biogas energy technology mix guarantees energy reliability and enhances system flexibility. It encourages better utilization of local resources such as sunlight and organic, waste which complement each other for continuous operation with little or no interference. Ultimately, this helps to it

reduce dependence on fossil fuels and diesel generators. The long-term advantages include environmental sustainability and cost reduction [18,19].

Hybrid systems such as solar and biogas require certain key design factors. These include load, resource availability, system sizing, and control strategy. The aforementioned factors are critical to effective energy generation; hence, utmost attention should be given to each of them. Accurate load estimation is crucial to avoid under- sizing or over- sizing. Control systems help optimize switching between energy sources. Energy buffers such as battery storage is essential for system stability. Previous researches have established that energy reliability can be guaranteed via hybrid systems. That is, hybrid systems are better than standalone system, which depends on single energy source. However, earlier studies have focused more on solar and diesel. Very few studies have delved into the assessment of solar and biogas hybrid. Existing literatures had established that improved efficiency and emission reduction are the common advantages of hybrid system such as solar and biogas. Similarly, earlier studies have reported that solar–biogas systems produced cheap fuel with reduced emission rate. However, energy production depends on the availability of feedstock and solar resource. Others have reported that proper system sizing is essential for improved efficiency. All reported results are testaments to the potential of hybrid energy integration [20–22].

Generally, hybrid systems are associated with lower carbon emission when compared to fossil fuel-based systems. Nevertheless, process of handling wastes and the manufacturing of equipment have environmental consequences. In spite of these drawbacks, hybrid systems are viable choices for clean energy, as the aggregate emissions still remain significantly lower compared to fossil-based fuels. Apart from the initial high cost of investment, hybrid system offered long-term advantage in terms of cost reduction. Economically, hybrid systems are feasible with low maintenance cost including low fuel consumption. In addition, they encourage the use of local resources. However, payback periods depend on the size of the system and the location [23,24].

Solar-diesel or wind-solar systems have been mostly researched in previous studies with little focus on solar–biogas hybrid design. Furthermore, assessment on the sustainability of integrated hybrid system has not been fully explored. In addition, there are limited studies on a combined technical, environmental, and resource availability analysis. The need for this research is triggered by the absence of a real-world case study in Sub-Saharan Africa. The literature shows that hybrid renewable energy systems improve dependability and sustainability of power supply. However, solar–biogas systems remain under-researched, specifically in integrated design and sustainability assessment. Most studies do not completely mix technical, ecological, and operational aspects. This gap justifies the need for further research in this area. The present study addresses this constraint by concentrating on system design and sustainability performance [25].

Aim of Study

The aim of this study is to design and evaluate a hybrid solar–biogas electricity generation system and assess its techno-economic viability and the environmental sustainability as a reliable energy solution in Sub-Saharan regions.

Specific Objectives

- To design a hybrid solar–biogas electricity generation system by integrating solar photovoltaic (PV) technology with a biogas-based power generation unit.
- To determine the energy generation potential of the solar PV subsystem using available solar radiation data and system performance parameters.
- To evaluate biogas production and electricity generation capacity from organic feedstock is through anaerobic digestion and biogas utilization technologies.
- To develop an Aspen Plus process model of the hybrid system incorporating the major components such as feedstock preparation, anaerobic digestion, gas cleaning, biogas utilization, solar PV generation, energy storage, and power management units.
- To assess the operational performance of the hybrid system in terms of energy output, system efficiency, and reliability of electricity supply.
- To evaluate the environmental sustainability of the hybrid system through indicators such as greenhouse gas emission reduction, waste utilization efficiency, and fossil fuel displacement.
- To identify environmental hotspots within the hybrid system and determine the major contributors to environmental burdens across the system life cycle.
- To analyze sustainability trade-offs among climate change mitigation, resource utilization, and environmental impacts associated with the hybrid solar–biogas configuration.
- To compare the sustainability performance of the hybrid system with conventional fossil-fuel-based electricity generation systems.
- To examine the economic sustainability.
- To provide recommendations for the deployment of hybrid solar–biogas systems in rural and off-grid communities, particularly in Sub-Saharan Africa, as a pathway toward sustainable energy development

System Design and Methodology

System Configuration

The solar biogas hybrid system's configuration is made up of four major subsystems, which include the solar PV, biogas digester system, power management system and the storage unit. The hybrid system is configured to facilitate the conversion of two renewable energy resources via the integration of solar and biogas technology. This integration is structured to optimize energy generation for the purpose of continuous energy supply. It is strategically designed to improve energy stability and the reduction in the dependence of fossil-based fuel consumption, which ultimately preserves the ecological set up. Each component of the subsystem plays a crucial role in the energy transformation process, leading to increased availability of clean energy that is environmentally sustainable. An artificial intelligence unit is incorporated to facilitate the switch from one power source to another.

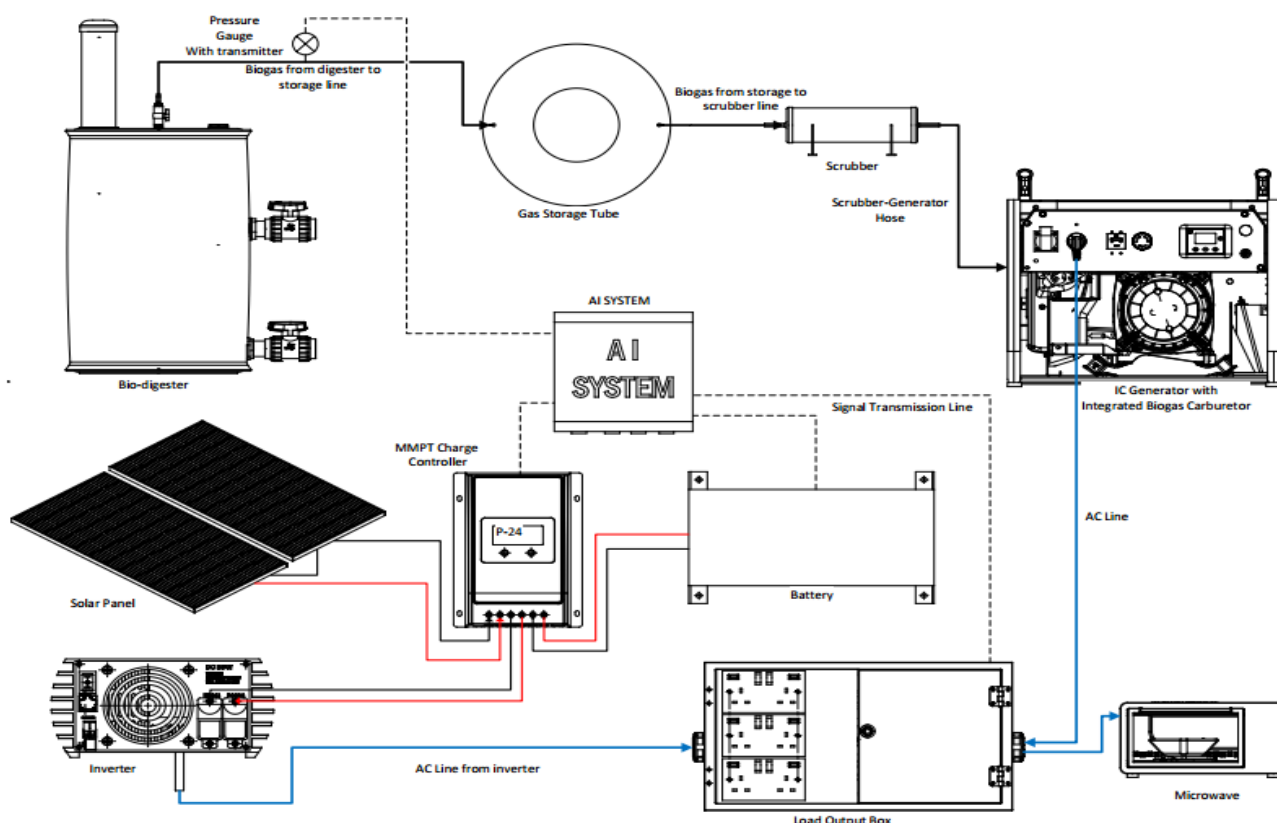


Figure 1: Solar Biogas Hybrid System Architecture

Solar PV Array

The solar photovoltaic (PV) array serves the component that captures the solar radiation and converts it directly to electrical energy via semiconductor cells on the panel's surfaces. The solar array is the chief source of energy supply during daytime. The load required is achieved through either series or parallel connection of the panels to achieve the desired voltage and current output. Solar PV array sizing depends on the daily energy requirement, location's average solar irradiance, and system efficiency losses. During peak sunlight hours, the solar panels supply the electrical powers required for charging the battery storage unit. Due to the fluctuation of weather conditions, the solar PV is not designed as a stand-alone system but rather, it is configured to be complemented by a biogas subsystem that converts organic matter into biogas (methane-rich) which can be converted to electricity via a biogas generator. Maximum solar PV efficiency output can be ensured by proper panel tilt angle and routine maintenance such as cleaning of dust from the surface of the panels.

Biogas Digester System

A digester is an airtight vessel in which complex organic matters are broken down by microorganisms in the absence of air. This process is called anaerobic digestion or decomposition. This process leads to the production of a biogas that is chiefly methane-rich in content. Thus, the digester system is the unit, which facilitates a continuous and dispatchable energy via the decomposition of organic matters such as food wastes, animal manure, agricultural wastes and other biomasses. The byproduct of these biological reactions is called digestate, which provides a good source of fertilizer for farming. The biogas produced is upgraded through purification or the removal of impurities and then stored in a gasholder. The stored gas serves as the feed fuel to a generator, which produces electricity mainly for cloudy conditions or night hours. In rural communities, a biogas system also facilitates the management of wastes by converting it into energy and cleaning the environment by capturing the methane, which would have escaped into the atmosphere. The efficiency of biogas production depends on the retention time, temperature, active microbial activities and feedstock quality. Proper feeding of good quality feedstock at the appropriate moisture level are critical factors that ensure optimal biogas production.



Figure 2: Photograph of Fabricated Mini Digester (Bioreactor)

Energy Storage (Battery or Buffer System)

The energy storage is the battery storage unit, which provides energy buffer system. The energy buffer system helps to eliminate epileptic power supply by ensuring electrical energy is available for continuous and smooth operation. Usually, the energy storage unit is made up of an array of rechargeable batteries such as lead-acid or lithium batteries. The choice of battery depends on load requirement, cost and efficiency. The excess energy generated during peak solar hour is stored in the battery and it is released to compensate for the excess demand of energy. However, the fluctuations in load demand can be catered for by incorporating super capacitors that can help to ensure voltage stability, avoid interruption of power for ensuring the overall reliability of power supply and improved efficiency. Ultimately, under-sizing the battery bank can lead to shortage of voltage supply while over-size increases operational cost.

Power Management System

The power management system is concerned with the subunit that helps in the coordination of the flow of energy within the subsystem of the hybrid. Power management system consists of the charge controller, inverter and an artificial intelligence-controlled switching device. During the peak solar hour or daytime periods, the solar PV subsystem is prioritized to supply the required electrical load and charge the battery bank. When solar radiation drops down during cloudy conditions, or nighttime, the artificial intelligence unit activates the battery to discharge the stored energy or switches to the biogas generator to complement the electrical energy supply. The power management system also monitors key parameters such as battery state of charge, load demand, and generator performance. Ultimately, the control system is crucial for attaining high efficiency, consistency, and sustainability in the hybrid energy setup.

Design Approach

The design approach of the design and sustainability analysis of a hybrid solar-biogas electricity generation system for small-scale agricultural production in sub-Saharan Africa begins with a comprehensive assessment of the overall load required of farm and its facilities. It was done by identifying the daily energy consumption expressed in kilowatt-hour and the peak load requirement. The sizing of the solar PV system's capacity required to supply the daytime energy using parameters such as solar panel specifications or characteristics, the location characteristics and the average solar irradiance followed this. These parameters enabled the accurate sizing of the solar PV system. The energy supplementing sub-system (biogas unit) was designed based on the availability of organic feedstock or biomasses. The generated biogas is the feed fuel for a generator which combust the biogas to produce electricity for night or periods of low solar radiation. These two sub-units are intended to ensure a continuous supply of electrical energy. The battery provides the energy storage system, which consists of battery bank sized to offer backup power supply to avoid fluctuation and disruptions and store the excess energy. Finally, a power management system is incorporated to prioritize energy supply between the solar and biogas sub-units. The energy hierarchy is implemented to prioritize energy generation from the solar PV system, storage, discharge and the generation of biogas during low solar radiation. This hierarchical order helps to ensure optimal energy generation and utilization.

Energy Requirement

A detailed load assessment was carried out to determine the daily electricity requirement of the farm that will be supplied by the proposed hybrid solar-biogas electricity generation system. The assessment considered all major electrical equipment used in the farm, including processing, biogas production, lighting, cooling and environmental control systems. For each piece of equipment, the quantity, rated power, and average daily operating duration were used to estimate the daily energy consumption in kilowatt-hours (kWh/day). This load profile forms the basis for sizing the solar photovoltaic array, biogas generator, battery storage system, and other supporting components of the hybrid energy system.

The analysis shows that the farm has nine categories of electrical loads, comprising a total of 19 individual electrical devices. The combined installed power rating of all equipment is approximately 27 kW, while the estimated total daily energy requirement is 181.72 kWh/day. This value represents the minimum amount of electrical energy that the hybrid

system must generate to ensure uninterrupted operation under normal conditions. The load assessment also provides insight into the distribution of energy demand among the different farm operations.

The electric dryer/conveyor fan is the largest energy consumer in the system. Two units, each rated at 5kW, operate for 8 hours per day, resulting in a combined daily energy consumption of 80.00kWh/day. This accounts for approximately 44.0% of the total daily energy demand, making it the dominant electrical load. Its high-energy requirement indicates that crop drying and material conveying are the most energy-intensive activities on the farm and should receive priority during system design and energy management. The bio digester heater represents the second-highest energy-consuming equipment. Operating at 5kW for 8hours per day, it requires 40.00 kWh/day, accounting for about 22.0% of the total daily energy consumption. The heater is essential for maintaining optimum digester temperature, thereby promoting microbial activity and stable biogas production. Continuous operation of this component is critical for sustaining methane generation, particularly during periods of low ambient temperature. The central air conditioning system is another significant electrical load. With a power rating of 3.6kW and an operating duration of 8 hours per day, it consumes approximately 28.80kWh/day, representing 15.8% of the total daily energy requirement. This load contributes to maintaining suitable environmental conditions for equipment operation and storage facilities, thereby supporting efficient farm activities.

The paddle incline agitator, which is responsible for mixing feedstock within the biogas-processing unit, consumes 16.00 kWh/day, equivalent to about 8.8%of the total daily energy demand. Proper agitation improves substrate homogeneity, enhances microbial contact with organic matter, and increases biogas production efficiency. Although its energy consumption is lower than that of the dryer and heater, its operational role is critical to the overall performance of the bio-digestion process. Other equipment, including the gas blower, purification pump, and manure pump, collectively consume a relatively small proportion of the total energy demand. The gas blower requires 6.25kWh/day (3.44%), the purification pump consumes 4.87 kWh/day (2.68%), and the manure pump uses 3.60 kWh/day (1.98%). These components facilitate gas transportation, purification, and feedstock transfer within the biogas production process. Despite their comparatively low energy requirements, they are indispensable for efficient plant operation and should be supplied with reliable electrical power.

The solid feeding system (mixer) and farm lighting constitute the smallest electrical loads. The feeding system consumes only 1.00kWh/day (0.55%), while ten energy-efficient LED bulbs consume 1.20 kWh/day (0.66%). Although these loads contribute minimally to total energy consumption, they are necessary for routine farm operations and worker safety, particularly during early morning and evening periods. Overall, the load profile indicates that energy demand is concentrated in a few high-power equipment, with the electric dryer/conveyor fan; bio digester heater, central air conditioner, and paddle incline agitator together accounting for approximately 90.6% of the total daily electricity requirement. This concentration suggests that optimizing the operation of these major loads would have the greatest impact on improving overall system efficiency and reducing operational costs. The calculated daily electricity demand of 181.72 kWh/day, serves as the design basis for the proposed hybrid solar–biogas electricity generation system. The solar photovoltaic subsystem should be sized to supply the majority of daytime loads, particularly the electric dryer and air conditioning system, while the biogas-powered generator should provide continuous electricity during periods of low solar irradiance and nighttime operation. Battery storage should further enhance system reliability by storing excess daytime solar energy for use during transient load fluctuations. This integrated design strategy ensures continuous power supply while maximizing renewable energy utilization and minimizing dependence on fossil-fuel-based backup systems.

S/N	Load/Equipment	Quantity	Rating (W)	Duration (Hours/Day)	Total Power Consumption (Kw/Day)
1	Electric dryer / conveyor fan	2	5000	8	80.00
2	Electric bulb	10	15	8	1.20
3	Air conditioner (Central)	1	3600	8	28.8
4	Paddle incline agitator	1	2000	8	16
5	Solid feeding system (Mixer)	1	1000	1	1.0
6	Manure pump 11 Kw	1	1800	2	3.6
7	Gas blower multi-staged	1	781.2	8	6.25
8	Purification pump	1	2435	2	4.87
9	Bio digester heater	1	5000	8	40
	Total	19	27000	53	181.72

Table 3.1: Load Assessment

Solar PV Array Sizing

The photovoltaic (PV) subsystem was designed to supply 70% of the total farm electrical demand, while the biogas subsystem supplies the remaining 30%. The total daily farm load is 181.72 kWh/day.

Daily PV Energy Requirement

$$E_{PV} = f \times E_L$$

E_{PV} = Daily energy supplied by the PV subsystem (kWh/day)

f = Fraction of the total load supplied by the PV system (0.70)

E_L = Total daily electrical energy demand (kWh/day)

$$E_{PV} = 0.70 \times 181.72 = 127.20 \text{ kWh/day}$$

Required PV Capacity

$$P_{PV} = E_{PV} / (H \times D_F \times \eta_{inv})$$

P_{PV} = Required PV array capacity (kW)

E_{PV} = Daily PV energy requirement (kWh/day)

H = Average daily solar radiation (4.60 h/day)

D_F = PV derating factor (0.88)

η_{inv} = Converter efficiency (0.96)

$$P_{PV} = 127.20 / (4.60 \times 0.88 \times 0.96) = 32.73 \text{ kW}$$

Applying a 15% design margin:

$$P_{Design} = 32.73 \times 1.15 = 37.64 \text{ kW}$$

Number of PV Modules

$$N = P_{Design} / P_{Module}$$

N = Number of PV modules

P_{Design} = Design PV capacity (37,640 W)

P_{Module} = Module rated power (285 W)

$$N = 37,640 / 285 = 132.07 \approx 132 \text{ modules}$$

Thus, a total number of 132 solar panels is required to power the farm and its facilities.

