

# Performance Assessment of a Solar Photovoltaic and Biogas Hybrid Renewable Energy System Under a Combined Dispatch Strategy

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## Abstract

This study investigates the techno-economic and environmental performance of a hybrid renewable energy system integrating solar photovoltaic (PV), biogas, and battery storage for a large-scale abattoir in Lagos, Nigeria. Using HOMER Pro simulations, the research evaluates the effectiveness of a combined dispatch (CD) strategy that dynamically alternates between load-following and cycle-charging modes based on net load conditions and future load forecasting. The abattoir's baseline empirical daily energy consumption of 626.05 kWh/day was scaled to a design load of 2,426.4 kWh/day to simulate a robust and long-term operational expansion, which was matched against a solar irradiance of 4.74 kWh/m<sup>2</sup>/day and biomass recovery potential of approximately 15 tons/day. The results based on this scaled design load demonstrate that the CD strategy significantly outperformed the conventional cycle-charging (CC) approach, reducing the Net Present Cost by approximately 24.7% (a saving of \$307,127) and lowering the cost of energy to \$0.267/kWh. Furthermore, the CD strategy optimized the utilization of renewable resources, with PV contributing 68.7% of the energy mix, and enhanced equipment longevity by reducing the biogas generator's annual run time from 3,178 hours to 1,194 hours. Environmentally, the CD strategy achieves a substantial reduction in CO<sub>2</sub> emissions, emitting only 58.8 kg/yr compared to 152 kg/yr under the CC strategy. These findings highlight the viability of PV/biogas hybrid systems under optimized dispatch control as a sustainable and cost-effective energy solution for agro-industrial facilities in sub-Saharan Africa.

**Categories:** Renewable Energy Systems, Energy Efficiency and Conservation, Environmental and Sustainable Engineering

**Keywords:** hybrid renewable energy system, solar pv, biogas, waste-to-watt, dispatch optimization, energy management, agro-industrial energy systems, sub-saharan africa

## Introduction

Access to reliable and sustainable energy is a fundamental driver of socio-economic development and a key indicator in assessing the Human Development Index (HDI) [1,2]. Nations with high HDI typically enjoy stable electricity supply, robust healthcare systems, and strong economic growth. In contrast, unreliable grid connections in developing countries hinder industrial productivity, limit access to modern services, and constrain overall development [3]. Global energy trends are shifting from fossil fuels toward renewable energy sources (RES) such as solar, wind, hydro, and biomass. This transition is motivated by the finite nature of fossil reserves, price volatility, and the environmental consequences of greenhouse gas emissions. Projections suggest that renewable energy could account for 36% of global electricity generation by 2030 [4]. However, despite the promise, individual renewable technologies face challenges: solar and wind are intermittent, biomass requires consistent feedstock, and most systems demand high upfront capital investment [5,6]. These limitations underscore the importance of hybrid renewable energy systems (HRES), which integrate multiple sources to enhance reliability, sustainability, and cost-effectiveness. A hybrid system's performance depends not only on optimal component sizing but

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also on effective energy management [7]. In a typical model of a hybrid energy system, the Energy Management Unit (EMU) coordinates energy flow among sources and storage, guided by dispatch strategies [7]. Common dispatch strategies include: Load-following (LF), in which generation matches demand directly; cycle-charging (CC), in which excess generation charges batteries, ensuring reliability during shortages; and combined dispatch (CD), which integrates LF and CC to balance cost, reliability, and sustainability. Some earlier studies have applied dispatch strategies primarily to rural electrification projects, desalination plants, and small-scale micro-grids. While the works demonstrate technical and economic benefits, limited attention has been given to energy-intensive agro-industrial facilities such as abattoirs, cold storage outlets, and small-scale industries. These sectors face unique challenges like high and variable energy demand, reliance on diesel generators, and abundant biomass waste streams that remain underutilized. Thus, this present study addresses this gap by assessing the performance of a photovoltaic (PV)/biogas hybrid energy system for a large-scale abattoir in Lagos, Nigeria, under a CD strategy. The abattoir generates significant biomass waste daily, offering a sustainable feedstock for biogas production. By integrating solar PV, biogas, and battery storage, and simulating the system with HOMER Pro, this research evaluates the techno-economic and environmental impact performance. The findings from this work provide a replicable model for agro-industrial hubs across sub-Saharan Africa, contributing to both energy transition and sustainable development.