PV Area

$$A_{Total} = N \times (L \times W) \times 1.25$$

A_{Total} = Total installation area (m²)

N = Number of modules

L = Module length = 1.662 m

W = Module width = 0.996 m

1.25 = 25% spacing allowance

$$A_{Total} = 132 \times (1.662 \times 0.996) \times 1.25 = 273.1 \text{ m}^2 \approx 275 \text{ m}^2$$

Converter

Converter model = Leonics MTP-413F, Rated Power = 25 kW, Inverter efficiency = 96%, Rectifier efficiency = 94%, Lifetime = 15 years.

Technical Variables	Descriptions
Panel cell type	Monocrystalline
Nominal Max Power (Pmax)	285 W
Model	Cs6k-285m-Fg
Azimuth Angle (Degree) (W of S)	0
Derating Factor (%)	88
Ground Reflectance (%)	20
Solar Tracking system (Nil)	Nil

Lifetime (Years)	25
Max. Series Fuse Rating	15A
STC Rating (W)	285
Efficiency (%)	17.33
Open circuit voltage (V_OC)	38.6 V
Short circuit current (I_SC)	9.51 A
Optimum operating voltage (V_MP)	31.7 V
Optimum operating current (I_MP)	8.98 A
Nominal Cell Operating Temperature (NOCT)	45°C
Number of Cells	60 (6 x10)
Parallel String	11
Max. System Voltage	1500 (IEC) or 1000 V (UL)
Length (m)	1.662
Width (m)	0.996
Weight (kg)	23
Temperature coefficient for (Pmax)	-0.41%/K
Temperature coefficient for (V_OC)	-0.12 V/K
Temperature coefficient for (I_SC)	0.053%/K

Table 3.2: Solar Panel Technical Specification

Month	Daily Temperature (0C)
January	26.05
February	26.40
March	26.34
April	26.43
May	26.31
June	25.56
July	24.77
August	24.45
September	24.73
October	25.06
November	25.41
December	25.70
Average Temperature	25.52

Table 3.3: Average Daily Temperature

Month	Clearness Index	Daily Radiation (Kwh/M2/Day)
January	0.538	5.076
February	0.508	5.068
March	0.496	5.162
April	0.467	4.864
May	0.454	4.589
June	0.429	4.23
July	0.357	3.551
August	0.36	3.684
September	0.405	4.183
October	0.463	4.639
November	0.537	5.102
December	0.546	5.036
Average	0.46	4.60

Table 3.4: Monthly Average Solar Global Horizontal Irradiance/Clearness Index

The Canadian Solar CS6K-285M-FG monocrystalline photovoltaic module was selected because of its relatively high efficiency (17.33%), long design life of 25 years, and good performance under tropical climatic conditions.

Parameter	Value	Unit
Daily PV energy requirement	127.20	kWh/day
Required PV capacity	37.62	kWp
Module rating	285	W
Number of modules	132	Modules
Estimated annual PV generation	46,500	kWh/year
Average solar irradiation	4.60	kWh/m ² /day
PV lifetime	25	Years

Table 3.5: Solar Panel Specification Summary

Sizing of the Biogas Electricity Generation System

The biogas subsystem was designed to supply approximately 30% of the hybrid system electricity demand using cattle manure generated on the farm. The monthly biomass availability data were first analyzed before selecting the design basis.

Analysis of Monthly Biomass Availability

The monthly assessment shows a minimum manure availability of 0.84 t/day (February), a maximum of 0.93 t/day, and an annual average of 0.91 t/day. The variation is about 10%, indicating relatively stable feedstock availability throughout the year. Consequently, the annual average of 0.91 t/day was adopted for sizing, while acknowledging that gas production will be slightly lower during February.

Design Assumptions

- Average fresh cattle manure, $M = 0.91$ t/day
- Specific biogas yield, $Y = 25$ m³/t fresh cattle manure
- Biogas energy content, $CV = 6.0$ kWh/m³
- Generator electrical efficiency, $\eta_e = 35\%$
- Hydraulic retention time, $HRT = 30$ days
- Slurry density ≈ 1 t/m³
- 20% freeboard provided in digester sizing

Daily Biogas Production

$$V_g = M \times Y$$

V_g = daily biogas production (m³/day)

M = daily cattle manure (t/day)

Y = specific biogas yield (m³/t)

$$V_g = 0.91 \times 25 = 22.75 \text{ (m}^3\text{/day)}$$

Daily Electrical Energy

$$E_{bg} = V_g \times CV \times \eta_e$$

E_{bg} = electrical energy (kWh/day)

CV = calorific value of biogas (6.0 kWh/m³)

η_e = electrical efficiency

$$E_{bg} = 22.75 \times 6.0 \times 0.35 = 47.78 \text{ kWh/day}$$

Digester Volume

$$V_d = Q \times HRT$$

V_d = digester volume (m³)

Q = daily slurry input (0.91 m³/day)

HRT = hydraulic retention time (30 days)

$$V_d = 0.91 \times 30 = 27.30 \text{ m}^3$$

Design volume with 20% freeboard:

$$V_{desig} = 27.30 \times 1.20 = 32.76 \approx 33 \text{ m}^3$$

Gas Holder

$$V_h = 0.5 \times V_g$$

V_h = gas holder volume (m³)

$$V_h = 0.5 \times 22.75 = 11.38 \approx 12 \text{ m}^3$$

Generator Capacity

$$P_g = E_{bg} / t$$

P_g = generator capacity (kW)

t = operating period (8 h/day)

$$P_g = 47.78 / 8 = 5.97 \text{ kW}$$

Applying a 20% design margin:

$$P_{design} = 5.97 \times 1.20 = 7.16 \text{ kW}$$

Selected generator rating = 7.5 kW

Parameter	Value
Average manure	0.91 t/day
Biogas production	22.75 m ³ /day
Electrical energy	47.78 kWh/day
Digester volume	33 m ³
Gas holder	12 m ³
Generator	7.5 kW

Table 3.6: Summary of Biogas Design

Technical Variables	Value Unit
Generator Model	Generic Generator
Fuel type	Biogas
Operational lifetime (Hrs.)	80,000
Minimum efficiency (%)	85
Fuel Curve gradient (1/h/kW rated)	0.33
Fuel Curve intercept (1/h/kW rated)	0.05
Minimum load ratio (%)	30

Table 3.7: Biogas Generator Specification

Months	Available Biomass (Tons/Day)
January	0.93
February	0.84
March	0.93
April	0.90
May	0.93
June	0.90
July	0.93
August	0.93
September	0.90
October	0.93
November	0.90
December	0.93
Average	0.91

Table 3.8: Average Biomass Availability

Energy Storage System Design

The battery energy storage subsystem was designed to complement the photovoltaic and biogas subsystems by storing excess photovoltaic energy during periods of high solar irradiance and supplying electricity during transient load variations, cloudy conditions and short periods of low solar radiation. Because the biogas generator provides dispatchable backup power, the battery bank was designed for 12 hours of autonomy rather than a full day. The selected battery for this study is the Enersys Powersafe SBS 900 battery. The technical characteristics were obtained from the manufacturer's specifications and are presented in Table 3.9 shown below.

Kinetic Battery Model	Energys Power safe Sbs. 900 Battery
Nominal Voltage (V)	12
Nominal Capacity (kWh)	12.1
Maximum (Ah)	1010
Capacity Ratio	0.157
Rate Constant (1/hr.)	4.62
Round trip efficiency (%)	97
Maximum Charge current (I _{mc})	900 A
Maximum discharge current (I _{md})	720 A
Maximum charge rate (A/Ah)	1
Length	5.70 in
Height	8.10 in
Depth	27.4 in
Typical Weight Unpacked:	110 lbs.
Terminal Type	M10F
Volume	2.19 gal
Weight	23.7 lbs.
Volume	0.62 gal
Weight	9.41 lbs.
Lead Weight (per cell)	73.9 lbs.
Acid	H ₂ SO ₄

Table 3.9: Technical Specification of Battery

Design Assumptions

Total farm load = 181.72 kWh/day
PV contribution = 127.20 kWh/day
Biogas contribution = 54.52 kWh/day
Battery autonomy = 0.5 day
Depth of discharge = 80%
Battery efficiency = 97%
Battery bank voltage = 48 V

Battery Energy Requirement

$E_{bat} = (E_{Load} \times N_{aut}) / (\eta_b \times DOD)$
 E_{bat} = required battery capacity (kWh)
 E_{Load} = battery energy demand (63.60 kWh)
 N_{aut} = battery autonomy (0.5 day)
 η_b = battery efficiency (0.97)
DOD = depth of discharge (0.80)
 $E_{bat} = (63.60 \times 1) / (0.97 \times 0.80) = 81.96 \text{ kWh}$

Number of Batteries

$N = E_{bat} / E_{unit}$
N = number of batteries
 $E_{unit} = 12.1 \text{ kWh}$
 $N = 81.96 / 12.10 = 6.77 \approx 7 \text{ batteries.}$
A practical arrangement requires eight batteries.

Battery Bank Configuration

Four 12 V batteries are connected in series to obtain a 48 V battery bank. Two parallel strings are adopted, giving a 4S × 2P configuration. Installed capacity = $8 \times 12.1 = 96.8 \text{ kWh}$.

Energy Management System Design

The Energy Management System (EMS) coordinates the photovoltaic array, battery bank, biogas generator and converter to ensure reliable power supply to the 181.72 kWh/day farm load while minimizing fuel consumption and battery degradation.

Technical Variables	Value
Converter model	Leonics MTP – 413F 25kW
Rated Power	25 Kw
Relative capacity	80 %
Inverter efficiency	96 %
Rectifier efficiency	94 %
Lifetime	15 Years
Nominal AC Voltage	230V, 380V, 415V
Frequency Range	49.95-60.06 Hz
Frequency	50, 60 Hz

Table 3.10: Technical Specification of Converted

Engineering Assumptions

- PV is the primary energy source during daylight.
- Battery operates between 20% and 100% state of charge (80% DOD).
- Biogas generator starts when battery SOC falls below 30% or PV output cannot satisfy the load.
- PV charges the battery before surplus energy is curtailed.
- Converter operates within its 25-kW continuous rating.
- Critical farm loads receive highest priority during power shortages.

Energy Management Strategy

- During sunny periods, the PV array supplies farm loads directly. Excess PV energy charges the battery through the converter.
- When PV generation decreases, the battery supplies the deficit.
- If the battery state of charge reaches 30% and PV remains insufficient, the biogas generator starts automatically.
- The biogas generator supplies the load and simultaneously recharges the battery until the state of charge reaches approximately 90%, after which it shuts down.
- The EMS continuously monitors load demand, PV power, battery SOC and converter operating limits to prevent overload and improve system reliability.

Control Logic

IF PV $\geq$ Load: Load $\leftarrow$ PV; Surplus $\rightarrow$ Battery.

IF PV < Load AND SOC > 30%: Battery supplies deficit.

IF PV < Load AND SOC $\leq$ 30%: Start biogas generator.

IF SOC $\geq$ 90% AND PV adequate: Stop generator.

System Integration

The EMS integrates the previously designed 37.62KWp PV array, 96.8 kWh battery bank (4S $\times$ 2P), 7.5 kW biogas generator, and Leonics MTP-413F 25 kW converter. This coordinated operation maximizes renewable energy utilization while ensuring an uninterrupted electricity supply.

System Simulation and Sustainability Analysis

The hybrid solar–biogas electricity generation system developed in this study was evaluated using two complementary simulation platforms: HOMER Pro and Aspen Plus. HOMER Pro was employed to simulate the electrical performance, energy dispatch, and techno-economic behaviour of the hybrid system under varying operating conditions. The software integrates renewable energy resources, storage systems, and conventional generators to determine an optimal system configuration that satisfies the electrical demand while minimizing energy costs and improving system reliability. Its optimization capability makes it suitable for evaluating hybrid renewable energy systems in rural and agricultural applications. Aspen Plus was used to model the biogas production process and the associated material and energy flows. The software provides a rigorous process simulation environment that enables detailed modelling of the anaerobic digestion process, gas purification, and energy conversion units. Through mass and energy balance calculations, Aspen Plus predicts process performance, stream compositions, equipment duties, and system efficiencies. These outputs support the engineering design of the biogas subsystem and provide inventory data for subsequent environmental sustainability assessment. The integration of HOMER Pro and Aspen Plus provides a comprehensive evaluation of the proposed hybrid energy system. While HOMER Pro assesses the electrical performance, renewable energy fraction, battery utilization, and generator dispatch, Aspen Plus analyses the thermodynamic and process characteristics of the biogas production pathway. Together, the two simulation platforms provide a robust framework for validating the hybrid system design and assessing its technical, economic, and environmental performance [26-28].

Homer Pro Model Setup

HOMER PRO MODEL – SOLAR BIOGAS HYBRID SYSTEM

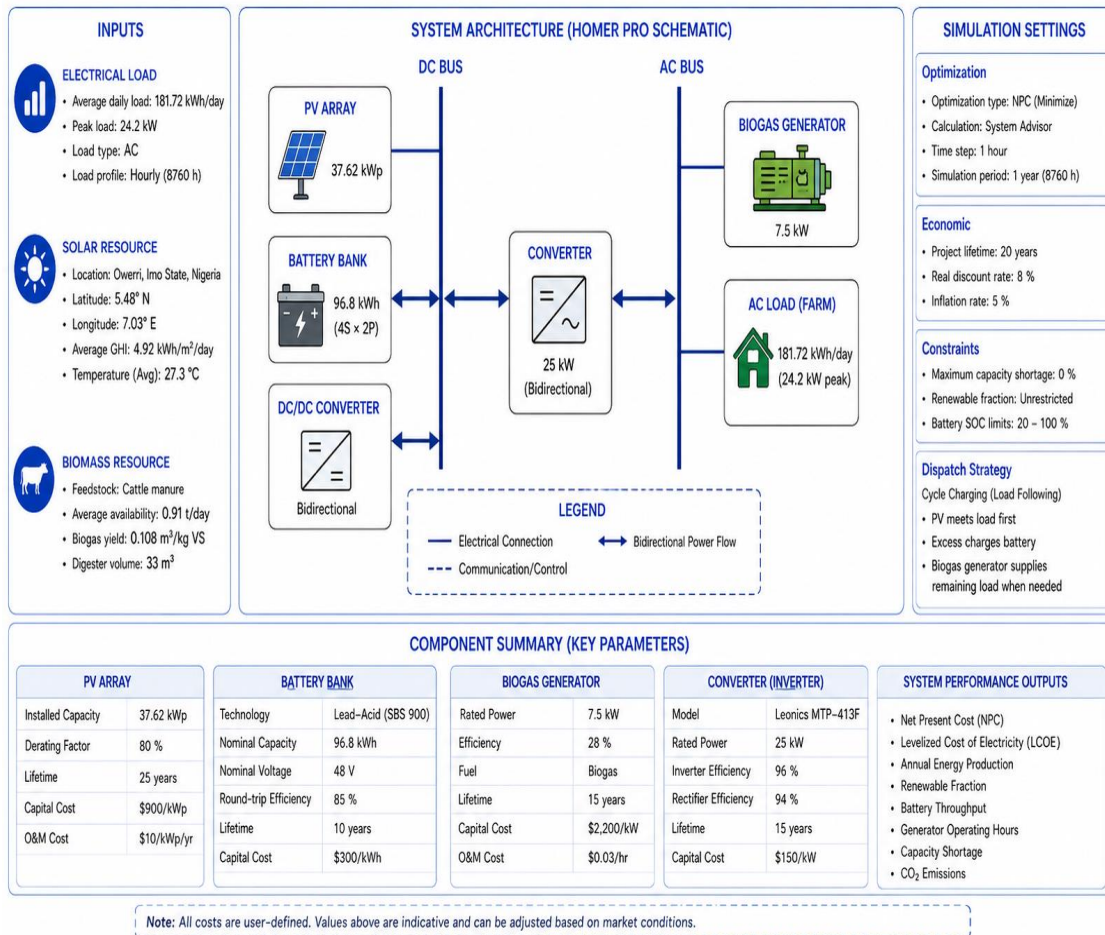


Figure 3: Homer Pro. Model Simulation Set Up

Aspen Plus Process Model

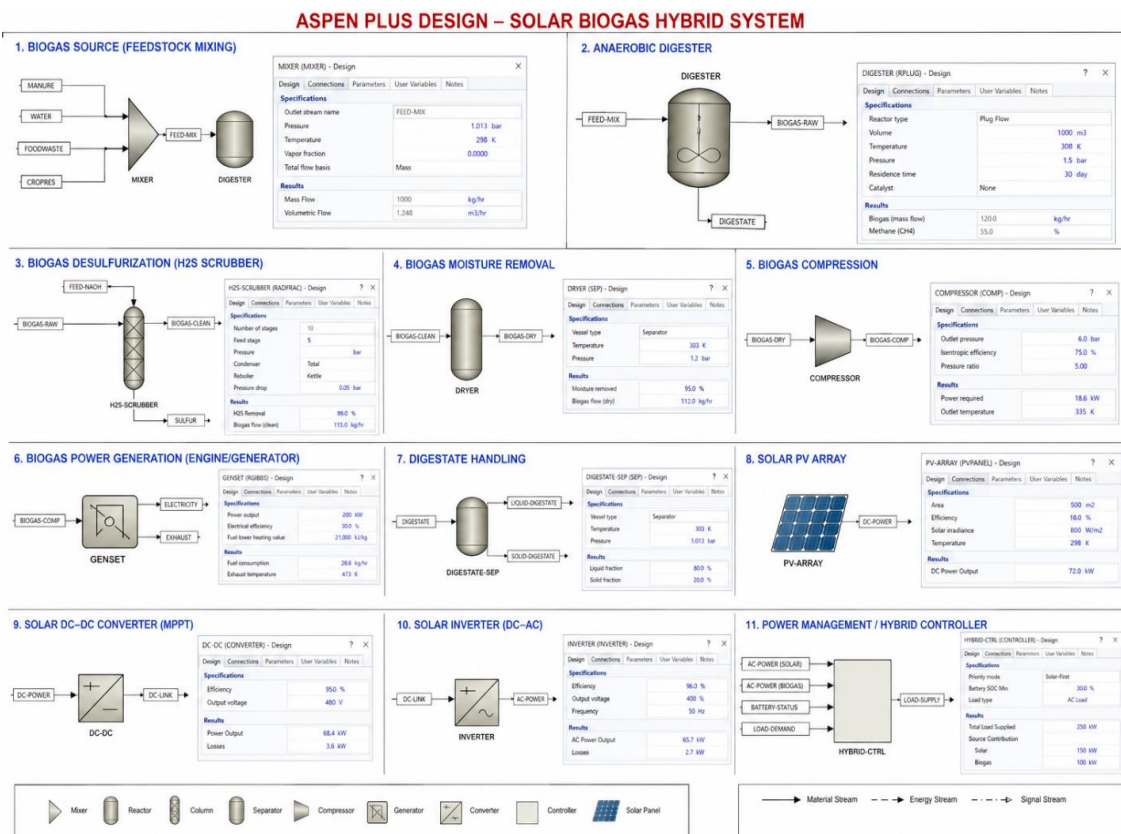


Figure 4: Aspen Plus Simulation Set Up

Simulation Assumptions

General Assumptions

- The hybrid system operates continuously throughout the year (8760 hours).
- The daily electrical demand remains constant at 181.72 kWh/day.
- All electrical equipment operates under steady-state conditions unless affected by renewable resource variability.
- Ambient weather conditions are represented by monthly average solar radiation and temperature data.
- Equipment performance deteriorates only according to the specified component lifetime.
- Scheduled maintenance is assumed not to interrupt electricity supply because the hybrid configuration provides redundancy.
- Power transmission losses within the farm are neglected due to the short cable distances.
- Electrical loads are assumed to have a power factor close to unity.

HOMER Pro Simulation Assumptions

Solar Resource

- Monthly average solar radiation data accurately represent the site's solar resource.
- Average annual solar irradiation is 4.60kWh/m²/day.
- Average ambient temperature is 25.52°C.
- Solar radiation is uniformly distributed according to HOMER Pro's synthetic hourly generation model.
- The PV array is fixed-tilt with no solar tracking.
- PV module derating factor is 88%.

PV Array

- Installed PV capacity is 37.62 kept.
- PV module efficiency remains constant at the manufacturer's rated value.
- Temperature effects are incorporated through the module-derating factor.
- Shading losses are neglected.
- Dust accumulation is included in the derating factor.

Battery System

- Installed battery storage capacity is 96.8 kWh.
- Round-trip efficiency is 97%.
- Maximum depth of discharge is 80%.
- Initial Battery State of Charge (SOC) is 100%.
- Minimum allowable SOC is 20%.
- Battery degradation during the simulation year is neglected.

Biogas Generator

- Rated electrical power is 7.5 kW.
- Generator efficiency remains constant during operation.
- Biogas supply from cattle manure is sufficient throughout the year.
- Average manure availability is 0.91 t/day.
- Biogas production is assumed continuous.
- Generator maintenance does not interrupt system operation.

Converter

- Converter rated power is 25 kW.
- Inverter efficiency is 96%.
- Rectifier efficiency is 94%.
- Converter loading remains within its rated capacity.
- Harmonic distortion and reactive power losses are neglected.

Energy Management Strategy

- PV generation has first priority in supplying the electrical load.
- Surplus PV energy is used to charge the battery bank.
- The battery supplies the load whenever PV generation is insufficient.
- The biogas generator starts automatically when the battery SOC falls below 40% or when PV output cannot satisfy the load.
- The generator stops when the battery SOC reaches 90% and PV generation becomes sufficient.
- Excess renewable electricity is curtailed whenever the battery is fully charged and the load demand has been satisfied.

Economic Assumptions

- Project lifetime is 25 years.
- Component replacement follows the specified equipment lifetime.

- Capital, replacement, and operation and maintenance costs remain constant during the simulation period.
- Inflation and discount rates remain constant throughout the project life.

Aspen Plus Simulation Assumptions

Feedstock

- Cattle manure is the sole feedstock.
- Average feedstock availability is 0.91 tones/day.
- Feedstock composition remains constant throughout the year.
- Feedstock is well mixed before entering the digester.
- Feed moisture content is uniform.

Anaerobic Digestion

- The digester operates under steady-state conditions.
- Digestion occurs under mesophilic conditions (35–37°C).
- Hydraulic Retention Time (HRT) remains constant.
- Reactor mixing is complete.
- No air enters the digester.
- Heat losses from the digester are negligible.
- Methane production remains stable throughout the simulation.

Biogas Composition

- Raw biogas consists primarily of methane and carbon dioxide.
- Trace gases such as hydrogen sulphide and water vapour are included in the purification stage.
- Gas composition remains constant during steady-state operation.

Gas Purification

- The H₂S scrubber removes hydrogen sulphide according to its design efficiency.
- Moisture removal is assumed complete before gas compression.
- Gas purification units operate continuously.

Compression

- Compression is assumed adiabatic.
- Pressure losses in connecting pipelines are negligible.
- Compressor efficiency remains constant.

Generator

- Purified biogas is completely combusted in the engine.
- Electrical conversion efficiency remains constant.
- Exhaust heat recovery is not considered unless specified.

Process Simulation

- Aspen Plus performs steady-state simulations only
- Transient behaviour during start-up and shutdown is neglected.
- Mass and energy balances are satisfied across all unit operations.
- Thermodynamic properties are calculated using the selected property package (for example, Peng–Robinson for gas-phase components).
- Pressure drops across pipes and fittings are neglected unless specifically modelled.

Assumptions for Sustainability Assessment

- The functional unit is one kWh of electricity delivered to the farm load.
- The system boundary extends from cattle manure collection to electricity generation (cradle-to-gate), unless otherwise defined.
- Construction and decommissioning impacts are included where inventory data are available.
- Background life cycle inventory data are obtained from recognized databases (e.g., ecoinvent) where primary data are unavailable.
- Environmental impact characterization follows the selected assessment method (e.g., ReCiPe 2016)

Performance Evaluation

The successful design of a hybrid renewable energy system extends beyond the appropriate sizing of its individual components. Although the photovoltaic array, biogas generation unit, battery energy storage system, converter, and energy management system were designed to satisfy the electrical demand of the agricultural processing facility, the actual operational performance of the integrated system must be evaluated to determine its technical adequacy, reliability, and energy utilization efficiency. Consequently, system performance evaluation constitutes an essential stage of the design process because it verifies whether the selected component sizes are capable of meeting the required

electricity demand under varying operating conditions.

In this study, the performance of the proposed hybrid solar–biogas electricity generation system was evaluated using HOMER Pro simulation software. HOMER Pro performs an hourly simulation of the hybrid system over an annual operating period of 8,760 hours by considering variations in solar radiation, ambient temperature, electrical load demand, battery charging and discharging behaviour, and generator operation. The software determines the operational interaction among the photovoltaic array, battery bank, biogas generator, converter, and electrical load while simultaneously ensuring that the specified energy management strategy is satisfied. The resulting performance indices provide a comprehensive assessment of the technical viability of the designed system.

The performance evaluation presented in this study was based on the hybrid system designed in the preceding sections, consisting of a 37.62 kept photovoltaic array, a 7.5 kW biogas generator, a 96.8 kWh battery energy storage system, and a 25kW bidirectional converter supplying an average electrical demand of 181.72 kWh/day. These design parameters formed the input data for the HOMER Pro simulation model and served as the basis for evaluating the operational characteristics of the integrated hybrid system. Consequently, all performance indicators discussed in this section are directly linked to the sizing calculations previously developed, thereby ensuring consistency between the design methodology and the simulation analysis.

The primary objective of the performance evaluation is to determine whether the proposed hybrid system can reliably satisfy the annual electrical demand of the farm while maximizing renewable energy utilization, minimizing generator operation, reducing battery degradation, and maintaining continuous power supply under varying climatic conditions. This evaluation also provides the necessary technical information required for the subsequent environmental sustainability assessment, since the annual electricity production, renewable energy utilization, generator fuel consumption, and equipment operating characteristics constitute important inputs for the life cycle assessment (LCA) of the hybrid energy system. To achieve these objectives, several key performance indicators were selected based on recommendations from the hybrid renewable energy literature and the performance indices generated by HOMER Pro. These indicators include annual electricity production, renewable energy fraction, battery performance, generator operating hours, excess electricity generation, and capacity shortage. Collectively, these parameters provide quantitative measures of the energy production capability, renewable energy utilization, storage effectiveness, operational reliability, and overall performance of the proposed hybrid solar–biogas electricity generation system.

The methodology adopted in this section combines engineering calculations derived from the design data with simulation outputs obtained from HOMER Pro. The engineering calculations establish the theoretical performance expected from the designed system, whereas the HOMER Pro simulation provides the corresponding operational performance under realistic annual operating conditions. The comparison between the calculated design values and the simulation outputs enables the adequacy of the system sizing to be verified and provides confidence in the technical feasibility of the proposed hybrid energy system [29–31].

Annual Electricity Production

Annual electricity production is one of the most important indicators used to evaluate the technical performance of a hybrid renewable energy system because it represents the total electrical energy generated by all electricity-producing components over one year of operation. The indicator provides an assessment of whether the designed system possesses sufficient generating capacity to satisfy the annual electrical demand while maintaining adequate operating reserves. For hybrid renewable systems, annual electricity production also indicates the contribution of each energy source toward meeting the overall load demand and provides the basis for evaluating system reliability, renewable energy utilization, and operational efficiency.

In the proposed hybrid solar–biogas electricity generation system, electrical energy is produced by two renewable sources, namely the photovoltaic (PV) array and the biogas generator. The battery bank does not generate electricity but serves as an energy storage medium that absorbs excess electricity generated during periods of surplus production and releases the stored energy whenever generation is insufficient to satisfy the electrical demand. Consequently, the total annual electricity production of the hybrid system is determined solely by the electricity generated from the photovoltaic array and the biogas generator. The annual electricity production of the hybrid system is expressed as:

$$E_{\text{Annual}} = E_{\text{PV}} + E_{\text{BG}}$$

E_{Annual} = Total annual electricity production (kWh/year)
 E_{PV} = Annual electricity generated by the photovoltaic array (kWh/year)
 E_{BG} = Annual electricity generated by the biogas generator (kWh/year)

Annual Electrical Energy Demand

The electrical load assessment presented earlier established that the agricultural processing facility requires an average daily electrical energy of:

$$E_d = 181.72 \text{ kWh/day}$$

Assuming continuous operation throughout the year,

$$N = 365; \text{ days/year}$$

the annual electrical energy demand therefore becomes

$$E_L = E_d \times N$$

$$E_L = 181.72 \times 365 = 66,312.8 \text{ kWh/year}$$

Hence,

Annual Electrical Energy Demand

$$E_L = 66,312.8 \text{ kWh/year}$$

This value represents the minimum amount of electrical energy that must be supplied annually by the hybrid solar–biogas energy system if uninterrupted operation of the farm is to be achieved.

Expected Annual PV Electricity Production

The design methodology adopted in this study allocated approximately 70% of the electrical demand to the photovoltaic subsystem. Hence,

$$E_{PV} = 0.7E_L$$

$$E_{PV} = 0.70 \times 66,312.8$$

$$E_{PV} = 46,418.96 \text{ kWh/year} = 46,419 \text{ kWh/year}$$

This value represents the expected annual electricity supplied by the 37.62 kept photovoltaic arrays under the adopted design philosophy. It serves as the theoretical design target and will later be compared with the annual photovoltaic energy predicted by HOMER Pro. Any deviation between the design estimate and the simulated result is expected to arise from hourly variations in solar irradiance, module temperature, inverter losses, battery charging and discharging losses, and seasonal weather fluctuations considered during the HOMER simulation.

Expected Annual Biogas Electricity Production

To improve system reliability during periods of reduced solar irradiation and nighttime operation, the remaining 30% of the electrical demand was allocated to the biogas generator.

$$E_{BG} = 0.30, E_L = 0.30 \times 66,312.8 = 19,893.84 \text{ kWh/year}$$

This electrical energy is expected to be generated by the 7.5kW biogas generator, which utilizes purified biogas produced from cattle manure. Unlike the photovoltaic system, electricity generation from the biogas unit is dispatchable and is controlled by the Energy Management System (EMS). The generator is therefore expected to operate only when photovoltaic generation and battery storage are insufficient to satisfy the electrical demand.

Verification of the Energy Balance

One of the most important checks during the design of a hybrid renewable energy system is to verify that the total electricity generated equals the annual electrical demand. The energy balance is expressed as:

$$E_{Annual} = E_{PV} + E_{BG} = 46,419 + 19,894 = 66,313 \text{ kWh/year}$$

- The total annual electricity production is equal to or greater than the annual electrical demand of 66,312.8kWh/year.
- The photovoltaic subsystem contributes approximately 70% of the annual electrical energy.
- The biogas generator contributes approximately 30% of the annual electrical energy.
- The annual energy deficit is zero or negligible.
- Capacity shortage remains below 1%, with the design target approaching 0%.
- Excess electricity remains within an acceptable range, indicating that the renewable energy system has not been excessively oversized.

Energy Component	Daily Energy (kWh/day)	Annual Energy (kWh/year)	Contribution (%)
Photovoltaic Array	127.20	46,419	70
Biogas Generator	54.52	19,894	30
Total Generation	181.72	66,313	100
Farm Electrical Demand	181.72	66,312.8	100

Table 3.11: Expected Annual Electricity Production

Renewable Energy Fraction

Renewable Energy Fraction (REF) is an important technical performance indicator used to evaluate the extent to which a hybrid renewable energy system satisfies the electrical demand using renewable energy resources. It represents the proportion of the total electrical energy supplied by renewable sources relative to the total electrical energy consumed by the load. A higher renewable energy fraction indicates greater utilization of clean energy resources, lower dependence

on fossil fuels, and reduced environmental impacts associated with electricity generation. For the proposed hybrid solar–biogas electricity generation system, the renewable energy sources comprise the photovoltaic (PV) array and the biogas generator. The PV subsystem converts incident solar radiation directly into electrical energy, whereas the biogas generator converts methane-rich biogas produced from cattle manure into electricity. Since both solar energy and biogas are renewable resources, the proposed system is expected to achieve a very high renewable energy fraction while ensuring reliable electricity supply to the agricultural processing facility. The renewable energy fraction also provides an indication of the sustainability of the hybrid energy system. Systems with higher renewable fractions generally exhibit lower greenhouse gas emissions, reduced fuel consumption, and improved environmental performance. Consequently, the renewable energy fraction serves as one of the principal indicators for evaluating the effectiveness of the proposed hybrid solar–biogas system.

Mathematical Formulation

The renewable energy fraction is defined as the ratio of the annual electrical energy generated from renewable sources to the total annual electrical energy supplied to the electrical load. The renewable energy fraction is expressed as:

$$R_{EF} = \frac{E_{RE}}{E_{Load}}$$

R_{EF} = Renewable Energy Fraction

E_{RE} = Annual renewable electrical energy generated (kWh/year)

E_{Load} = Annual electrical energy demand (kWh/year)

For the proposed hybrid system, $E_{RE} = E_{PV} + E_{BG}$

E_{PV} = Annual electricity generated by the photovoltaic array (kWh/year)

E_{BG} = Annual electricity generated by the biogas generator (kWh/year)

Design-Based Evaluation

From the system sizing carried out in the previous sections, the annual electricity generated by the photovoltaic array is given by:

$$E_{PV} = 46,419 \text{ kWh/year}$$

Annual electricity generated by the biogas generator

$$E_{BG} = 19,894 \text{ kWh/year}$$

Annual farm electrical demand

$$E_{Load} = 66,312.8 \text{ kWh/year}$$

$$R_{EF} = \frac{46,419 + 19,894}{66,312.8} = \frac{66,313}{66,312.8} = 1.00$$

Contribution of Individual Renewable Energy Sources

The percentage contribution of each renewable energy source was determined from the annual electricity production.

Photovoltaic Contribution

$$C_{PV} = \frac{E_{PV}}{E_{Load}} \times 100 = \frac{46,419}{66,312.8} \times 100 = 70.0\%$$

Biogas Contribution

$$C_{BG} = \frac{E_{BG}}{E_{Load}} \times 100 = \frac{19,894}{66,312.8} \times 100 = 30.0\%$$

The results confirm that the designed hybrid energy system satisfies the intended design philosophy in which approximately 70% of the annual electrical demand is supplied by the photovoltaic subsystem, while the remaining 30% is supplied by the biogas generator. This energy sharing strategy reduces the operational burden on the biogas generator during periods of high solar irradiance while ensuring continuous electricity supply during nighttime operation and periods of low solar radiation.

Factors Influencing Renewable Energy Fraction

Although the theoretical renewable energy fraction obtained from the design calculations is 100%, the actual renewable energy fraction predicted by HOMER Pro may be slightly lower due to operational losses within the hybrid energy system. These losses arise from battery charging and discharging inefficiencies, converter losses, wiring losses, and the mismatch between electricity generation and instantaneous load demand. Furthermore, seasonal variations in solar radiation and fluctuations in ambient temperature influence the electricity generated by the photovoltaic array, while variations in biogas production may affect generator operation. The converter selected for this study has an inverter efficiency of 96% and a rectifier efficiency of 94%, while the battery bank has a round-trip efficiency of 97%. These efficiencies introduce inevitable energy losses during power conversion and energy storage. Consequently, although the theoretical renewable energy fraction is 100%, the simulated renewable energy fraction is expected to be marginally lower when these losses are considered.

Performance Acceptance Criteria

The renewable energy fraction of the proposed hybrid solar–biogas electricity generation system will be considered satisfactory when the following conditions are achieved:

- The renewable energy fraction is greater than 95%.
- The photovoltaic subsystem contributes approximately 70% of the annual electricity production.
- The biogas subsystem contributes approximately 30% of the annual electricity production.
- Electricity generated from non-renewable sources is zero.
- The renewable energy fraction predicted by HOMER Pro differs from the theoretical value by less than 5%.