### Review

A review of existing HRES shows that they have been broadly studied across different contexts. While standard dispatch strategies play a central role in optimizing performance, some scholarly contributions focus on rural electrification, desalination, or small-scale microgrids, with dispatch strategies applied to balance cost, reliability, and sustainability. The research [8] compared technical, economic, and environmental outcomes of different dispatch strategies, while another study [9] also proposed an optimal dispatch framework for PV/fuel cell/battery systems. Similarly, the study [10] demonstrated that combined dispatch strategies improve energy management in PV/diesel/battery systems, while the study [11] extended this approach to complex hybrid topologies, including SHP, PV, biomass, diesel, and biogas. More recent works, such as the study [12], applied dispatch-based optimization to grid-tied university systems, highlighting the adaptability of dispatch strategies to diverse settings focused on campus electrification. The study [13] assessed the performance of a hybrid PV/battery/diesel system using both the load-following and cycle-charging strategies; similarly, the study [14] investigated techno-economic and power optimization by deploying an optimal dispatch strategy on a renewable-rich islanded microgrid. This study demonstrated the adaptability of the dispatch strategy to achieve economic viability. The review by Marzabani and Abedelfatalin [15] focused on economic dispatch optimization and associated problem formulation; the paper calls for standardization of evaluation criteria to enhance practical (real-time) optimization techniques, in which the dispatch strategy plays a major role. Another dimension is another study [16], which adapted a novel dispatch strategy in the techno-economic analysis of a hybrid PV/wind/diesel/battery system. Jufri [17] optimized battery energy storage of a PV/battery hybrid system using an optimal dispatch strategy for a small-scale isolated renewable energy system with different load profile patterns without biomass integration. A multi-criteria decision-making study to determine the optimal energy management strategy of a hybrid PV-diesel battery-based desalination system was conducted by the authors of [18]. The study deployed an optimal dispatch strategy to achieve the result. In the same category, the study [19] investigated energy control and size optimization of a hybrid system using various storage technologies using economic dispatch on PV/battery storage systems. The study [20] also demonstrated the validity of dispatch strategies in the techno-economic design of a hybrid PV/wind system comprising battery energy storage in remote area electrification. Micangeli et al. [21] investigated the optimal design of isolated mini-grids with deterministic methods matching predictive operating strategies with low computational requirements. In the same line of reasoning, the study [22] focused on rural electrification by optimizing the design of a hybrid renewable energy system through load forecasting and different operating strategies.

Notwithstanding these advances, several gaps remain. First, most of these studies emphasize electrification in rural or academic environments, with limited attention to commercial agro-industrial facilities. Second, while combined dispatch strategies have been shown to outperform single-mode approaches, their application in biogas-integrated systems is underexplored. Third, few studies explicitly address waste-to-energy integration, even though biomass and biogas offer significant potential in regions with abundant organic waste streams. This gap is particularly evident in energy-intensive facilities such as abattoirs, which generate large volumes of biomass waste daily and require reliable power for slaughtering, refrigeration, and processing. Existing reliance on diesel generators is costly and environmentally consequential. Integrating biogas with solar PV under a CD strategy offers a promising solution, yet scholarly attention to this domain remains minimal.

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Therefore, this study contributes knowledge to the literature by extending dispatch strategy analysis to agro-industrial domains, demonstrating the viability of PV/biogas hybrid systems in meeting high, variable loads, and providing a techno-economic and environmental assessment using HOMER Pro simulations. This study also offers practical insights for policymakers and stakeholders seeking sustainable energy solutions in sub-Saharan Africa.

## Materials And Methods

### Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors utilized large language model tools solely to refine English grammar, clarify technical phrasing, and assist with academic paraphrasing to enhance readability. After using these services, the authors reviewed, edited, and verified all generated outputs and took responsibility for the final conceptual framework, literature analysis, data synthesis, and integrity of the published content.

In the combined dispatch strategy, the issue of when to export energy from any of the component sources lies in the difference between the load demand and the output generated from the sources. The controller in the EMU has two modes: load-following strategy mode and cycle-charging strategy mode. The choice of any of the modes is a function of the net load. If the net load is high, the load-following strategy is selected by the controller, but in the case of low net load, the controller changes to the cycle-charging strategy mode. In this manner, the management of the energy flow within the generating sources is optimized. However, the selection of the generating sources is prioritized based on the cost, such that the lowest cost is given the top priority for usage, followed by lower and lower costs. This comparison of costs enables economic dispatch optimization of the study based on cost decisions as described in Figure 7. However, the decision to select any of the strategies is a response to the net load, and this is based on the current status of the net load. The need to predict the future net load will make the CD strategy perform better. Thus, the forecasting of future net load will improve the viability of the CD strategy. Furthermore, the decision to select the generator to meet the abattoir load demand depends on the cost comparison of the options, which is determined by the EMU of HOMER Pro. In this instance, the State of Charge (SOC) performs the function of switching the generator ON/OFF, while the net load switches the dispatch strategy. This strategy ensures minimum operational cost to meet the load.

A large-scale abattoir located in southwest Nigeria is taken as a case study. It is located at Oko-Oba in the Agege Local Government Area of Lagos State (Lat. 60° 27.1834 N and Long. 30° 23.75 S) [23,24]. The operation of the abattoir depended on an unreliable grid connection and a 250 kVA diesel generator. The power supply challenge has become a big threat to the slaughterhouse business, despite the abattoir receiving thousands of animals daily and about 1,500 cows being slaughtered per day.