Component	Annual Energy (kWh/year)	Contribution (%)
Photovoltaic Array	46,419	70
Biogas Generator	19,894	30
Total Renewable Energy	66,313	100
Annual Farm Load	66,312.8	100
Renewable Energy Fraction	1.00	100

Table 3.12: Renewable Energy Contribution of the Hybrid System

Battery Performance

The battery energy storage system (BESS) is an essential component of the proposed hybrid solar–biogas electricity generation system because it provides energy storage during periods of excess electricity generation and supplies electricity whenever the photovoltaic array is unable to satisfy the instantaneous load demand. The battery therefore improves the reliability, stability, and operational flexibility of the hybrid system by minimizing interruptions in electricity supply arising from fluctuations in solar radiation and variations in load demand. In the proposed hybrid system, the battery bank operates under the supervision of the Energy Management System (EMS). During periods of high solar irradiance, excess photovoltaic electricity is directed to charge the battery bank after satisfying the electrical load. Conversely, during periods of low solar irradiation or night-time operation, the battery discharges to support the electrical load before the biogas generator is started. This operating strategy minimizes generator operating hours, reduces fuel consumption, and prolongs generator service life. The battery subsystem designed in this study consists of eight (8) Energys Powersafe SBS 900 batteries arranged in a 4-series × 2-parallel (4S × 2P) configuration, providing a nominal storage capacity of 96.8 kWh at a system voltage of 48V. The battery bank possesses a round-trip efficiency of 97%, making it suitable for renewable energy storage applications where high charging and discharging efficiencies are required. The battery specifications adopted for the performance evaluation are summarized in Table 3.13.

Parameter	Value
Battery Model	Energys Powersafe SBS 900
Battery Type	Valve Regulated Lead Acid (VRLA)
Number of Batteries	8
Configuration	4 Series × 2 Parallel
Nominal Voltage	48 V
Total Storage Capacity	96.8 kWh
Round-Trip Efficiency	97%
Recommended Maximum Depth of Discharge	80%
Battery Lifetime	10 Years
Maximum Charging Current	900 A
Maximum Discharging Current	720 A

Table 3.13: Battery Specifications

Usable Battery Capacity

The total installed battery capacity cannot be utilized completely because excessive discharge significantly reduces battery life and operational reliability. Subsequently, only the allowable depth of discharge (DOD) is considered available for normal operation. The

Usable battery Capacity Is Calculated As:

$$E_U = E_B \times \text{DOD}$$

E_U = Usable battery capacity (kWh)

E_B = Installed battery capacity (kWh)

(DOD) = Maximum allowable depth of discharge

For the proposed battery bank,

$$E_b = 96.8 \text{ kWh}$$

$$\text{DOD} = 80\% = 0.80$$

$$E_u = 96.8 \times 0.80 = 77.44 \text{ kWh}$$

This value represents the maximum amount of electrical energy that can be safely supplied by the battery bank without exceeding the recommended discharge limit.

Battery Autonomy

Battery autonomy represents the length of time that the battery bank can independently supply the electrical load without assistance from the photovoltaic array or the biogas generator. Battery autonomy is determined from:

$$Bat_A = \frac{E_u}{E_L}$$

Bat_A = Battery autonomy (days)

E_u = Usable battery capacity (kWh)

E_L = Daily electrical energy demand (kWh/day)

$$Bat_A = \frac{77.44}{181.72} = 0.426 \text{ days, converting to hours, } = 0.426 \times 24 = 10.22 \text{ hours.}$$

This autonomy is sufficient to maintain electricity supply during temporary reductions in solar generation while allowing adequate time for the Energy Management System to initiate the biogas generator when necessary.

Battery Charging and Discharging Efficiency

Energy losses occur during both battery charging and discharging processes. These losses are represented by the round-trip efficiency of the battery system. The battery round-trip efficiency is expressed as:

$$B_{Rte} = \frac{E_{out}}{E_{in}} \times 100$$

B_{Rte} = Battery round-trip efficiency (percentage)

E_{out} = Energy delivered by the battery (kWh)

E_{in} = Energy stored during charging (kWh)

For the selected battery, $B_{Rte} = 97\%$. Therefore, the energy loss during one complete charging–discharging cycle becomes $\text{Loss} = 100 - 97, = \text{Loss} = 3\%$. This indicates that only 3% of the stored electrical energy is lost during each complete charging and discharging cycle, demonstrating the high storage efficiency of the selected battery bank.

Battery State of Charge

The Battery State of Charge (SOC) represents the quantity of electrical energy remaining in the battery relative to its total storage capacity. It is expressed as:

$$\text{SOC} = \frac{E_s}{E_b} \times 100$$

(SOC) = State of Charge (percentage)

E_s = Energy currently stored in the battery (kWh)

E_b = Total battery capacity (kWh)

The Energy Management System maintains the battery SOC within safe operating limits in order to prevent excessive charging or deep discharge. In this study, the battery is allowed to operate between approximately 20% and 100% SOC; corresponding to the adopted maximum depth of discharge of 80%. Maintaining the battery within this operating range improves battery life, enhances storage reliability, and minimizes degradation associated with repeated deep discharge cycles [33-35]

Expected Battery Energy Throughput

Battery energy throughput represents the total electrical energy that passes through the battery during charging and discharging over the simulation period. The annual battery throughput can be evaluated using the equation below.

$$= E_u \times N_c$$

E_T = Annual battery throughput (kWh/year)

E_u = Usable battery capacity (kWh)

N_c = Number of equivalent full charge–discharge cycles per year

Performance Indicator	Calculated Value	Unit
Installed Battery Capacity	96.8	kWh
Usable Battery Capacity	77.44	kWh
Daily Farm Load	181.72	kWh/day
Battery Autonomy	10.22	Hours

Round-Trip Efficiency	97	%
Energy Loss per Cycle	3	%
Recommended SOC Range	20–100	%
Battery Configuration	4S × 2P	—

Table 3.14: Summary of Battery Performance Evaluation

Generator Operating Hours

The biogas generator serves as the dispatchable power source in the proposed hybrid solar–biogas electricity generation system. Unlike the photovoltaic array, whose electricity generation depends on the availability of solar radiation, the biogas generator can be operated whenever additional electrical energy is required to satisfy the load demand. Consequently, the generator enhances the reliability of the hybrid system by supplying electricity during periods of low solar irradiance, prolonged cloudy weather, nighttime operation, and whenever the battery state of charge falls below the prescribed operating limit. The operating hours of the generator constitute an important performance indicator because they directly influence biogas utilization, maintenance requirements, operating costs, equipment lifespan, and the overall efficiency of the hybrid energy system. An optimally designed hybrid system should minimize generator-operating hours while ensuring uninterrupted electricity supply. This objective is achieved through the coordinated operation of the photovoltaic array, battery energy storage system, and Energy Management System (EMS), which prioritize renewable electricity generation before initiating the generator.

Generator Operating Principle

The Energy Management System (EMS) adopted in this study operates according to a renewable-energy priority strategy. Under this control strategy, electricity generated by the photovoltaic array is first used to satisfy the electrical load. Any excess photovoltaic electricity is directed to charge the battery bank. The biogas generator is only started when the combined electricity supplied by the photovoltaic array and battery bank becomes insufficient to meet the electrical demand or when the battery state of charge falls below the prescribed operating limit. This operating strategy minimizes unnecessary generator operation, reduces biogas consumption, lowers maintenance costs, and increases the utilization of renewable energy resources.

Estimation of Daily Generator Operating Hours

The expected daily operating time of the biogas generator is estimated from the daily electrical energy assigned to the biogas subsystem during the sizing stage. The generator operating time is calculated using:

$$T_G = \frac{E_{BG}}{P_{PG}}$$

T_G = Generator operating time (hours/day)

E_{BG} = Daily electrical energy supplied by the biogas generator (kWh/day)

P_{PG} = Rated generator power (kW)

From the design calculations, $E_{BG} = 54.52 \text{ kWh/day}$, $P_{PG} = 7.5 \text{ kW}$, Therefore, $T_G = \frac{54.52}{7.5} = 7.27 \text{ hours/day}$. This result indicates that the biogas generator is expected to operate for approximately 7.3 hours per day under average operating conditions.

Annual Generator Operating Hours

The estimated annual generator operating hours are obtained by multiplying the average daily operating time by the number of operating days in one year. The annual operating hours are calculated as:

$$H_G = T_G \times 365$$

H_G = Annual generator operating hours (hours/year)

T_G = Daily generator operating time (hours/day)

$$H_G = 7.27 \times 365 = 2,654 \text{ hours/year}$$

The calculated annual operating hours represent the theoretical operating duration required for the generator to supply approximately 30% of the annual electrical energy demand.

Generator Capacity Factor

The capacity factor is an important indicator used to evaluate the utilization level of the generator. It represents the ratio of the actual electrical energy generated to the maximum electrical energy that could have been generated if the generator operated continuously at its rated capacity throughout the year. The generator capacity factor is expressed as:

$$CF_G = \frac{E_{GB}}{P_G} \times 87600$$

CF_G = Generator capacity factor

E_{GB} = Annual electrical energy generated by the biogas generator (kWh/year)

P_G = Generator rated power (kW)

$$CF_G = \frac{19,894}{7.5 \times 8760} = 0.303 = 0.303 \times 100 = 30\%$$

This indicates that the generator is utilized at approximately 30% of its maximum annual generating capability, reflecting its role as a supplementary rather than a primary electricity source.

Generator Load Factor

The generator load factor represents the average loading of the generator during the period it is in operation. It is expressed as:

$$LF_G = \frac{E_{BG}}{P_G \times H_G}$$

LF_G = Generator load factor

E_{BG} = Annual electrical energy generated (kWh/year)

H_G = Annual operating hours (hours/year)

$$LF_G = \frac{19,894}{7.5 \times 2654} = 1.00$$

This result indicates that whenever the generator operates, it is expected to operate close to its rated output, thereby maximizing fuel utilization efficiency and minimizing inefficient part-load operation.

Influence of Energy Management System

The Energy Management System significantly influences generator operating hours by determining the conditions under which the generator is started and stopped. Under the adopted control strategy, the generator operates only when the photovoltaic array cannot satisfy the electrical demand and the battery state of charge reaches its lower operating limit. Consequently, increasing photovoltaic electricity generation or improving battery utilization will reduce generator operating hours, whereas prolonged cloudy weather, increased electrical demand, or reduced battery capacity will increase generator-operating time. HOMER Pro accounts for these operational interactions during the annual simulation [36-38].

Performance Indicator	Calculated Value	Unit
Generator Rated Capacity	7.5	kW
Daily Energy Contribution	54.52	kWh/day
Annual Energy Contribution	19,894	kWh/year
Daily Operating Hours	7.27	h/day
Annual Operating Hours	2,654	h/year
Capacity Factor	30.3	%
Load Factor	100	%
Energy Contribution	30	%

Table 3.15: Summary of Generator Performance Evaluation

Excess Electricity

Excess electricity is the electrical energy generated by the hybrid renewable energy system that cannot be immediately utilized by the electrical load or stored within the battery energy storage system. It usually occurs when the electricity generated by the photovoltaic array exceeds the instantaneous electrical demand and the battery bank has reached its maximum state of charge. Although excess electricity indicates that sufficient renewable energy resources are available, excessive energy spillage represents inefficient utilization of installed generating capacity and may increase the overall capital cost of the system. For the proposed hybrid solar–biogas electricity generation system, excess electricity is expected to occur primarily during periods of high solar irradiance, particularly around midday when photovoltaic power production reaches its maximum while the electrical demand remains relatively constant. Since the Energy Management System (EMS) gives priority to supplying the electrical load and charging the battery bank before curtailing generation, excess electricity will only occur when both the load demand and battery charging requirements have been fully satisfied. The evaluation of excess electricity is important as it provides an indication of the adequacy of the photovoltaic array size, battery storage capacity, and the effectiveness of the adopted energy management strategy. A moderate amount of excess electricity is acceptable in hybrid renewable energy systems because it ensures system reliability during periods of low renewable energy availability. However, excessive energy spillage may indicate that the photovoltaic subsystem have been oversized beyond the actual energy requirements of the facility.

Mathematical Formulation

The annual excess electricity generated by the hybrid system is expressed as:

$$E_{Ex} = E_{Gen} - E_{Load} - E_{Loss}$$

• E_{Ex} = Annual excess electricity (kWh/year)

- E_{Gen} = Total annual electricity generated by the hybrid system (kWh/year)
- E_{Load} = Annual electrical energy supplied to the load (kWh/year)
- E_{Loss} = Annual electrical energy losses associated with battery storage, converter operation, and system inefficiencies (kWh/year)

Alternatively, HOMER Pro determines excess electricity from the hourly power balance throughout the simulation period. Whenever electricity generated by the photovoltaic array exceeds the combined demand of the electrical load and battery-charging requirement, the remaining electricity is classified as excess electricity.

Expected Excess Electricity

The hybrid system was designed to satisfy an average daily electrical demand of $E_{Load} = 181.72\text{kWh/day}$; with an installed photovoltaic capacity of: $P_{PV} = 37.62\text{Kw}$ and a battery storage capacity of: $E_B = 96.8\text{kWh}$. The photovoltaic array was intentionally oversized by approximately 4.1% above the minimum design requirement to compensate for seasonal reductions in solar radiation, module ageing, dust accumulation, and other operational losses. Consequently, small quantities of excess electricity are expected during periods of high solar irradiance when the battery bank has already reached full charge. The expected excess electricity is therefore considered to be low because:

- the photovoltaic array was only slightly oversized;
- the battery bank provides 77.44 kWh of usable storage capacity;
- the Energy Management System prioritizes battery charging before curtailment;
- The biogas generator operates only when required, thereby avoiding unnecessary simultaneous generation.

Factors Affecting Excess Electricity

Several factors influence the quantity of excess electricity produced by the hybrid energy system.

Solar Radiation

- Higher solar irradiance increases photovoltaic electricity generation and may produce excess electricity during periods when the electrical demand is relatively low.

Battery State of Charge

- When the battery reaches its maximum state of charge, additional photovoltaic electricity can no longer be stored and is therefore classified as excess electricity.

Electrical Load Variation

- Periods of reduced electricity consumption increase the probability of excess electricity generation because the available renewable electricity exceeds the instantaneous demand.

Converter Capacity

- The selected Leonics MTP-413F converter has a rated power of 25 kW. During periods when the instantaneous photovoltaic output exceeds the converter transfer capability, some renewable electricity may be curtailed depending on the operational conditions simulated by HOMER Pro. The adopted Energy Management System minimizes excess electricity by following the operational sequence below:
- Supply the electrical load.
- Charge the battery bank.
- Curtail surplus photovoltaic generation.
- Prevent unnecessary operation of the biogas generator.

This operational strategy maximizes renewable energy utilization while minimizing energy wastage [39].

Performance Indicator	Expected Value	Unit
Installed PV Capacity	37.62	kW
Installed Battery Capacity	96.8	kWh
Usable Battery Capacity	77.44	kWh
Annual Electrical Demand	66,312.8	kWh/year
Expected Excess Electricity	Low	—
Acceptable Excess Electricity	<10	%
Primary Cause	High PV output and fully charged battery	—

Table 3.16: Summary of Excess Electricity Evaluation

Capacity Shortage

Capacity shortage is an important performance indicator used to assess the reliability of a hybrid renewable energy system. It represents the amount of electrical energy that the generating system is unable to supply to the electrical

load due to insufficient generation or storage capacity. Capacity shortage occurs when the combined electricity supplied by the photovoltaic array, biogas generator, and battery bank is less than the instantaneous electrical demand. The occurrence of capacity shortage may result in interrupted power supply, reduced operational efficiency, and loss of productivity, particularly in agricultural processing facilities where continuous electricity supply is essential. The primary objective of the proposed hybrid solar–biogas electricity generation system is to provide uninterrupted electrical power to the farm throughout the year. Consequently, the photovoltaic array, biogas generator, battery energy storage system, converter, and Energy Management System (EMS) were appropriately sized to ensure that the available generating capacity is sufficient to satisfy the electrical demand under varying climatic and operating conditions. Therefore, the expected capacity shortage for the designed system should be negligible or zero.

Mathematical Formulation

Capacity shortage is defined as the difference between the electrical energy required by the load and the electrical energy actually supplied by the hybrid system during the simulation period. It is expressed as:

$$E_{CS} = E_{Load} - E_{Supplied}$$

E_{CS} = Capacity shortage (kWh/year)

E_{Load} = Annual electrical energy demand (kWh/year)

$- E_{Supplied}$ = Annual electrical energy supplied by the hybrid system (kWh/year)

The percentage capacity shortage is calculated as

$$CS\% = \frac{E_{CS}}{E_{Load}} \times 100$$

(CS) = Capacity shortage (percentage)

E_{CS} = Annual capacity shortage (kWh/year)

E_{Load} = Annual electrical energy demand (kWh/year)

Design-Based Evaluation

The annual electrical demand of the agricultural processing facility obtained from the load assessment is E_{Load} = 66,312.8 kWh/year. The designed hybrid system was also sized to produce:

$$E_{Supplied} = 66,313 \text{ kWh/year}$$

Therefore, $E_{CS} = 66,312.8 - 66,313 = 0 \text{ kWh/year}$

Similarly, the percentage capacity shortage becomes: $CS = \frac{0}{66,312.8} \times 100 = 0\%$

The result indicates that the proposed hybrid solar–biogas energy system has sufficient installed generation and storage capacity to satisfy the annual electrical demand of the agricultural processing facility under the adopted design assumptions.

Factors Affecting Capacity Shortage

Although the theoretical design predicts zero capacity shortage, several operational factors may influence the actual value obtained during simulation.

Solar Resource Variability

Daily and seasonal variations in solar radiation directly affect the electrical output of the photovoltaic array. Extended periods of cloudy weather may reduce photovoltaic electricity generation and increase dependence on the battery bank and biogas generator.

Battery State of Charge

If the battery bank becomes deeply discharged during periods of prolonged low solar radiation, the available stored energy may become insufficient to support the electrical load. The Energy Management System therefore maintains the Battery State of Charge within the recommended operating limits to minimize this possibility.

Biogas Availability

The quantity of electricity generated by the biogas subsystem depends on the availability of cattle manure and the efficiency of the anaerobic digestion process. Continuous availability of approximately 0.91 tones/day of cattle manure ensures adequate biogas production for reliable generator operation.

Converter Efficiency

The selected Leonics MTP–413F converter possesses an inverter efficiency of 96% and a rectifier efficiency of 94%. Although these efficiencies introduce minor conversion losses, they are sufficiently high to ensure reliable power transfer between the photovoltaic array, battery bank, generator, and electrical load.

Energy Management Strategy

The adopted Energy Management System significantly reduces the possibility of capacity shortage by prioritizing electricity supply in the following order: Photovoltaic array, Battery energy storage system and Biogas generator. This operational sequence ensures that all available renewable energy resources are fully utilized before any shortage occurs.

Performance Indicator	Calculated Value	Unit
Annual Electrical Demand	66,312.8	kWh/year
Annual Electricity Supplied	66,313	kWh/year
Capacity Shortage	0	kWh/year
Capacity Shortage	0	%
Electrical Load Served	100	%
Expected System Reliability	>99	%

Table 3.17: Summary of Capacity Shortage Evaluation

Economic Performance Evaluation

The economic performance evaluation of a hybrid renewable energy system is essential for determining its financial feasibility and long-term sustainability. Although the proposed solar–biogas hybrid energy system was designed primarily to provide reliable and environmentally friendly electricity for agricultural processing, its economic viability must also be assessed to justify the investment required for implementation. Economic evaluation provides quantitative measures that enable comparison of alternative energy systems and assists decision-makers in selecting the most cost-effective configuration. HOMER Pro performs a comprehensive techno-economic analysis by combining the technical performance of the hybrid system with the economic characteristics of each component. The software estimates the total investment cost, replacement cost, operation and maintenance cost, fuel cost, salvage value, annualized cost, and other financial indicators over the project lifetime. These indicators are then used to determine the overall economic attractiveness of the proposed hybrid energy system. In this study, the economic performance evaluation was carried out using the optimized hybrid system configuration consisting of a 37.62 kWp photovoltaic array, a 7.5kW biogas generator, a 96.8kWh battery energy storage system, and a 25kW bidirectional converter. The economic analysis assumes a project lifetime of 25 years, corresponding to the design life of the photovoltaic modules, while replacement costs for components with shorter service lives are incorporated into the life-cycle cost analysis. The principal economic indicators considered in this study include the Net Present Cost (NPC), Levelized Cost of Energy (LCOE), annual operating cost, initial capital cost, replacement cost, operation and maintenance cost, and salvage value. These indicators collectively provide a comprehensive assessment of the economic performance of the proposed hybrid solar–biogas energy system.

Performance Evaluation

The successful design of a hybrid renewable energy system extends beyond the appropriate sizing of its individual components. Although the photovoltaic array, biogas generation unit, battery energy storage system, converter, and energy management system were designed to satisfy the electrical demand of the agricultural processing facility, the actual operational performance of the integrated system must be evaluated to determine its technical adequacy, reliability, and energy utilization efficiency. Consequently, system performance evaluation constitutes an essential stage of the design process because it verifies whether the selected component sizes are capable of meeting the required electricity demand under varying operating conditions. In this study, the performance of the proposed hybrid solar–biogas electricity generation system was evaluated using HOMER Pro simulation software. HOMER Pro performs an hourly simulation of the hybrid system over an annual operating period of 8,760 hours by considering variations in solar radiation, ambient temperature, electrical load demand, battery charging and discharging behaviour, and generator operation. The software determines the operational interaction among the photovoltaic array, battery bank, biogas generator, converter, and electrical load while simultaneously ensuring that the specified energy management strategy is satisfied. The resulting performance indices provide a comprehensive assessment of the technical viability of the designed system.

The performance evaluation presented in this study was based on the hybrid system designed in the preceding sections, consisting of a 37.62kWp photovoltaic array, a 7.5kW biogas generator, a 96.8 kWh battery energy storage system, and a 25kW bidirectional converter supplying an average electrical demand of 181.72kWh/day. These design parameters formed the input data for the HOMER Pro simulation model and served as the basis for evaluating the operational characteristics of the integrated hybrid system. Consequently, all performance indicators discussed in this section are directly linked to the sizing calculations previously developed, thereby ensuring consistency between the design methodology and the simulation analysis. The primary objective of the performance evaluation is to determine whether the proposed hybrid system can reliably satisfy the annual electrical demand of the farm while maximizing renewable energy utilization, minimizing generator operation, reducing battery degradation, and maintaining continuous power supply under varying climatic conditions. This evaluation also provides the necessary technical information required for the subsequent environmental sustainability assessment, since the annual electricity production, renewable energy utilization, generator fuel consumption, and equipment operating characteristics constitute important inputs for the life cycle assessment (LCA) of the hybrid energy system.

To achieve these objectives, several key performance indicators were selected based on recommendations from the hybrid renewable energy literature and the performance indices generated by HOMER Pro. These indicators include annual electricity production, renewable energy fraction, battery performance, generator operating hours, excess electricity generation, and capacity shortage. Collectively, these parameters provide quantitative measures of the

energy production capability, renewable energy utilization, storage effectiveness, operational reliability, and overall performance of the proposed hybrid solar–biogas electricity generation system. The methodology adopted in this section combines engineering calculations derived from the design data with simulation outputs obtained from HOMER Pro. The engineering calculations establish the theoretical performance expected from the designed system, whereas the HOMER Pro simulation provides the corresponding operational performance under realistic annual operating conditions. The comparison between the calculated design values and the simulation outputs enables the adequacy of the system sizing to be verified and provides confidence in the technical feasibility of the proposed hybrid energy system.

Annual Electricity Production

Annual electricity production is one of the most important indicators used to evaluate the technical performance of a hybrid renewable energy system because it represents the total electrical energy generated by all electricity-producing components over one year of operation. The indicator provides an assessment of whether the designed system possesses sufficient generating capacity to satisfy the annual electrical demand while maintaining adequate operating reserves. For hybrid renewable systems, annual electricity production also indicates the contribution of each energy source toward meeting the overall load demand and provides the basis for evaluating system reliability, renewable energy utilization, and operational efficiency.

In the proposed hybrid solar–biogas electricity generation system, electrical energy is produced by two renewable sources, namely the photovoltaic (PV) array and the biogas generator. The battery bank does not generate electricity but serves as an energy storage medium that absorbs excess electricity generated during periods of surplus production and releases the stored energy whenever generation is insufficient to satisfy the electrical demand. Consequently, solely the electricity generated from the photovoltaic array and the biogas generator determines the total annual electricity production of the hybrid system. The annual electricity production of the hybrid system is expressed as:

$$E_{\text{Annual}} = E_{\text{PV}} + E_{\text{BG}}$$

E_{Annual} = Total annual electricity production (kWh/year)
 E_{PV} = Annual electricity generated by the photovoltaic array (kWh/year)
 E_{BG} = Annual electricity generated by the biogas generator (kWh/year)

Annual Electrical Energy Demand

The electrical load assessment presented earlier established that the agricultural processing facility requires an average daily electrical energy of:

$$E_d = 181.72 \text{ kWh/day}$$

Assuming continuous operation throughout the year, then, $N=365$; days/year

The annual electrical energy demand therefore becomes

$$E_L = E_d \times N$$

$$E_L = 181.72 \times 365 = 66,312.8 \text{ kWh/year}$$

Hence,

Annual Electrical Energy Demand

$$E_L = 66,312.8 \text{ kWh/year}$$

This value represents the minimum amount of electrical energy that must be supplied annually by the hybrid solar–biogas energy system if uninterrupted operation of the farm is to be achieved.

Expected Annual PV Electricity Production

The design methodology adopted in this study allocated approximately 70% of the electrical demand to the photovoltaic subsystem. Hence,

$$E_{\text{PV}} = 0.7 E_L$$

$$E_{\text{PV}} = 0.70 \times 66,312.8$$

$$E_{\text{PV}} = 46,418.96 \text{ kWh/year} = 46,419 \text{ kWh/year}$$

This value represents the expected annual electricity supplied by the 37.62KWp photovoltaic array under the adopted design philosophy. It serves as the theoretical design target and will later be compared with the annual photovoltaic energy predicted by HOMER Pro. Any deviation between the design estimate and the simulated result is expected to arise from hourly variations in solar irradiance, module temperature, inverter losses, battery charging and discharging losses, and seasonal weather fluctuations considered during the HOMER simulation.

Expected Annual Biogas Electricity Production

To improve system reliability during periods of reduced solar irradiation and nighttime operation, the remaining 30% of the electrical demand was allocated to the biogas generator.

$$E_{\text{BG}} = 0.30 E_L = 0.30 \times 66,312.8 = 19,893.84 \text{ kWh/year}$$

This electrical energy is expected to be generated by the 7.5kW biogas generator, which utilizes purified biogas produced from cattle manure. Unlike the photovoltaic system, electricity generation from the biogas unit is dispatchable and is controlled by the Energy Management System (EMS). The generator is therefore expected to operate only when photovoltaic generation and battery storage are inadequate to satisfy the electrical demand.

Verification of the Energy Balance

One of the most important checks during the design of a hybrid renewable energy system is to verify that the total electricity generated equals the annual electrical demand. The energy balance is expressed as:

$$E_{Annual} = E_{PV} + E_{BG} = 46,419 + 19,894 = 66,313 \text{ kWh/year}$$

Performance Acceptance Criteria

The annual electricity production of the proposed hybrid system will be considered satisfactory when the following conditions are achieved:

- The total annual electricity production is equal to or greater than the annual electrical demand of 66,312.8 kWh/year.
- The photovoltaic subsystem contributes approximately 70% of the annual electrical energy.
- The biogas generator contributes about 30% of the annual electrical energy.
- The annual energy deficit is zero or negligible.
- Capacity shortage remains below 1%, with the design target approaching 0%.
- Excess electricity remains within an acceptable range, indicating that the renewable energy system has not been excessively oversized.

Energy Component	Daily Energy (kWh/day)	Annual Energy (kWh/year)	Contribution (%)
Photovoltaic Array	127.20	46,419	70
Biogas Generator	54.52	19,894	30
Total Generation	181.72	66,313	100
Farm Electrical Demand	181.72	66,312.8	100

Table 3.18: Expected Annual Electricity Production

Renewable Energy Fraction

Renewable Energy Fraction (REF) is an important technical performance indicator used to evaluate the extent to which a hybrid renewable energy system satisfies the electrical demand using renewable energy resources. It represents the proportion of the total electrical energy supplied by renewable sources relative to the total electrical energy consumed by the load. A higher renewable energy fraction indicates greater utilization of clean energy resources, lower dependence on fossil fuels, and reduced environmental impacts associated with electricity generation. For the proposed hybrid solar–biogas electricity generation system, the renewable energy sources comprise the photovoltaic (PV) array and the biogas generator. The PV subsystem converts incident solar radiation directly into electrical energy, whereas the biogas generator converts methane-rich biogas produced from cattle manure into electricity. Since both solar energy and biogas are renewable resources, the proposed system is expected to achieve a very high renewable energy fraction while ensuring reliable electricity supply to the agricultural processing facility. The renewable energy fraction also provides an indication of the sustainability of the hybrid energy system. Systems with higher renewable fractions generally exhibit lower greenhouse gas emissions, reduced fuel consumption, and improved environmental performance. Consequently, the renewable energy fraction serves as one of the principal indicators for evaluating the effectiveness of the proposed hybrid solar–biogas system.

Mathematical Formulation

The renewable energy fraction is defined as the ratio of the annual electrical energy generated from renewable sources to the total annual electrical energy supplied to the electrical load. The renewable energy fraction is expressed as:

$$R_{EF} = \frac{E_{RE}}{E_{Load}}$$

R_{EF} = Renewable Energy Fraction

E_{RE} = Annual renewable electrical energy generated (kWh/year)

E_{Load} = Annual electrical energy demand (kWh/year)

For the proposed hybrid system, $E_{RE} = E_{PV} + E_{BG}$

E_{PV} = Annual electricity generated by the photovoltaic array (kWh/year)

E_{BG} = Annual electricity generated by the biogas generator (kWh/year)

Design-Based Evaluation

From the system sizing carried out in the previous sections, the annual electricity generated by the photovoltaic array is given by:

$$E_{PV} = 46,419 \text{ kWh/year}$$

Annual electricity generated by the biogas generator

$$E_{BG} = 19,894 \text{ kWh/year}$$

Annual farm electrical demand

$$E_{Load} = 66,312.8 \text{ kWh/year}$$

$$R_{EF} = \frac{46,419 + 19,894}{66,312.8} = \frac{66,313}{66,312.8} = 1.00$$

Contribution of Individual Renewable Energy Sources

The percentage contribution of each renewable energy source was determined from the annual electricity production.

Photovoltaic Contribution

$$C_{PV} = \frac{E_{PV}}{E_{Load}} \times 100 = \frac{46,419}{66,312.8} \times 100 = 70.0\%$$

Biogas Contribution

$$C_{BG} = \frac{E_{BG}}{E_{Load}} \times 100 = \frac{19,894}{66,312.8} \times 100 = 30.0\%$$

The results confirm that the designed hybrid energy system satisfies the intended design philosophy in which approximately 70% of the annual electrical demand is supplied by the photovoltaic subsystem, while the remaining 30% is supplied by the biogas generator. This energy sharing strategy reduces the operational burden on the biogas generator during periods of high solar irradiance while ensuring continuous electricity supply during nighttime operation and periods of low solar radiation.

Factors Influencing Renewable Energy Fraction

Although the theoretical renewable energy fraction obtained from the design calculations is 100%, the actual renewable energy fraction predicted by HOMER Pro may be slightly lower due to operational losses within the hybrid energy system. These losses arise from battery charging and discharging inefficiencies, converter losses, wiring losses, and the mismatch between electricity generation and instantaneous load demand. Furthermore, seasonal variations in solar radiation and fluctuations in ambient temperature influence the electricity generated by the photovoltaic array, while variations in biogas production may affect generator operation. The converter selected for this study has an inverter efficiency of 96% and a rectifier efficiency of 94%, while the battery bank has a round-trip efficiency of 97%. These efficiencies introduce unavoidable energy losses during power conversion and energy storage. Consequently, although the theoretical renewable energy fraction is 100%, the simulated renewable energy fraction is expected to be marginally lower when these losses are considered.

Performance Acceptance Criteria

The renewable energy fraction of the proposed hybrid solar–biogas electricity generation system will be considered satisfactory when the following conditions are achieved:

- The renewable energy fraction is greater than 95%.
- The photovoltaic subsystem contributes around 70% of the annual electricity production.
- The biogas subsystem contributes about 30% of the annual electricity production.
- Electricity generated from non-renewable sources is zero.
- The renewable energy fraction predicted by HOMER Pro differs from the theoretical value by less than 5%.

Meeting these criteria will demonstrate that the proposed hybrid system effectively utilizes renewable energy resources while maintaining reliable electricity supply.

Component	Annual Energy (kWh/year)	Contribution (%)
Photovoltaic Array	46,419	70
Biogas Generator	19,894	30
Total Renewable Energy	66,313	100
Annual Farm Load	66,312.8	100
Renewable Energy Fraction	1.00	100

Table 3.19: Renewable Energy Contribution of the Hybrid System

Battery Performance

The battery energy storage system (BESS) is an essential component of the proposed hybrid solar–biogas electricity generation system because it provides energy storage during periods of excess electricity generation and supplies electricity whenever the photovoltaic array is unable to satisfy the instantaneous load demand. The battery therefore improves the reliability, stability, and operational flexibility of the hybrid system by lessening interruptions in electricity supply arising from variations in solar radiation and variations in load demand. In the proposed hybrid system, the

battery bank operates under the supervision of the Energy Management System (EMS). During periods of high solar irradiance, excess photovoltaic electricity is directed to charge the battery bank after satisfying the electrical load. Conversely, during periods of low solar irradiation or nighttime operation, the battery discharges to support the electrical load before the biogas generator is started. This operating strategy minimizes generator operating hours, reduces fuel consumption, and prolongs generator service life. The battery subsystem designed in this study consists of eight (8) EnerSys Powersafe SBS 900 batteries arranged in a 4-series × 2-parallel (4S × 2P) configuration, offering a nominal storage capacity of 96.8 kWh at a system voltage of 48V. The battery bank possesses a round-trip efficiency of 97%, making it suitable for renewable energy storage applications where high charging and discharging efficiencies are required.

Battery Specifications

The battery specifications adopted for the performance evaluation are summarized in Table 3.20.

Parameter	Value
Battery Model	EnerSys Powersafe SBS 900
Battery Type	Valve Regulated Lead Acid (VRLA)
Number of Batteries	8
Configuration	4 Series × 2 Parallel
Nominal Voltage	48 V
Total Storage Capacity	96.8 kWh
Round-Trip Efficiency	97%
Recommended Maximum Depth of Discharge	80%
Battery Lifetime	10 Years
Maximum Charging Current	900 A
Maximum Discharging Current	720 A

Table 3.20: Battery Specifications

Usable Battery Capacity

The total installed battery capacity cannot be utilized completely because excessive discharge significantly reduces battery life and operational reliability. Consequently, only the allowable depth of discharge (DOD) is considered available for normal operation. The usable battery capacity is calculated as:

$$E_U = E_B \times \text{DOD}$$

E_U = Usable battery capacity (kWh)

E_B = Installed battery capacity (kWh)

(DOD) = Maximum allowable depth of discharge

For the proposed battery bank,

$$E_B = 96.8 \text{ kWh}$$

$$\text{DOD} = 80\% = 0.80$$

$$E_U = 96.8 \times 0.80 = 77.44 \text{ kWh}$$

This value represents the maximum amount of electrical energy that can be safely supplied by the battery bank without exceeding the recommended discharge limit.

Battery Autonomy

Battery autonomy represents the length of time that the battery bank can independently supply the electrical load without assistance from the photovoltaic array or the biogas generator. Battery autonomy is obtained from the equation given by:

$$Bat_A = \frac{E_U}{E_L}$$

Bat_A = Battery autonomy (days)

E_U = Usable battery capacity (kWh)

E_L = Daily electrical energy demand (kWh/day)

$$Bat_A = \frac{77.44}{181.72} = 0.426 \text{ days, converting to hours, } = 0.426 \times 24 = 10.22 \text{ hours.}$$

This autonomy is sufficient to maintain electricity supply during temporary reductions in solar generation while allowing adequate time for the Energy Management System to initiate the biogas generator when necessary.

Battery Charging and Discharging Efficiency

Energy losses occur during both battery charging and discharging processes. These losses are represented by the round-trip efficiency of the battery system. The battery round-trip efficiency is expressed as:

$$B_{Rte} = \frac{E_{out}}{E_{in}} \times 100$$

B_{Rte} = Battery round-trip efficiency (%)

E_{out} = Energy delivered by the battery (kWh)

E_{in} = Energy stored during charging (kWh)

For the selected battery, $B_{Rte} = 97\%$. Therefore, the energy loss during one complete charging–discharging cycle becomes $\text{Loss} = 100 - 97 = \text{Loss} = 3\%$. This indicates that only 3% of the stored electrical energy is lost during each complete charging and discharging cycle, demonstrating the high storage efficiency of the selected battery bank.