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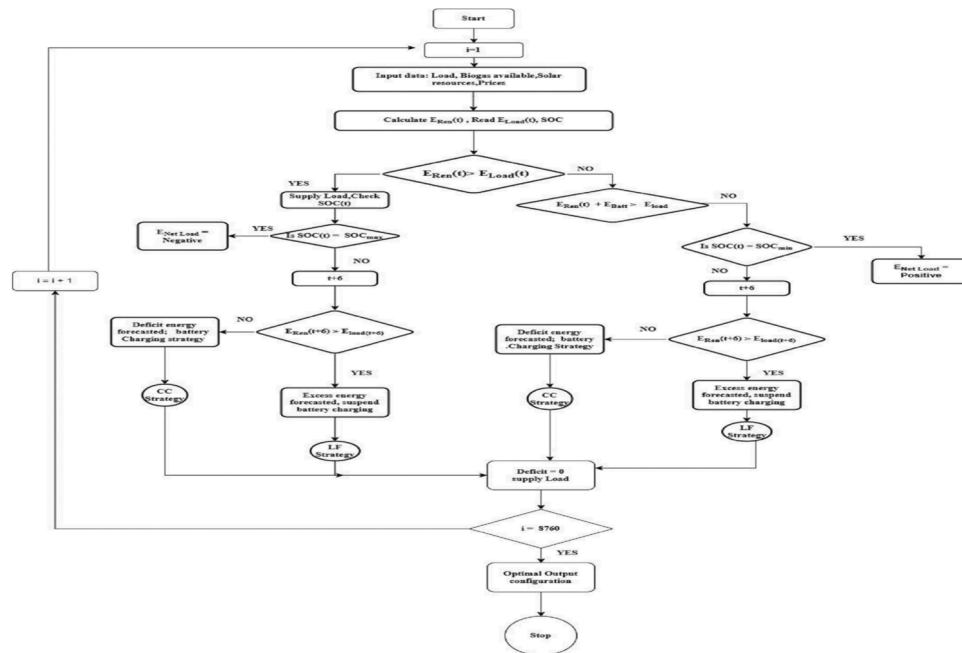


FIGURE 1: The flow diagram of the combined dispatch strategy forecast

CC, Cycle-Charging; LF, Load-Following

### Site load estimation and development load profile

An appropriate load profile that will sufficiently capture the hourly operating characteristics of the abattoir sites throughout the 24-hour time scale is required. Energy consumption by each appliance is a function of the product of the appliance-rated capacity in watts and time of operation in hours, usually for a 24-hour time scale. The energy demand in kWh was estimated using Equations (1) and (2) [25].

$$E = P \cdot Q \cdot t \quad (1)$$

Where P is the rated power of the equipment (kW), Q is the total number of such equipment in the facility, and t is the operated time of the equipment.

The detailed electrical equipment in use is shown in Table 1. For electrical equipment the total energy demanded is given by the study [25]:

$$E_T = (P \cdot Q \cdot t)_1 + (P \cdot Q \cdot t)_2 + (P \cdot Q \cdot t)_3 + \dots + (P \cdot Q \cdot t)_n \quad (2a)$$

$$E_{d(Wh)} = \sum_{i=1}^N P_n \cdot Q_n \cdot t_n \quad (2b)$$

Where  $E_d$  is the total energy demand (load in watts), P is the appliance's rated power, and Q is the number of appliances. It represents the operation hours of the appliances, and n = 1, 2, 3... N is the number of appliances or pieces of equipment in the facility.

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| Appliance         | Power Rating (W) | Quantity | Total Power (W) | Duration | Energy    |
|-------------------|------------------|----------|-----------------|----------|-----------|
|                   |                  |          |                 | (Hr)     | Demand    |
|                   |                  |          |                 |          | (kWh/day) |
| Lighting          | 18               | 20       | 360             | 24       | 8.64      |
| Fan               | 60               | 4        | 240             | 14       | 3.36      |
| Television        | 55               | 1        | 55              | 13       | 0.72      |
| Radio             | 20               | 2        | 40              | 11       | 0.44      |
| Refrigerator      | 300              | 4        | 1200            | 15       | 18        |
| Conveyor          | 750              | 4        | 3000            | 7        | 21        |
| Air compressor    | 1500             | 4        | 6000            | 8        | 48        |
| Heating vessel    | 1000             | 4        | 4000            | 8        | 32        |
| Hoist             | 2400             | 5        | 12000           | 7        | 84        |
| Leading machine   | 1500             | 5        | 7500            | 8        | 60        |
| Lift machine      | 1500             | 6        | 9000            | 9        | 81        |
| Overhead conveyor | 1000             | 5        | 5000            | 10       | 50        |
| Slitting Saws     | 2200             | 5        | 11000           | 10       | 110       |
| Borehole          | 11186            | 2        | 22,372          | 4        | 89.49     |
| Electronic scales | 200              | 10       | 2000            | 10       | 20        |
| Total Energy      | Demand           |          |                 |          | 626.05    |
|                   |                  |          |                 |          | kWh/day   |

**TABLE 1: The electrical appliances in use in the abattoir**

While the empirical data collection at the abattoir established the baseline daily energy consumption of 626.05 kWh with a peak load demand of 77.13 kW, a scaled factor of 3.87 was applied within the HOMER Pro environment. This adjusts the system to a scaled annual average of 2,426.40 kWh/day and a peak demand of 298.96 kW. This scaling factor is used by HOMER Pro to ensure that peak seasonal variations in the abattoir load and fluctuations remain proportional, allowing the model to design a system that is robust against realistic load variability. Consequently, all component sizing, economic evaluations, and dispatch strategy simulations in this study are based on this scaled design load.

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### Mathematical modeling of the hybrid energy system components

The hybrid components of the energy topology are solar PV, biogas, battery, and diesel. The modeling of the subsystems of the architecture is based on mathematical equations, as discussed in the next subsections

#### Solar PV Unit Modeling

The hourly output of solar PV modules depends on three major factors, which are conversion efficiency, global horizontal irradiance, and the active area of the solar PV module. The mathematical relationship that describes these three factors, which provides for the computation of the active area (A) of the solar PV array, is given in Equation (3a) [25,26]:

$$A_{PV} = \frac{E_{PV}}{E_{SR}} \quad (3a)$$

Where  $E_{PV}$  is the energy generated by the solar PV array and  $E_{SR}$  is the solar radiation at the study location.

#### Photovoltaic System Derating Factors

The instant DC output power of the PV array  $P_{PV}$  is modeled considering environmental derating effects according to Equation (3b):

$$P_{PV} = Y_{PV} \cdot f_{PV} \cdot \left( \frac{G_T}{G_{T,STC}} \right) \cdot [1 + \alpha_p (T_c - T_{c,STC})] \quad (3b)$$

Where  $Y_{PV}$  is the rated capacity of the PV array under Standard Test Conditions (kW);  $f_{PV}$  is the overall PV derating factor accounting for dust/soiling (3%), thermal losses, and manufacturing tolerances;  $G_T$  is the solar irradiance incident on the array surface (kW/m<sup>2</sup>);  $G_{T,STC}$  is the standard irradiance (1 kW/m<sup>2</sup>);  $\alpha_p$  is the temperature coefficient of power (-0.38%/°C);  $T_c$  is the PV cell temperature; and  $T_{c,STC}$  is the standard cell temperature (25°C). Monthly clearness indices varying between 0.387 and 0.569 were incorporated to reflect seasonal cloud cover variations.

Sizing the PV is achieved using:

$$PV_{array(kW_p)} = \frac{DailyEnergyDemand}{DailyPVenergyOutput} \quad (4)$$

$$Dailyload(kWh) = \frac{Dailyload(kWh)}{(\eta_{inverter} \cdot \eta_{mppt}) \cdot \eta_{battery}} \quad (5)$$

$$PVenergyoutput(kWh) = DailySolarinput \cdot \eta_{inverter} \cdot ModuleArea \quad (6)$$

The number of PV modules in series is evaluated by using Equation (7) [27]:

$$N_s = \frac{V_{dc}}{V_m} \quad (7)$$

Where  $N_s$  is the number of PV modules in series,  $V_{dc}$  is the DC voltage, and  $V_m$  is the PV module optimum voltage

While the number of PV modules in parallel is obtained by using Equation (8) [25]:

$$N_p = \frac{P_{PV}}{N_s \cdot P_{module}} \quad (8)$$

Where  $P_{PV}$  is the PV array size required and  $P_{module}$  is the nominal peak power of the PV module.

To sustain the solar PV energy system, the bank of batteries is crucial as a storage mechanism, and the ability to size the batteries correctly has a lot of impact on the energy sustainability of the solar PV plant during the absence of sunlight. Therefore, to determine the number of days of autonomy (the days during which the battery will supply input energy to sustain the load due to bad weather or other environmental factors). The days of autonomy have to be specified, for

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instance, 2 days or 3 days, depending on the strength of the batteries. Also, the SOC and depth of discharge (DOD) are factors that must be known. DOD could be 90%, implying that the battery cannot discharge below 10% of its total charged capacity, i.e., the SOC.

To determine the nominal capacity of the battery energy storage system required to sustain the load during periods of low solar radiation and organic waste deficits, the required battery capacity is determined as follows:

The capacity of the battery  $C_B$  was modeled as shown in Equation (9) [25]:

$$C_B = \frac{E_d \cdot D_{Aut}}{DoD \cdot \eta_{inv} \cdot \eta_{batt}} \quad (9)$$

where  $E_d$  is the average daily energy consumption and  $D_{Aut}$  is the required number of operational days of autonomy.  $\eta_{inv}$  and  $\eta_{batt}$  are the conversion efficiencies of the inverter and the battery round-trip charge/discharge efficiency, respectively.

To determine the structural layout of the battery bank, the total number of series-connected units  $N_s$  required to establish the nominal DC-link voltage ( $V_{DC,bus}$ ) is calculated as:

$$N_s = \frac{V_{DC}}{V_B} \quad (10)$$

Where  $V_B$  is the nominal battery voltage and  $V_{DC}$  is the DC operating voltage

Also, the number of batteries in parallel ( $N_P$ ) is determined by Equation (11) [24]:

$$N_P = \frac{C_B}{C_{batt,nominal}} \quad (11)$$

Where  $C_{batt,nominal}$  is the nominal storage capacity of an individual battery module. The total number of battery modules  $N_{total}$  comprising the storage architecture is  $N_{Total} = N_s \cdot N_P$

Sizing the inverter and charge controller is critical aspects to be considered when designing a solar PV system. The inverter transforms the direct current from the battery/solar cells into alternating current for AC loads. The output power of the inverter is AC and can be determined as shown in Equation (12) [25]:

$$Totalpower(kW) = Load_{peak} \cdot Safetyfactor \quad (12)$$

The actual inverter power (rated) can be determined by Equation (13) [25]:

$$Inverterratedpower = \frac{Total(kW)required}{powerfactor} \quad (13)$$

A charge controller regulates the charging of the batteries to prevent overcharging. Thus, sizing the charge controller appropriately is crucial; otherwise, the lifespan of the batteries will be shortened. Therefore, the charge controller input (DC) voltage must match the solar array voltage and the battery bank. Also, it should be noted that the charge controller has to withstand the maximum current from the PV array, and this is determined by Equation (14) [26]:

$$Controller = \frac{PeakCapacityofPV_{array}}{V_{dc}} \quad (14)$$

#### Modeling Diesel Generator Capacity

The HOMER Pro software has a built-in capacity to auto-size the capacity of the diesel generator required for backup purposes, and it was used to determine the capacity of the diesel generator required for backup purposes, with the generator's capacity proportional to the abattoir's peak load.