Battery State of Charge

The Battery State of Charge (SOC) represents the quantity of electrical energy remaining in the battery relative to its total storage capacity. It is expressed as:

$$\text{SOC} = \frac{E_s}{E_B} \times 100$$

(SOC) = State of Charge (%)

E_s = Energy currently stored in the battery (kWh)

E_B = Total battery capacity (kWh)

The Energy Management System maintains the battery SOC within safe operating limits in order to prevent excessive charging or deep discharge. In this study, the battery is allowed to operate between approximately 20% and 100% SOC, corresponding to the adopted maximum depth of discharge of 80%. Maintaining the battery within this operating range improves battery life, enhances storage reliability, and minimizes degradation associated with repeated deep discharge cycles.

Expected Battery Energy Throughput

Battery energy throughput represents the total electrical energy that passes through the battery during charging and discharging over the simulation period. The annual battery throughput can be evaluated using the equation below.

$$= E_U \times N_c$$

E_T = Annual battery throughput (kWh/year)

E_U = Usable battery capacity (kWh)

N_c = Number of equivalent full charge–discharge cycles per year

Performance Indicator	Calculated Value	Unit
Installed Battery Capacity	96.8	kWh
Usable Battery Capacity	77.44	kWh
Daily Farm Load	181.72	kWh/day
Battery Autonomy	10.22	Hours
Round-Trip Efficiency	97	%
Energy Loss per Cycle	3	%
Recommended SOC Range	20–100	%
Battery Configuration	4S × 2P	—

Table 3.21: Summary of Battery Performance Evaluation

Generator Operating Hours

The biogas generator serves as the dispatchable power source in the proposed hybrid solar–biogas electricity generation system. Unlike the photovoltaic array, whose electricity generation depends on the availability of solar radiation, the biogas generator can be operated whenever additional electrical energy is required to satisfy the load demand. Consequently, the generator enhances the reliability of the hybrid system by supplying electricity during periods of low solar irradiance, prolonged cloudy weather, nighttime operation, and whenever the battery state of charge falls below the prescribed operating limit. The operating hours of the generator constitute an important performance indicator because they directly influence biogas consumption, maintenance requirements, operating costs, equipment lifespan, and the overall efficiency of the hybrid energy system. An optimally designed hybrid system should minimize generator-operating hours while ensuring uninterrupted electricity supply. This objective is achieved through the coordinated operation of the photovoltaic array, battery energy storage system, and Energy Management System (EMS), which prioritize renewable electricity generation before initiating the generator.

Generator Operating Principle

The Energy Management System (EMS) adopted in this study operates according to a renewable-energy priority strategy. Under this control strategy, electricity generated by the photovoltaic array is first used to satisfy the electrical load. Any excess photovoltaic electricity is directed to charge the battery bank. The biogas generator is only started when the combined electricity supplied by the photovoltaic array and battery bank becomes insufficient to meet the electrical demand or when the battery state of charge falls below the prescribed operating limit. This operating strategy minimizes unnecessary generator operation, reduces biogas consumption, lowers maintenance costs, and increases the utilization of renewable energy resources.

Estimation of Daily Generator Operating Hours

The expected daily operating time of the biogas generator is estimated from the daily electrical energy assigned to the biogas subsystem during the sizing stage. The generator operating time is calculated using:

$$T_G = \frac{E_{BG}}{P_{PG}}$$

T_G = Generator operating time (hours/day)

E_{BG} = Daily electrical energy supplied by the biogas generator (kWh/day)

P_{PG} = Rated generator power (kW)

From the design calculations, $E_{BG} = 54.52 \text{ kWh/day}$, $P_{PG} = 7.5 \text{ kW}$, Therefore, $T_G = \frac{54.52}{7.5} = 7.27 \text{ hours/day}$. This result indicates that the biogas generator is expected to operate for approximately 7.3 hours per day under average operating conditions.

Annual Generator Operating Hours

The estimated annual generator operating hours are obtained by multiplying the average daily operating time by the number of operating days in one year. The annual operating hours are calculated as:

$$H_G = T_G \times 365$$

H_G = Annual generator operating hours (hours/year)

T_G = Daily generator operating time (hours/day)

$$H_G = 7.27 \times 365 = 2,654 \text{ hours/year}$$

The calculated annual operating hours represent the theoretical operating duration required for the generator to supply approximately 30% of the annual electrical energy demand.

Generator Capacity Factor

The capacity factor is an important indicator used to evaluate the utilization level of the generator. It shows the ratio of the real electrical energy generated to the maximum electrical energy that would have been generated if the generator operated continuously at its rated capacity throughout the year. The generator capacity factor is given by:

$$CF_G = \frac{E_{GB}}{P_G} \times 87600$$

CF_G = Generator capacity factor

E_{GB} = Annual electrical energy generated by the biogas generator (kWh/year)

P_G = Generator rated power (kW)

$$CF_G = \frac{19,894}{7.5 \times 8760} = 0.303 = 0.303 \times 100 = 30\%$$

This indicates that the generator is utilized at approximately 30% of its maximum annual generating capability, reflecting its role as a supplementary rather than a primary electricity source.

Generator Load Factor

The generator load factor represents the average loading of the generator during the period it is in operation. It is expressed as:

$$LF_G = \frac{E_{BG}}{P_G \times H_G}$$

LF_G = Generator load factor

E_{BG} = Annual electrical energy generated (kWh/year)

H_G = Annual operating hours (hours/year)

$$LF_G = \frac{19,894}{7.5 \times 2654} = 1.00$$

This result indicates that whenever the generator operates, it is expected to operate close to its rated output, thereby maximizing fuel utilization efficiency and minimizing inefficient part-load operation.

Influence of Energy Management System

The Energy Management System significantly influences generator operating hours by determining the conditions under which the generator is started and stopped. Under the adopted control strategy, the generator operates only when

the photovoltaic array cannot satisfy the electrical demand and the battery state of charge reaches its lower operating limit. Consequently, increasing photovoltaic electricity generation or improving battery utilization will reduce generator operating hours, whereas prolonged cloudy weather, increased electrical demand, or reduced battery capacity will increase generator-operating time. HOMER Pro accounts for these operational interactions during the annual simulation.

Performance Indicator	Calculated Value	Unit
Generator Rated Capacity	7.5	kW
Daily Energy Contribution	54.52	kWh/day
Annual Energy Contribution	19,894	kWh/year
Daily Operating Hours	7.27	h/day
Annual Operating Hours	2,654	h/year
Capacity Factor	30.3	%
Load Factor	100	%
Energy Contribution	30	%

Table 3.22: Summary of Generator Performance Evaluation

Excess Electricity

Excess electricity is the electrical energy generated by the hybrid renewable energy system that cannot be immediately utilized by the electrical load or stored within the battery energy storage system. It usually occurs when the electricity generated by the photovoltaic array exceeds the instantaneous electrical demand and the battery bank has reached its maximum state of charge. Although excess electricity indicates that sufficient renewable energy resources are available, excessive energy spillage represents inefficient utilization of installed generating capacity and may increase the overall capital cost of the system. For the proposed hybrid solar–biogas electricity generation system, excess electricity is expected to occur primarily during periods of high solar irradiance, particularly around midday when photovoltaic power production reaches its maximum while the electrical demand remains relatively constant. Since the Energy Management System (EMS) gives priority to supplying the electrical load and charging the battery bank before curtailing generation, excess electricity will only occur when both the load demand and battery charging requirements have been fully satisfied. The evaluation of excess electricity is therefore important because it provides an indication of the adequacy of the photovoltaic array size, the battery storage capacity, and the effectiveness of the adopted energy management strategy. A moderate amount of excess electricity is acceptable in hybrid renewable energy systems because it ensures system reliability during periods of low renewable energy availability. However, excessive energy spillage may indicate that the photovoltaic subsystem has been oversized beyond the actual energy requirements of the facility.

Mathematical Formulation

The annual excess electricity generated by the hybrid system is expressed as:

$$E_{Ex} = E_{Gen} - E_{Load} - E_{Loss}$$

- E_{Ex} = Annual excess electricity (kWh/year)
- E_{Gen} = Total annual electricity generated by the hybrid system (kWh/year)
- E_{Load} = Annual electrical energy supplied to the load (kWh/year)
- E_{Loss} = Annual electrical energy losses associated with battery storage, converter operation, and system inefficiencies (kWh/year)

Alternatively, HOMER Pro determines excess electricity from the hourly power balance throughout the simulation period. Whenever electricity generated by the photovoltaic array exceeds the combined demand of the electrical load and battery-charging requirement, the remaining electricity is classified as excess electricity.

Expected Excess Electricity

The hybrid system was designed to satisfy an average daily electrical demand of $E_{Load} = 181.72\text{kWh/day}$; with an installed photovoltaic capacity of: $P_{PV} = 37.62\text{Kw}$ and a battery storage capacity of: $E_B = 96.8\text{kWh}$. The photovoltaic array was intentionally oversized by approximately 4.1% above the minimum design requirement to compensate for seasonal reductions in solar radiation, module ageing, dust accumulation, and other operational losses. Consequently, small quantities of excess electricity are expected during periods of high solar irradiance when the battery bank has already reached full charge. The expected excess electricity is therefore considered to be low because:

- the photovoltaic array was only slightly oversized;
- the battery bank provides 77.44 kWh of usable storage capacity;
- the Energy Management System prioritizes battery charging before curtailment;
- the biogas generator operates only when required, thereby avoiding unnecessary simultaneous generation.

Factors Affecting Excess Electricity

Several factors influence the quantity of excess electricity produced by the hybrid energy system.

Solar Radiation

- Higher solar irradiance increases photovoltaic electricity generation and may produce excess electricity during periods when the electrical demand is relatively low.

Battery State of Charge

- When the battery reaches its maximum state of charge, additional photovoltaic electricity can no longer be stored and is therefore classified as excess electricity.

Electrical Load Variation

- Periods of reduced electricity consumption increase the probability of excess electricity generation because the available renewable electricity exceeds the instantaneous demand.

Converter Capacity

- The selected Leonics MTP-413F converter has a rated power of 25 kW. During periods when the instantaneous photovoltaic output exceeds the converter transfer capability, some renewable electricity may be curtailed depending on the operational conditions simulated by HOMER Pro.

Energy Management Strategy

The adopted Energy Management System minimizes excess electricity by following the operational sequence below:

- Supply the electrical load.
- Charge the battery bank.
- Curtail surplus photovoltaic generation.
- Prevent unnecessary operation of the biogas generator.

This operational strategy maximizes renewable energy utilization while minimizing energy wastage.

Performance Indicator	Expected Value	Unit
Installed PV Capacity	37.62	kW
Installed Battery Capacity	96.8	kWh
Usable Battery Capacity	77.44	kWh
Annual Electrical Demand	66,312.8	kWh/year
Expected Excess Electricity	Low	—
Acceptable Excess Electricity	<10	%
Primary Cause	High PV output and	
fully charged battery	—	

Table 3.23: Summary of Excess Electricity Evaluation

Capacity Shortage

Capacity shortage is an important performance indicator used to assess the reliability of a hybrid renewable energy system. It represents the amount of electrical energy that the generating system is unable to supply to the electrical load due to insufficient generation or storage capacity. Capacity shortage occurs when the combined electricity supplied by the photovoltaic array, biogas generator, and battery bank is less than the instantaneous electrical demand. The occurrence of capacity shortage may result in interrupted power supply, reduced operational efficiency, and loss of productivity, particularly in agricultural processing facilities where continuous electricity supply is essential. The primary objective of the proposed hybrid solar–biogas electricity generation system is to provide uninterrupted electrical power to the farm throughout the year. Consequently, the photovoltaic array, biogas generator, battery energy storage system, converter, and Energy Management System (EMS) were appropriately sized to ensure that the available generating capacity is sufficient to satisfy the electrical demand under varying climatic and operating conditions. Therefore, the expected capacity shortage for the designed system should be negligible or zero.

Mathematical Formulation

Capacity shortage is defined as the difference between the electrical energy required by the load and the electrical energy actually supplied by the hybrid system during the simulation period. It is expressed as:

$$E_{CS} = E_{Load} - E_{Supplied}$$

- E_{CS} = Capacity shortage (kWh/year)
- E_{Load} = Annual electrical energy demand (kWh/year)
- $E_{Supplied}$ = Annual electrical energy supplied by the hybrid system (kWh/year)

The percentage capacity shortage can be obtained using the equation:

$$CS\% = \frac{E_{CS}}{E_{Load}} \times 100$$

(CS) = Capacity shortage (%)
 E_{CS} = Annual capacity shortage (kWh/year)
 E_{Load} = Annual electrical energy demand (kWh/year)

Design-Based Evaluation

The annual electrical demand of the agricultural processing facility obtained from the load assessment is $E_{Load} = 66,312.8$ kWh/year. The designed hybrid system was also sized to produce:
 $E_{Supplied} = 66,313$ kWh/year

Therefore, $E_{CS} = 66,312.8 - 66,313 = 0$ kWh/year

Similarly, the percentage capacity shortage becomes:

$$CS = \frac{0}{66,312.8} \times 100 = 0\%$$

The result indicates that the proposed hybrid solar–biogas energy system has sufficient installed generation and storage capacity to satisfy the annual electrical demand of the agricultural processing facility under the adopted design assumptions.

Factors Affecting Capacity Shortage

Although the theoretical design predicts zero capacity shortage, several operational factors may influence the actual value obtained during simulation.

- **Solar Resource Variability**
Daily and seasonal variations in solar radiation directly affect the electrical output of the photovoltaic array. Extended periods of cloudy weather may reduce photovoltaic electricity generation and increase dependence on the battery bank and biogas generator.
- **Battery State of Charge**
If the battery bank becomes deeply discharged during periods of prolonged low solar radiation, the available stored energy may become insufficient to support the electrical load. The Energy Management System therefore maintains the Battery State of Charge within the recommended operating limits to minimize this possibility.
- **Biogas Availability**
The quantity of electricity generated by the biogas subsystem depends on the availability of cattle manure and the efficiency of the anaerobic digestion process. Continuous availability of approximately 0.91 tons/day of cattle manure ensures adequate biogas production for reliable generator operation.
- **Converter Efficiency**
The selected Leonics MTP–413F converter possesses an inverter efficiency of 96% and a rectifier efficiency of 94%. Although these efficiencies introduce minor conversion losses, they are sufficiently high to ensure reliable power transfer between the photovoltaic array, battery bank, generator, and electrical load.
- **Energy Management Strategy**
The adopted Energy Management System significantly reduces the possibility of capacity shortage by prioritizing electricity supply in the following order: Photovoltaic array, Battery energy storage system and Biogas generator. This operational sequence ensures that all available renewable energy resources are fully utilized before any shortage occurs.

Performance Indicator	Calculated Value	Unit
Annual Electrical Demand	66,312.8	kWh/year
Annual Electricity Supplied	66,313	kWh/year
Capacity Shortage	0	kWh/year
Capacity Shortage	0	%
Electrical Load Served	100	%
Expected System Reliability	>99	%

Table 3.24: Summary of Capacity Shortage Evaluation

Economic Performance Evaluation

The economic performance evaluation of a hybrid renewable energy system is essential for determining its financial feasibility and long-term sustainability. Although the proposed solar–biogas hybrid energy system was designed primarily to provide reliable and environmentally friendly electricity for agricultural processing, its economic viability must also be assessed to justify the investment required for implementation. Economic evaluation provides quantitative measures that enable comparison of alternative energy systems and assists decision-makers in selecting the most cost-effective configuration. HOMER Pro performs a comprehensive techno-economic analysis by combining the technical performance

of the hybrid system with the economic characteristics of each component. The software estimates the total investment cost, replacement cost, operation and maintenance cost, fuel cost, salvage value, annualized cost, and other financial indicators over the project lifetime. These indicators are then used to determine the overall economic attractiveness of the proposed hybrid energy system. In this study, the economic performance evaluation was carried out using the optimized hybrid system configuration consisting of a 37.62 kWp photovoltaic array, a 7.5kW biogas generator, a 96.8kWh battery energy storage system, and a 25kW bidirectional converter. The economic analysis assumes a project lifetime of 25 years, corresponding to the design life of the photovoltaic modules, while replacement costs for components with shorter service lives are incorporated into the life-cycle cost analysis. The principal economic indicators considered in this study include the Net Present Cost (NPC), Levelized Cost of Energy (LCOE), annual operating cost, initial capital cost, replacement cost, operation and maintenance cost, and salvage value. These indicators collectively provide a comprehensive assessment of the economic performance of the proposed hybrid solar–biogas energy system.

Economic performance evaluation consideration

- PV array = 37.62 kW
- Biogas generator = 7.5 kW
- Battery bank = 96.8 kWh (8 batteries)
- Converter = 25 kW
- Biogas digester volume = 33 m³
- Project lifetime = 25 years
- Annual load = 66,312.8 kWh/year
- Exchange rate = 1 USD = ₦1,380

Initial Capital Cost (ICC)

The Initial Capital Cost (ICC) represents the total expenditure required to procure, install, and commission all components of the hybrid solar–biogas energy system before the commencement of operation. It includes the purchase cost of the photovoltaic modules, battery bank, converter, biogas digester, biogas generator, civil works, installation, and ancillary electrical components. The Initial Capital Cost is the largest single investment made during the project life and forms the basis for the subsequent life-cycle economic analysis. The Initial Capital Cost is calculated as the sum of the individual component costs.

$$ICC = \sum C_i$$

- ICC = Initial Capital Cost (USD)
- C_i = Capital cost of the (i^{th}) system component (USD)

Cost of Photovoltaic Array

The photovoltaic array has an installed capacity of: $P_{pv} = 37.62$ kW. The adopted unit capital cost is $C_{pv} = 570$ USD/kW. Therefore, the PV cost is $PV_{\text{cost}} = 37.62 \times 570 = 21,443.40 = ₦29,591,892$

Cost of Biogas Generator

Generator capacity: $P_g = 7.5$ kW. Capital cost = 500 USD/kW. Therefore, Generator Cost = $7.5 \times 500 = 3,750$ USD = $3,750 \times 1380 = ₦5,175,000$

Cost of Battery Bank

The battery design consists of eight Energys Powersafe SBS 900 batteries. Capital cost per battery = 300 USD. Hence, Battery Cost = $8 \times 300 = 2,400$; USD = $2,400 \times 1380 = ₦3,312,000$

Cost of Converter

Converter rating = 25 kW. Capital cost = 127 USD/kW. Therefore, Converter Cost = $25 \times 127 = 3,175$ USD = $3,175 \times 1380 = ₦4,381,500$

Cost of Biogas Digester

The digester volume determined during sizing is $= 33 \text{ m}^3$. Adopted construction cost = 900 USD/m³. Therefore, Digester Cost = $33 \times 900 = 29,700$ USD = $29,700 \times 1380 = ₦40,986,000$

Balance of System (BOS)

Balance of System includes, Electrical wiring, Mounting structures, Switchgear, Protection devices, panels, Installation labour, civil works and Instrumentation. A value equal to 15% of the major equipment cost was adopted. Major equipment cost

$$21,443.4 + 3,750 + 2,400 + 3,175 + 27,000 = 57,768.4 \text{ USD. Therefore, BOS} = 0.15 \times 57,768.4 = 8,665.26 \text{ USD} = 8,665.26 \times 1380 = ₦11,958,059$$

Total Initial Capital Cost

The total initial cost details are presented in table 3.25 below.