Fuel consumption of the diesel generator is modeled by the Equation (15) [27]:

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$$\text{FuelConsumption} = x \cdot G_c + y \cdot G_{Po} \quad (15)$$

where  $x$  is the fuel intercept,  $y$  is the fuel curve,  $G_c$  is the rated capacity of the generator, and  $G_{Po}$  is the power output.

#### Modeling of Biogas Energy System

Waste generated in the abattoir is meant to be converted into electricity. Transformation of dung and paunch from slaughtered cows in anaerobic digesters produces biogas, which is used as a fuel to power an internal combustion engine to generate electricity. The biogas yield from the anaerobic digester can be estimated using Equation (16) [27]:

$$\text{Biogasyield} = f_{gas} \cdot B_{fs} \quad (16a)$$

where  $f_{gas}$  is the gasification ratio used in the Homer tool, and  $B_{fs}$  is the biomass feedstock.

#### Biogas Yield Dependencies

The biogas power generation model accounts for environmental and seasonal variations in the feedstock availability factor. The empirical daily biogas volume  $V_{bio}$  (m<sup>3</sup>/day) generated from the anaerobic digester depends on ambient temperature dynamics affecting mesophilic bacterial digestion rates governed by Equation (16b).

$$V_{bio} = M_{waste} \cdot TS \cdot VS \cdot Y_{specific} \cdot \eta_{digester}(T_{amb}) \quad (16b)$$

Where  $M_{waste}$  is the daily wet organic mass supply (mixed abattoir wet waste) (15 tons/day),  $TS$  is the total solids fraction,  $VS$  is the volatile solids fraction,  $Y_{specific}$  is the specific methane yield for a mixed abattoir wet waste, and  $\eta_{digester}(T_{amb})$  is the thermal correction factor evaluating anaerobic digestion efficiency across the site's ambient temperature range (23.1°C–29.4°C).

The following assumptions, based on the FAO and IRENA biogas manuals, were considered: a recovery factor of 0.70 and a biogas yield of 0.036 to 0.15 m<sup>3</sup> of biogas/kg for a mixed wet waste of punch, dung, fat, blood, protein, and water; 0.73 m<sup>3</sup> of biogas generates 1 kWh of electricity [28,29]

Moreover, the energy obtainable from the digester can be estimated by Equation (17) [27]:

$$E = \frac{\eta_{burner} \cdot CV_{methane} \cdot Volumeofbiogas \cdot Methanefactorinbiogas}{86400} \quad (18)$$

where  $\eta_{burner}$  is the efficiency of the burner and  $CV_{methane}$  is the calorific value of methane.

#### Validation of empirical models and cross-verification

To validate the reliability of the HOMER Pro simulation framework, the key parameters and operational outputs of the proposed solar PV-biogas hybrid system were cross-verified against empirical field measurements gathered at the Oke-Oba abattoir facility (Lagos State, Nigeria) and empirical data reported in contemporary sub-Saharan microgrid literature. The baseline electrical load profile (626.05 kWh/day, peak 77.13 kW) was synthesized from direct site measurements and physical inventory audits at the facility. Furthermore, the modeled biogas generator consumption rate (0.73 m<sup>3</sup>/kWh) and local solar yield (4.74 kWh/m<sup>2</sup>/day) align closely with reported operational data from decentralized hybrid renewable energy installations in sub-Saharan West Africa. While HOMER Pro performs system optimization through deterministic energy balance equations, these empirical benchmarks verify that the techno-economic performance indicators (net present cost (NPC) and cost of energy (COE)) reflect actual physical plant dynamics.

#### Economic analysis

Cost analysis of the CD strategy, which includes NPC and COE, operating cost, and the initial capital cost of the project, is the key index for economic assessment of the performance of the generating sources under different dispatch strategies. The total NPC represents the system's life cycle cost (LCC), and it is determined by Equations (19) and (20) [27]:

$$NPC = \frac{TAC}{CRF} \quad (19)$$

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But,

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (20)$$

Where TAC is the total annualized cost and CRF is the capital recovery factor. N is the number of years. i is the annual real interest rate.

The COE is calculated by dividing the total annual cost by the total electricity consumption, as shown in Equation (21) [27]:

$$COE = \frac{C_{(ann, tot)}}{E} \quad (21)$$

Where  $C_{ann, tot}$  is the annual total cost, and E is the total electricity consumption (kW) per year.

### Performance evaluation metrics

The performance of the system was assessed based on economic, technical, and environmental impact evaluations. The comparative assessment is based on the cost of energy, electricity production, unmet energy needs, and the operational behavior of storage systems and biogas generators under different dispatch strategies.