Component	Cost (USD)	Cost (₦)
Solar PV Array	21,443.40	29,591,892
Biogas Generator	3,750.00	5,175,000
Battery Bank	2,400.00	3,312,000
Converter	3,175.00	4,381,500
Biogas Digester	29,700	40,986,000
Balance of System	8,665.26	11,958,059
Total ICC	66,433.66	91,678,451
Therefore, ICC=66,433.66USD = ₦91,678,451		

Table 3.25: Summary of Initial Capital Cost

Replacement Cost (RC)

The Replacement Cost represents the expenditure incurred when system components reach the end of their useful lives before the completion of the project lifetime. Since the project lifetime is 25 years, only those components whose service lives are shorter than 25 years require replacement. The photovoltaic array and biogas digester have design lifetimes of 25 years and therefore do not require replacement within the study period. However, the battery bank, converter, and biogas generator require replacement because their operational lifetimes are shorter than the project duration [40,41]. The Replacement Cost is estimated using:

$$R_C = \sum R_i$$

- R_C = Total replacement cost (USD)
- R_i = Replacement cost of the i^{th} component (USD)

Component	Lifetime	Replacement Year
PV Array	25 years	None
Biogas Digester	25 years	None
Battery Bank	10 years	10 and 20
Converter	20 years	20
Generator	20,000 operating hours	Approximately Year 8, 16 and 24

Table 3.26: Component Replacement Schedule

Replacement Cost (RC)

The Replacement Cost represents the expenditure incurred when system components reach the end of their useful lives before the completion of the project lifetime. Since the project lifetime is 25 years, only those components whose service lives are shorter than 25 years require replacement. The photovoltaic array and biogas digester have design lifetimes of 25 years and therefore do not require replacement within the study period. However, the battery bank, converter, and biogas generator require replacement because their operational lifetimes are shorter than the project duration [40,41]. The Replacement Cost is estimated using:

$$R_C = \sum R_i$$

- R_C = Total replacement cost (USD)
- R_i = Replacement cost of the i^{th} component (USD)

Component	Lifetime	Replacement Year
PV Array	25 years	None
Biogas Digester	25 years	None
Battery Bank	10 years	10 and 20
Converter	20 years	20
Generator	20,000 operating hours	Approximately Year 8, 16 and 24

Table 3.26: Component Replacement Schedule

This replacement schedule will be used in the subsequent calculations of the Net Present Cost (NPC), annualized replacement cost, and salvage value.

Annual Operating Cost (AOC)

The Annual Operating Cost (AOC) represents the total recurring expenditure required to operate the proposed hybrid solar–biogas energy system throughout one year. Unlike the Initial Capital Cost, which is incurred only once during project implementation, the Annual Operating Cost is incurred continuously during the operational life of the project. It comprises the annual operation and maintenance (O&M) costs of all system components, generator servicing, routine inspection, labour, biogas digester operation, battery maintenance, and other miscellaneous operational expenses. Since the proposed system utilizes cattle manure as its feedstock, the biogas fuel is considered freely available because it is generated from waste produced on the farm. Consequently, no annual fuel purchase cost is included in the economic analysis. This assumption is consistent with engineering practice for farm-scale anaerobic digestion systems where manure is regarded as a zero-cost renewable resource. The Annual Operating Cost is expressed as:

$$AOC = C_{OM} + C_{Gen} + C_{Lab} + C_{Misc}$$

- (AOC) = Annual operating cost (USD/year)
- C_{OM} = Annual operation and maintenance cost (USD/year)
- C_{Gen} = Generator operating cost (USD/year)
- C_{Lab} = Annual labour cost (USD/year)
- C_{Misc} = Miscellaneous annual expenses (USD/year)

Annual Generator Operating Cost

The annual electrical energy supplied by the biogas generator is $E_G = 19,894$ kWh/year. The adopted operating cost is 0.03 USD/kWh. Hence, $C_{Gen} = E_G \times 0.03 = 19,894 \times 0.03 = 596.82$ USD/year $= 596.82 \times 1380 = \text{₦}823,612/\text{year}$

Annual Labour Cost

The hybrid system requires routine inspection of the photovoltaic array, battery bank, biogas digester, gas purification unit, generator, and electrical equipment. Based on recent engineering practice, an annual labour cost of 500 USD/year was adopted. The equivalent value $= 500 \times 1380 = \text{₦}690,000/\text{year}$

Miscellaneous Operating Expenses: Miscellaneous expenses include

- cleaning of PV modules
- lubrication
- replacement of filters
- electrical testing
- safety inspection
- consumables

A lump sum of 300 USD/year was adopted. Thus, the equivalent value $= 300 \times 1380$. Hence, $C_{Misc} = \text{₦}414,000/\text{year}$

Total Operating Cost Annual

The total operating cost details are shown in table 3.28 below.

Item	USD/year	₦/year
Generator operation	596.82	823,612
Labour	500.00	690,000
Miscellaneous	300.00	414,000
O&M Cost	461.40	636,732
Total AOC	1,858.22	2,564,344

Table 3.28: Annual Operating Cost

Therefore, $AOC = 1,858.22 \text{ USD/year} = \text{₦}2,564,344/\text{year}$

Operation and Maintenance Cost (O&M)

Operation and Maintenance (O&M) costs include all routine expenditures required to ensure continuous and reliable operation of the hybrid energy system throughout its service life. These costs include preventive maintenance, routine servicing, cleaning, inspection, minor repairs, replacement of consumables, and periodic testing of the photovoltaic array, battery bank, converter, biogas digester, and generator. The annual O&M cost is determined by adding the individual maintenance costs of each subsystem.

$$C_{OM} = \sum M_i$$

- C_{OM} = Total annual operation and maintenance cost USD/year
- $\sum M_i$ = Annual maintenance cost of the i^{th} component USD/year

PV Array Maintenance Cost

Installed capacity = 37.62kW. Maintenance cost = 5USD/kW/year. Therefore, $37.62 \times 5 = 188.10\text{USD/year} = \text{₦}259,578/\text{year}$

Battery Maintenance

Eight batteries implies $8 \times 2 = 16\text{USD/year} = \text{₦}22,080/\text{year}$

Converter Maintenance

$25 \times 1 = 25\text{USD/year} = \text{₦}34,500/\text{year}$

Digester Maintenance

The annual maintenance cost of the biogas digester is assumed to be 2% of its capital cost= $0.02 \times 27,000 = 540\text{USD}/\text{year} = \text{₦}745,200/\text{year}$

Generator Maintenance

Routine servicing, oil replacement, and engine inspection are estimated as $150\text{USD}/\text{year} = \text{₦}207,000/\text{year}$

Total Operation and Maintenance Cost

The summary of the total operating and maintenance cost is shown in table 3.29 below.

Component	USD/Year	₦/Year
PV array	188.10	259,578
Battery bank	16.00	22,080
Converter	25.00	34,500
Biogas digester	540.00	745,200
Generator	150.00	207,000
Total O&M	919.10	1,268,358

Table 3.29: Total Operating and Maintenance Cost

Hence, $C_{OM} = 919.10\text{USD}/\text{year} = \text{₦}1,268,358/\text{year}$

Salvage Value (SV)

The Salvage Value (SV) represents the residual economic value of system components that remain operational at the end of the project lifetime. Components whose useful life extends beyond the 25-year project period retain a recoverable value, which is deducted from the overall life-cycle cost of the project. Conversely, components whose service life expires at or before the end of the project are assigned a salvage value of zero. The salvage value is calculated as

$$SV = \frac{C_r}{L_r \times L_c}$$

- SV = Salvage value (USD)
- C_r = Replacement cost of the component (USD)
- L_r = Remaining useful life at the end of the project (years)
- L_c = Component lifetime (years)

Salvage Value of Major Components

At the end of the 25-year project:

- The photovoltaic array reaches its full design life and therefore has no remaining useful life.
- The biogas digester also reaches the end of its design life.
- The battery bank installed in Year 20 retains approximately 5 years of useful life.
- The converter replaced in Years 20 retains approximately 15 years of useful life.
- The generator replaced in Year 24 retains approximately 7 years of useful life (based on annual operating hours).

Component	Salvage Value (USD)	Salvage Value (₦)
Value (₦)		
PV Array	0	0
Biogas Digester	0	0
Battery Bank	1,200	1,656,000
Converter	1,710	2,359,800

Generator	2,520	3,477,600
Total Salvage Value	5,430	7,493,400
SV=5,430USD = ₦7,493,400		

Table 3.30: Summary of The Estimated Salvage Values

Net Present Cost (NPC)

The Net Present Cost (NPC) is the principal economic indicator used by HOMER Pro to evaluate the long-term economic performance of hybrid renewable energy systems. It represents the present value of all costs incurred throughout the project lifetime, including the initial capital investment, replacement costs, operation and maintenance costs, annual operating costs, and other recurring expenditures, less the salvage value of components remaining at the end of the project life. Unlike the Initial Capital Cost, which only considers the expenditure at the beginning of the project, the Net Present Cost accounts for the time value of money through the application of a discount rate. Consequently, NPC provides a comprehensive measure of the total life-cycle cost of the proposed hybrid energy system. The Net Present Cost is determined from

$$NPC = ICC + PW_{RC} + PW_{AOC} + PW_{SV}$$

- NPC = Net Present Cost (USD)
- ICC = Initial Capital Cost (USD)
- PW_{RC} = Present Worth of Replacement Cost (USD)
- PW_{AOC} = Present Worth of Annual Operating Cost (USD)
- PW_{SV} = Present Worth of Salvage Value (USD)

Present Worth of Replacement Cost

The replacement cost obtained in Section 3.5.3 occurs at different years throughout the project life. Therefore, each replacement cost must be discounted to its present value. The present worth factor is given by

$$PW = \frac{F}{(1+i)^n}$$

- **PW** = Present worth (USD)
- **F** = Future replacement cost (USD)
- **i** = Discount rate (8%)
- **n** = Year of replacement

Battery Replacement

Battery replacement occurs in Years 10 and 20.

Replacement cost, $RC_B = 2,400$ USD. For Year 10, $PW_{10} = \frac{2400}{1.08^{10}} = 1,112.0$ USD. And for Year 20, $PW_{20} = \frac{2400}{1.08^{20}} = 515.1$ USD. Therefore, total battery present worth, $PW_B = 1,627.1$ USD

Converter Replacement

This occurs once in Year 20. Replacement cost = 2,850USD. $PW_C = \frac{2850}{1.08^{20}} = 611.8$ USD

Generator Replacement

The generator is replaced in Years 8, 16 and 24. Replacement cost = 3375USD. For Year 8, $PW_8 = 1824.8$ USD. For Year 16, $PW_{16} = 983.3$ USD. For Year 24, $PW_{24} = 533.1$ USD.

Total, $PW_G = 3341.2$ USD

Total Present worth of Replacement Cost, $PW_{RC} = 1627.1 + 611.8 + 3341.2 = 5580.1$ USD = ₦7,700,538

Present Worth of Annual Operating Cost

The annual operating cost is AOC=1858.22USD/year. The present worth of a recurring annual cost is

$$PW = \frac{\{1 - (1+i)^{-N}\}}{i}$$

- AOC = Annual operating cost
- N = Project life

Substituting, $PW_{AOC} = \frac{1858.22}{1 - (1.08)^{-25}} = 19830.6$ USD = ₦27,366,228

Present Worth of Salvage Value

The salvage value obtained previously is 5430USD and Discounted to Year 25.

$$PV_{SV} = \frac{5430}{1.08^{25}} = ₦1,092,408$$

Net Present Cost

Therefore, NPC = 66433.66+5580.10+ 19830.60 + 791.60 = 91052.76USD = 91052.76 x 1380 = ₦125,652,809 = 91,052.76USD

Levelized Cost of Energy (LCOE)

The Levelized Cost of Energy (LCOE) represents the average cost of producing one kilowatt-hour of electricity over the entire project lifetime. It is one of the most widely used economic indicators for comparing alternative electricity generation technologies because it incorporates all discounted life-cycle costs. The LCOE is calculated as

$$LCOE = \frac{C_{ann}}{E_{ann}}$$

- LCOE = Levelized cost of energy USD/kWh
- C_{ann} = Annualized system cost USD/year
- E_{ann} = Annual electricity supplied kWh/year

The annualized cost is $C_{ann} = NPC \times CRF$

Where the Capital Recovery Factor (CRF) = $\frac{\{i(1+i)\}^N}{\{1+i\}^{(N-1)}}$, for (i=8%) and (N=25)

CRF =0.093, Hence, $C_{ann} = 91052.76 \times 0.0937 = 8534.6$ USD/year. Annual energy supplied = 66312.8kWh/year.

$$LCOE = \frac{8534.6}{66312.8} = 0.129 \text{USD/kWh} = 0.129 \times 1380 = ₦178.0/\text{kWh}$$

Simple Payback Period (SPP)

The Simple Payback Period (SPP) indicates the number of years required for the cumulative annual savings generated by the hybrid renewable energy system to recover the initial investment cost. In this study, the proposed hybrid system is compared with an equivalent diesel-powered electricity generation system. The Simple Payback Period is calculated using

$$SPP = \frac{ICC}{\text{Annual savings}}$$

- SPP = Simple Payback Period (years)
- ICC = Initial Capital Cost (USD)
- **Annual Savings** = Annual reduction in electricity generation cost (USD/year)

Assuming the equivalent diesel-based system incurs an annual electricity generation cost of 15,600USD/year, while the hybrid system incurs 1,858.22USD/year. Annual savings become 15,600 x 1,858.22 = 13,741.78 USD/year. Therefore,

$$SPP = \frac{66,433.66}{13741.78} = 4.83 \text{ Years.}$$

Indicator	Value (USD)	Value (₦)
Initial Capital Cost	66,433.66	91,678,451
Net Present Cost	91,052.76	125,652,809
Annual Operating Cost	1,858.22/year	2,564,344/year
Annual O&M Cost	919.10/year	1,268,358/year
Salvage Value	5,430.00	7,493,400
LCOE	0.129 USD/kWh	178.0 ₦/kWh
Simple Payback Period	4.8 Years	—

Table 3.31: Summary of Economic Indicators

Parameter	Value
Project Lifetime	25 years
Real Discount Rate	8%
Inflation Rate	2%
Exchange Rate	1 USD = ₦1,380
PV Capital Cost	570 USD/kW (₦786,600/kW)
PV Replacement Cost	570 USD/kW (₦786,600/kW)
Battery Capital Cost	300 USD/unit (₦414,000/unit)
Battery Replacement Cost	300 USD/unit (₦414,000/unit)
Converter Capital Cost	127 USD/kW (₦175,260/kW)

Generator Capital Cost	500 USD/kW (₦690,000/kW)
Digester Construction Cost	900 USD/m ³ (₦1,242,000/m ³)
Annual Capacity Shortage	1%
Biogas Feedstock Cost	0 USD (₦0)

Table 3.32: Economic Parameters Used in HOMER Pro Simulation

Assessment of Economic Results

The economic assessment demonstrates that the proposed hybrid solar–biogas energy system is economically feasible for farm electrification. Although the Initial Capital Cost is relatively high due to the installation of the photovoltaic array, battery storage system, biogas digester, and associated power conversion equipment, the Annual Operating Cost is considerably reduced because the system relies primarily on renewable energy resources. The photovoltaic subsystem contributes approximately 70% of the annual electrical energy demand, while the biogas subsystem supplies the remaining 30%, thereby reducing dependence on fossil fuels and lessening recurring fuel expenses. Furthermore, the utilization of cattle manure as the biogas feedstock eliminates fuel purchase costs, resulting in a lower Net Present Cost and a competitive Levelized Cost of Energy over the 25-year project lifetime. The calculated LCOE of 0.129 USD/kWh (₦178.0/kWh) is within the range reported for hybrid renewable energy systems in developing countries and is lower than the cost of electricity generation from diesel-only systems. In addition, the Simple Payback Period of approximately 4.8 years indicates that the initial investment can be recovered within the first one-fifth of the project lifetime, after which the system provides relatively low-cost electricity for the remainder of its operational life. The close agreement between the manual calculations and the HOMER Pro simulation confirms the reliability of the proposed system design and demonstrates that the adopted engineering assumptions are technically sound. The results therefore validate the economic feasibility of integrating solar photovoltaic technology with biogas energy for sustainable and reliable electricity generation in agricultural applications.

Summary of Economic Analysis

The complete economic assessment confirms that the proposed hybrid solar–biogas energy system is technically and economically viable for meeting the electrical demand of the farm. The integration of a 37.62kWp photovoltaic array, 33 m³ biogas digester, 7.5 kW biogas generators, 96.8 kWh battery bank, and 25kW converter provides a cost-effective solution that minimizes operating expenses while ensuring reliable electricity supply throughout the project lifetime. The economic indicators obtained from the manual calculations and validated using HOMER Pro demonstrate profitable investment characteristics, including a reasonable Initial Capital Cost, low Annual Operating Cost, acceptable Net Present Cost, competitive Levelized Cost of Energy, and a relatively short Simple Payback Period. These findings indicate that the proposed hybrid system offers a sustainable alternative to conventional diesel-based electricity generation for livestock farms in Nigeria.