### Resource assessment

#### Solar Energy Data for the Case Study

As shown in Figure 2 and Table 2, solar irradiance data (average hourly and daily temperature) for the study location, obtained from the online PVGIS-SARAH database, indicate an average solar irradiation of 4.74 kWh/m<sup>2</sup>/day average solar irradiation and a 25.75°C daily temperature, while January, February, March, November, and December have the highest daily irradiation with an average solar irradiation of 5.27 kWh/m<sup>2</sup>/day at a clearness index of 0.5492. The lowest solar irradiation, of about 3.980 kWh/m<sup>2</sup>/day, is at a 0.387 clearness index and is obtained in August.

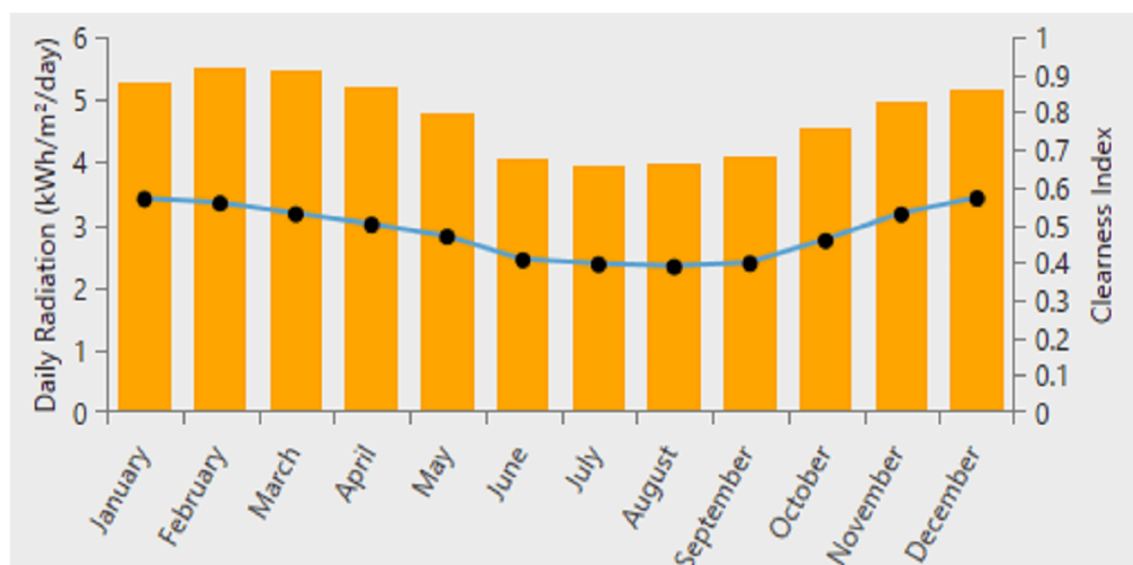


FIGURE 2: Solar irradiation data of the central abattoir location

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| Month     | Clearness Index | Daily Radiation (kWh/m/day) |
|-----------|-----------------|-----------------------------|
| January   | 0.567           | 5.280                       |
| February  | 0.556           | 5.490                       |
| March     | 0.527           | 5.460                       |
| April     | 0.499           | 5.210                       |
| May       | 0.499           | 4.760                       |
| June      | 0.405           | 4.040                       |
| July      | 0.393           | 3.980                       |
| August    | 0.387           | 3.950                       |
| September | 0.396           | 4.090                       |
| October   | 0.457           | 4.550                       |
| November  | 0.527           | 4.950                       |
| December  | 0.569           | 5.170                       |

**TABLE 2: Clearness index and daily radiation of the study location**

Annual Average (kWh/m<sup>2</sup>/day): 4.74

#### *Biomass Data Collection for the Case Study*

Biomass data from the abattoir were collected through observations and interviews. An average of 1,500 cattle are slaughtered daily (Monday to Saturday). The collection of biomass data from the abattoir was based on the following assumptions: the average weight of a cow is 350 kg [30]; the average paunch from the slaughtered cows is about 10% of the weight of the cow; the average cow dung of 5-15 kg is produced per cow per day [31]; and the average number of cows slaughtered per day is 1,500.

Therefore,

$$W_{TG} = W_{kg(cattle)} \cdot N_{(cattleperday)} + W_{kg(dungperday)} \quad (22)$$

$$W_{TG} = 0.10W_{kg}N + W_{kg(dung)} \quad (23)$$

Where  $W_{TG}$  is the total waste generated per day,  $0.10W_{kg}$  is the total weight of generated paunch,  $W_{dung}$  is the cow dung weight in kg, and  $W_{kg}$  is the weight (kg) of the cattle.  $N$  is the number of cattle slaughtered per day.  $W_{kg}$  is the weight (kg) of cattle dung per day.

It was also assumed that about 30% of the entire biomass was lost through handling. Therefore, the actual biomass recovered was about 70% and was computed as shown in Equation (24) [32,33]:

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$$A. R_{Biomass} = 0.7. W_{(TG)}$$

(24)

where  $A. R_{Biomass}$  is the biomass average recovery. and the recovery factor is 0.70.