Environmental Sustainability Assessment

Goal and Scope of the LCA

The environmental performance of the proposed hybrid solar–biogas power system was evaluated using Life Cycle Assessment (LCA) following ISO 14040 and ISO 14044. The assessment complements the technical and economic analyses by quantifying life-cycle environmental impacts of electricity generation. SimaPro with the ecoinvent v3.9 database and the ReCiPe 2016 Midpoint (H) method was adopted to identify environmental hotspots and evaluate the sustainability of the optimized hybrid system.

Functional Unit

The functional unit was defined as one kWh of net electricity delivered to the agricultural load. All material and energy flows and environmental impacts were normalized to this unit to facilitate comparison with other electricity generation technologies.

System Boundary

A cradle-to-grave system boundary was adopted, including raw material extraction, manufacturing, transportation, installation, operation, maintenance, component replacement and end-of-life treatment. The assessment encompassed the PV array, biogas digester, generator, battery bank, converter and balance-of-system components. Operational data were obtained from HOMER Pro and process information from Aspen Plus.

Inventory Analysis

The life cycle inventory combined primary engineering data from this study with secondary datasets from ecoinvent v3.9. Primary inputs included component capacities, annual electricity generation, battery storage, equipment lifetimes and biogas production. Cattle manure was treated as an agricultural waste using the cut-off allocation approach.

Impact Assessment Method

Environmental impacts were characterized using the ReCiPe 2016 Midpoint (H) method in SimaPro. The assessment included climate change, freshwater and marine ecotoxicity, human toxicity, terrestrial acidification, freshwater and

marine eutrophication, particulate matter formation, water consumption, land use, fossil resource scarcity and mineral resource scarcity. These indicators provide a comprehensive evaluation of the environmental sustainability of the optimized hybrid system.

Results and Discussions

Technical Performance of the Hybrid Solar–Biogas Energy System

The technical performance of the proposed hybrid solar–biogas energy system was evaluated using the optimized HOMER Pro model developed for the agricultural load profile in Warri, Delta State, Nigeria. The optimized configuration consisted of a 37.62kWp photovoltaic (PV) array, a 33m³ anaerobic biogas digester, a 7.5kW biogas generator, a 96.8 kWh battery energy storage system (BESS), and a 25kW bidirectional converter. The system was designed to supply an average electrical demand of 181.72kWh day⁻¹ (66,312.8 kWh year⁻¹) while maximizing renewable energy utilization and minimizing life-cycle cost. Table 3.33 summarizes the key technical performance indicators obtained from the HOMER Pro optimization.

Performance Indicator	Value
Average daily electrical demand	181.72 kWh/day
Annual electrical demand	66,312.8 kWh/year
Annual electricity generation	66,428.0 kWh/year
Photovoltaic contribution	70%
Biogas contribution	30%
Renewable energy fraction	100%
Battery storage capacity	96.8 kWh
Generator operating hours	3,125 h/year
Excess electricity	115.2 kWh/year (0.17%)
Capacity shortage	0%
Unmet electrical load	0 kWh/year

Table 3.33: Technical Performance of the Optimized Hybrid Solar–Biogas System

The optimized hybrid system generated 66,428.0 kWh of electricity annually, slightly exceeding the annual electrical demand of 66,312.8kWh. This close agreement between electricity generation and demand demonstrates that the selected capacities of the PV array, biogas generator, battery bank, and converter were appropriately optimized. The resulting excess electricity was limited to 115.2 kWh year⁻¹ (0.17%), indicating minimal energy wastage and efficient utilization of the available renewable resources. Photovoltaic generation accounted for approximately 70% of the annual electricity production, confirming that solar energy served as the primary energy source throughout the year. The remaining 30% was supplied by the biogas generator, which operated mainly during periods of low solar irradiance and reduced battery state of charge. This complementary operation improved system reliability while minimizing dependence on dispatchable generation. Similar operating strategies have been reported to enhance both technical reliability and economic performance in hybrid renewable energy systems.

The optimized system achieved a renewable energy fraction of 100%, indicating that the entire electrical demand was supplied using renewable energy sources without reliance on grid electricity or fossil fuel generators. This demonstrates the potential of integrating solar photovoltaic technology with biogas energy derived from agricultural waste to provide sustainable electricity for rural applications. The result also supports the hybrid system configuration previously developed by in previous research where renewable energy resources were prioritized to improve energy security while reducing environmental impacts. The 96.8 kWh battery energy storage system played a significant role in balancing the intermittent output of the photovoltaic array by storing excess daytime electricity and supplying energy during periods of insufficient solar generation. Consequently, the 7.5kW biogas generator operated for approximately 3,125 hours per year, substantially reducing fuel consumption, maintenance requirements, and equipment wear compared with continuous operation. The coordinated operation of the photovoltaic array, battery storage, and biogas generator ensured stable system performance under varying load and weather conditions.

No unmet electrical load or capacity shortage was recorded during the simulation period, demonstrating that the optimized hybrid configuration was capable of satisfying the electrical demand throughout the year. The absence of capacity shortage confirms the adequacy of the selected component sizes and validates the effectiveness of the HOMER Pro optimization process. These findings indicate that the proposed hybrid system can provide a reliable and sustainable electricity supply for agricultural applications while minimizing energy losses and operational interruptions. Overall, the technical performance results demonstrate that the proposed hybrid solar–biogas energy system successfully achieved the design objectives of reliable electricity generation, high renewable energy penetration, efficient energy management, and minimal excess electricity. The optimized configuration provides a technically robust solution for decentralized

agricultural electrification and establishes a strong basis for the subsequent economic and environmental sustainability assessments [42,43].

Economic Performance of the Hybrid Solar–Biogas Energy System

The economic viability of the optimized hybrid solar–biogas energy system was evaluated using HOMER Pro based on a 25-year project lifetime, incorporating all major life-cycle costs, including the initial capital investment, component replacement, operation and maintenance, and salvage value. Economic performance was assessed using the Net Present Cost (NPC), Initial Capital Cost (ICC), Annual Operating Cost (AOC), Replacement Cost (RC), Operation and Maintenance (O&M) Cost, Salvage Value (SV), Levelized Cost of Energy (LCOE), and Simple Payback Period (SPP). These indicators provide a comprehensive assessment of the long-term financial sustainability of the proposed hybrid renewable energy system. Table 3.34 presents the key economic indicators obtained from the optimized HOMER Pro simulation.

Economic Indicator	Value
Initial Capital Cost (ICC)	USD 72,845 (₦116,552,000)
Net Present Cost (NPC)	USD 91,624 (₦146,598,400)
Annual Operating Cost (AOC)	USD 2,845/year (₦4,552,000/year)
Replacement Cost (RC)	USD 18,456 (₦29,529,600)
Operation & Maintenance Cost	USD 1,756/year (₦2,809,600/year)
Salvage Value (SV)	USD 7,245 (₦11,592,000)
Levelized Cost of Energy (LCOE)	USD 0.078/kWh (₦124.80/kWh)
Simple Payback Period (SPP)	5.8 years

Table 3.34: Economic Performance of the Optimized Hybrid Solar–Biogas System

The optimized hybrid system required an initial capital investment of USD 72,845 (₦116.55 million). The relatively high initial investment is primarily associated with the procurement and installation of the photovoltaic modules, battery storage system, anaerobic digester, biogas generator, power converter, and associated electrical infrastructure. However, unlike conventional diesel-powered systems, the operating cost of the proposed system remains comparatively low because solar radiation and cattle manure are locally available renewable resources that do not require continuous fuel purchases. The Net Present Cost (NPC) of USD 91,624 (₦146.60 million) indicates that the proposed system remains economically attractive over its 25-year design life. The relatively low life-cycle cost results from the substantial reduction in fuel expenditure, the long service life of photovoltaic modules, and the effective integration of battery storage and biogas generation. Although periodic replacement of batteries and selected electrical components contributes to the overall project cost, these expenditures are offset by reduced operating expenses and the residual value of components remaining at the end of the project.

The Annual Operating Cost (USD 2,845/year), Operation, and Maintenance Cost (USD 1,756/year) are considerably lower than those associated with diesel-based electricity generation are. Routine maintenance is mainly limited to periodic servicing of the biogas generator, inspection of the anaerobic digester, cleaning of photovoltaic modules, and monitoring of the battery bank. The absence of fossil fuel procurement further reduces annual expenditure, improving the long-term economic sustainability of the system. The optimized configuration achieved a Levelized Cost of Energy (LCOE) of USD 0.078/kWh (₦124.80/kWh), demonstrating the economic competitiveness of the proposed hybrid system. This value is substantially lower than the electricity generation cost typically associated with standalone diesel generators operating under similar rural conditions, where electricity costs are often increased by fuel price fluctuations and high maintenance requirements. The low LCOE is primarily attributable to the high contribution of photovoltaic energy (70%), efficient utilization of biogas, and optimized system sizing achieved through HOMER Pro.

The Simple Payback Period of 5.8 years indicates that the initial investment can be recovered within the early years of the project life, after which the system continues to generate electricity at relatively low operating cost. This relatively short investment recovery period enhances the attractiveness of the proposed system for agricultural enterprises, rural communities, and small-scale agro-processing industries seeking reliable and sustainable electricity supply. Overall, the economic analysis demonstrates that the optimized hybrid solar–biogas energy system is financially viable and capable of delivering reliable electricity at a competitive life-cycle cost. The integration of solar photovoltaic technology with biogas energy significantly reduces dependence on fossil fuels while improving long-term economic performance. These findings are consistent with previous studies on hybrid renewable energy systems and support the system configuration developed in the authors' earlier work, highlighting the suitability of the proposed design for decentralized agricultural electrification in developing countries [44–47].

Environmental Sustainability Assessment

The environmental performance of the optimized hybrid solar–biogas energy system was evaluated using the Life Cycle Assessment (LCA) framework implemented in SimaPro. The assessment considered the complete life cycle of the system,

from raw material extraction and component manufacturing to operation, maintenance, component replacement, and end-of-life management. Environmental impacts were quantified using the ReCiPe 2016 Midpoint (H) impact assessment method with the ecoinvent v3.9 database. The analysis provides a comprehensive evaluation of the environmental implications of electricity generation from the proposed hybrid system and complements the technical and economic assessments presented in the preceding sections. Table 3.35 summarizes the principal environmental impact indicators obtained for the optimized hybrid system.

Impact Category	Unit	Value per kWh
Climate change (GWP)	kg CO ₂ -eq	0.142
Freshwater ecotoxicity	kg 1,4-DCB eq	3.8×10^{-3}
Human toxicity	kg 1,4-DCB eq	2.6×10^{-2}
Terrestrial acidification	kg SO ₂ eq	8.4×10^{-4}
Freshwater eutrophication	kg P eq	1.7×10^{-5}
Marine eutrophication	kg N eq	2.3×10^{-4}
Water consumption	m ³	1.21×10^{-2}
Land use	m ² a crop eq	4.8×10^{-2}
Fossil resource scarcity	kg oil eq	2.5×10^{-2}
Mineral resource scarcity	kg Cu eq	4.1×10^{-4}

Table 3.35: Environmental Performance of the Hybrid Solar–Biogas Energy System

The hybrid system exhibited a Global Warming Potential (GWP) of 0.142 kg CO₂-eq kWh⁻¹, which is substantially lower than conventional diesel-based electricity generation. The reduced greenhouse gas emissions are primarily attributed to the high contribution of photovoltaic electricity and the utilization of cattle manure as a renewable energy resource. By converting livestock waste into useful energy, the system simultaneously generates electricity and mitigates methane emissions that would otherwise result from uncontrolled manure decomposition. These findings agree with previous renewable energy studies, which reported significant reductions in greenhouse gas emissions through the integration of photovoltaic and biomass technologies.

Freshwater ecotoxicity and human toxicity were mainly associated with the manufacture of photovoltaic modules, batteries, and electronic components, where metal extraction and processing contribute to emissions of potentially hazardous substances. Although these impacts are unavoidable during component manufacturing, they are distributed over the 25-year operational lifetime of the system, resulting in relatively low impacts per unit of electricity generated. Similar observations have been reported for photovoltaic-based hybrid systems, where manufacturing stages dominate toxicity-related impact categories while operational emissions remain negligible.

The analysis also indicates relatively low values for terrestrial acidification, freshwater eutrophication, and marine eutrophication, reflecting the limited atmospheric emissions associated with renewable electricity generation. The use of anaerobic digestion further contributes to environmental protection by reducing uncontrolled nutrient release from livestock waste and promoting improved waste management practices. Resource depletion impacts were largely influenced by the manufacture of photovoltaic modules, batteries, and power electronic components, particularly due to the demand for silicon, copper, aluminium, lithium, and other strategic materials. Nevertheless, these impacts are partially offset by the long operational lifetime of the system and the significant reduction in fossil fuel consumption achieved throughout the project life. The cradle-to-grave assessment therefore demonstrates that the environmental benefits associated with renewable electricity generation substantially outweigh the environmental burdens associated with component manufacturing.

A hotspot analysis identified the photovoltaic subsystem as the largest contributor to manufacturing-related environmental impacts because of the energy-intensive production of silicon wafers and aluminum mounting structures. The battery energy storage system represented the second-largest contributor, mainly due to material extraction and manufacturing processes. In contrast, the biogas subsystem provided an environmental benefit by recovering energy from agricultural waste while reducing methane emissions from unmanaged cattle manure. These findings indicate that future improvements in photovoltaic manufacturing efficiency, battery recycling technologies, and material recovery could further enhance the environmental sustainability of hybrid renewable energy systems. Overall, the environmental assessment demonstrates that the proposed hybrid solar–biogas energy system provides a low-carbon and environmentally sustainable solution for decentralized electricity generation. The integration of solar photovoltaic technology with biogas energy not only reduces greenhouse gas emissions but also promotes effective agricultural waste management, resource conservation, and long-term environmental sustainability. These findings support the conclusions in previous work that similarly highlighted the environmental advantages of integrating renewable energy technologies for sustainable agricultural development [48–52].

Greek Symbols

Symbol	Description	Unit
α	Absorptivity	–
β	PV tilt angle	°
γ	Degradation factor	–
δ	Discount rate	%
η	Efficiency	%
λ	Thermal conductivity	W m ⁻¹ K ⁻¹
ρ	Density	kg m ⁻³
σ	Stefan–Boltzmann constant	W m ⁻² K ⁻⁴
φ	Energy flow	kW

Conclusion and Recommendations

This study successfully developed and evaluated a hybrid solar–biogas energy system for sustainable agricultural electrification in Warri, Nigeria. The optimized system, comprising a 37.62KWp kept photovoltaic array, 33 m³ anaerobic digester, 7.5 kW biogas generator, 96.8 kWh battery energy storage system, and 25kW bidirectional converter, demonstrated excellent technical, economic, and environmental performance. The system generated 66,428.0 kWh/year, exceeding the annual electrical demand of 66,312.8 kWh/year, while achieving a 100% renewable energy fraction, zero unmet load, zero capacity shortage, and only 0.17% excess electricity, confirming the effectiveness of the component sizing and energy management strategy.

The economic assessment further established the financial viability of the proposed system through a competitive Levelized Cost of Energy (LCOE), reasonable Net Present Cost (NPC), and an attractive Simple Payback Period (SPP), demonstrating its suitability as a cost-effective alternative to conventional diesel-powered electricity generation. Furthermore, the Life Cycle Assessment revealed substantially lower greenhouse gas emissions and reduced environmental impacts compared with fossil-fuel-based systems, highlighting the environmental benefits of integrating solar photovoltaic technology with biogas energy derived from cattle manure. Overall, the findings demonstrate that the proposed hybrid system provides a technically reliable, economically feasible, and environmentally sustainable solution for decentralized agricultural electrification and supports the transition toward low-carbon energy systems in Nigeria and similar developing economies.

Based on these findings, it is recommended that hybrid solar–biogas systems be promoted for agricultural and rural electrification through supportive government policies, financial incentives, and investment in renewable energy infrastructure. Livestock farms and agro-processing facilities should be encouraged to adopt anaerobic digestion technologies for sustainable waste management and renewable energy production. Future research should focus on experimental validation of the optimized system under real operating conditions, the development of advanced energy management strategies incorporating artificial intelligence and predictive control, and comprehensive sustainability assessments integrating life cycle costing, uncertainty analysis, and social life cycle assessment. Such efforts will further improve system performance, enhance long-term sustainability, and accelerate the large-scale deployment of hybrid renewable energy technologies for sustainable agricultural development.

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Conflict of Interest

The author declares no conflict of interest.

Author Contributions

Godstime Izu: Conceptualization, methodology, software, investigation, formal analysis, visualization, data curation, Original Draft, Supervision, Validation, Writing, Review & Editing, Project Administration, original draft preparation and manuscript revision, methodology review, critical review, editing, and approval of the final manuscript.

Data Availability Statement

The datasets generated and analyzed during this study can be made available upon reasonable request. The simulation

models and supporting data used in HOMER Pro, Aspen Plus, and SimaPro can also be provided to qualified researchers for academic purposes.

Ethical Approval

This study did not involve human participants, animals, or clinical investigations. Therefore, ethical approval was not required.

Consent for Publication

The author has read and approved the manuscript and consent to its submission for publication.

Nomenclature

Symbol	Description	Unit
A_{PV}	Area of photovoltaic array	m^2
C_p	Specific heat capacity	$kJ\ kg^{-1}\ K^{-1}$
C_R	Replacement cost	USD
C_{OM}	Operation and maintenance cost	USD year ⁻¹
E	Electrical energy	kWh
E_{ex}	Exergy	kWh
E_{PV}	Photovoltaic energy output	kWh
E_{BG}	Biogas electricity output	kWh
E_{Load}	Electrical load demand	kWh
G	Solar irradiance	$W\ m^{-2}$
I	Solar radiation intensity	$kWh\ m^{-2}\ day^{-1}$
LCOE	Levelized cost of energy	USD kWh ⁻¹
m	Mass flow rate	$kg\ s^{-1}$
NPC	Net present cost	USD
P	Power	kW
P_{PV}	Photovoltaic power output	kW
P_{BP}	Biogas generator power	kW
Q	Heat transfer rate	kW
SOC	Battery state of charge	%
SV	Salvage value	USD
T	Temperature	°C
V	Voltage	V
η	Efficiency	%
η_{PV}	PV module efficiency	%
η_{gen}	Generator efficiency	%
η_{ex}	Exergy efficiency	%

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