The average daily biomass generated in the abattoir is 15 tons/day (Table 3), also presented as available biomass in tons per day in Figure 3, while the monthly biomass generated is as shown in Table 4.

| Cow slaughtered (daily) | Paunch content (kg/cow) | Total manure (kg/day) | Recovery (0.70 kg/day) |
|-------------------------|-------------------------|-----------------------|------------------------|
| 1,300-1,500             | 17.5                    | 22,750                | 15,925                 |

TABLE 3: Daily average biomass generated from the abattoir

| Month     | Available Biomass (ton/month) |
|-----------|-------------------------------|
| January   | 406                           |
| February  | 369.6                         |
| March     | 410.8                         |
| April     | 400                           |
| May       | 410                           |
| June      | 403                           |
| July      | 418.5                         |
| August    | 410.8                         |
| September | 408                           |
| October   | 397.8                         |
| November  | 405.6                         |
| December  | 416                           |

TABLE 4: Monthly biomass generated from the abattoir

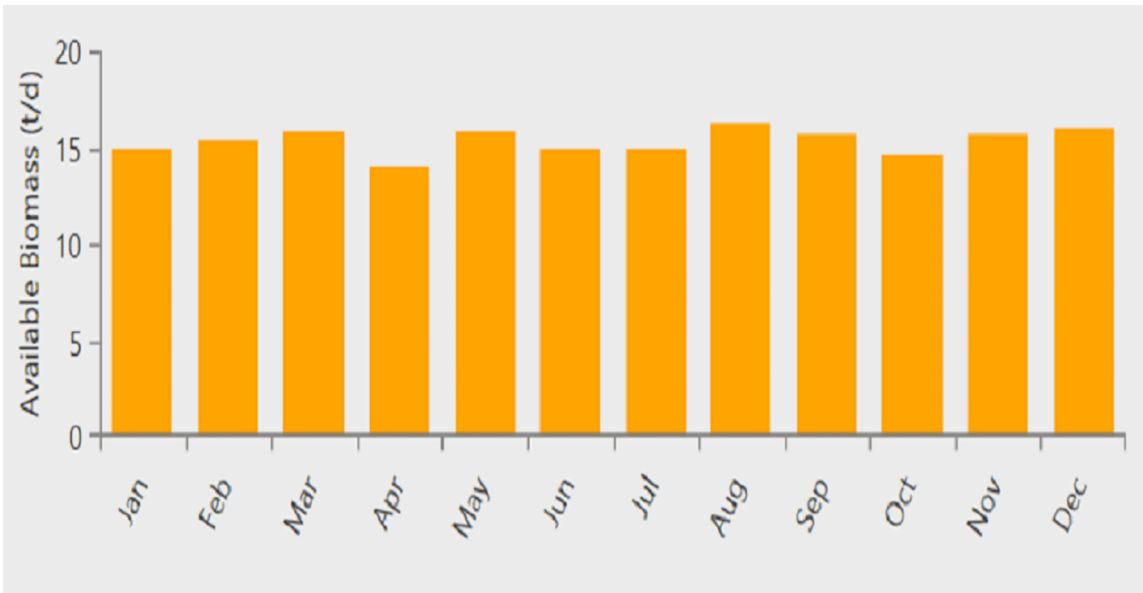


FIGURE 3: Available biomass in tons per day

Development of the hybrid energy system for the Abattoir

In this study, solar radiation and the quantified biomass are the renewable energy resources that were used (while the existing diesel generator (250 kVA) was put into standby). Thus, solar PV, biogas, and battery, as shown in Figure 4, were integrated. The HOMER Pro models and simulates the abattoir load under various dispatch strategies. The load profile is shown in Figure 5, representing daily, seasonal, and yearly profiles. It could be observed that the daily average demand, average load, peak load, and load factor are 626 kWh/d, 26.08 kW, 77.13 kW, and 0.34, respectively, based on the input data. The yearly energy demand of the abattoir is 228,490 kWh/yr. Table 5 shows how HOMER Pro applied a scale factor to the empirical data to ensure that peak seasonal variations in the abattoir load and fluctuations remain proportional, allowing the model to design a system that is robust against realistic load variability. Consequently, all component sizing, economic evaluations, and dispatch strategy simulations in this study are based on this scaled design load.

How to cite this article:

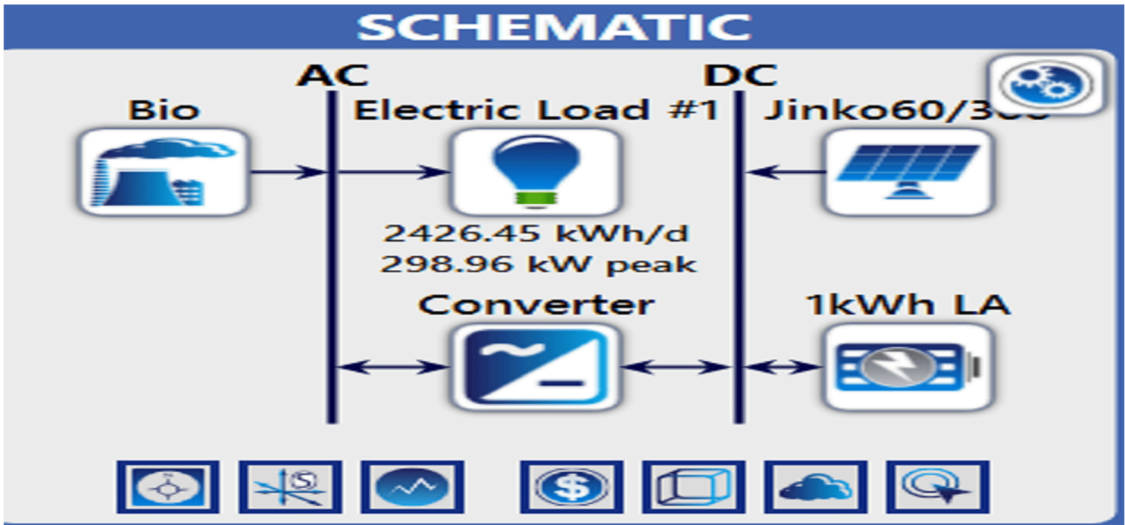


FIGURE 4: The hybrid energy system architecture of the abattoir

| Metric            | Baseline | Scale   |
|-------------------|----------|---------|
| Average (kWh/day) | 626      | 2,426.4 |
| Average (kW)      | 26.08    | 101.1   |
| Peak (kW)         | 77.13    | 298.96  |
| Load factor       | 0.34     | 0.34    |

TABLE 5: HOMER Pro baseline and scaled data

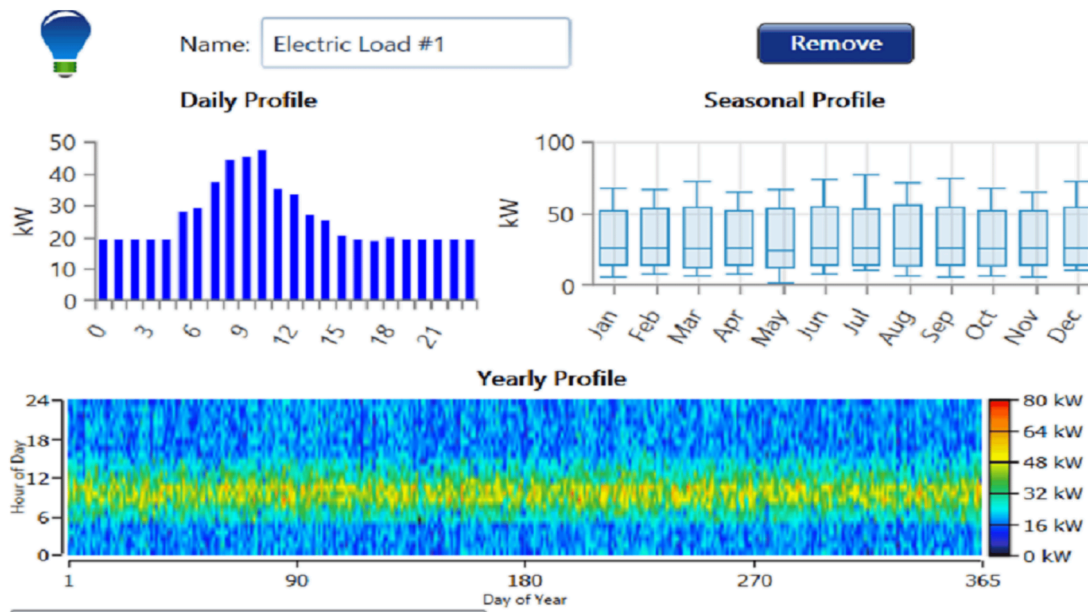


FIGURE 5: Abattoir load profile

### The combined dispatch strategy

The CD strategy takes decisions on maximizing the renewable resources in the integrated energy architecture such that the selection of sources to meet the demand is based on the cost of generating energy, and the decision to charge the battery system is based on the predicted future load and renewable energy generation. Equations (25-31) show the algorithm that estimates the net load from the load demand and the generated energy under different scenarios. The net load is the difference between the load demand and the renewable energy generated. From these estimations, the net load could be either positive, zero, or negative. When the net load is positive, it shows that energy generation is insufficient (i.e., a deficit). If the net load is negative, it is an indication that the energy generation is surplus (i.e., excess). In this approach, solar PV, a biogas generator, and a battery storage system were integrated into the hybrid energy system. The existing diesel generator (250 kVA) is considered a worst-case option. The various energy management schemes to ensure a reliable energy system are discussed as follows:

Scenario I:  $E_{netload} = 0$

When the net load is equal to zero, i.e., the generated energy is equal to the energy demand,

$$E_{Demand}(t) = E_{generated}(t) \quad (25)$$

In this case, the output energy generated from the renewable sources matches the energy demand, resulting in a zero net load; there is no excess or deficit energy.

Scenario II:  $[E_{Demand}(t) < E_{generated}(t), \text{and } SOC = SOC_{max}], E_{(netload)} = -ve$

This scenario considers the battery SOC. If the total generated energy by the renewable sources exceeds the demand, there is excess energy production; this is a negative net load. If the SOC is at its maximum, the excess energy is either dumped or exported to the grid if there is a facility to support it. In expressing this mathematically, it must be noted that renewable energy generators engage battery charging units and an inverter for the conversion of DC output into AC. Therefore, the generated output energy is influenced by the efficiencies of the inverter and rectifier.

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$$E_{Demand}(t) = [\eta_{inv} \cdot E_{ren}(t)] \quad (26)$$

Scenario III:  $[E_{Demand}(t) < E_{generated}(t), SOC < SOC_{max}]$

In this case, the renewable energy generated output is more than the energy demand, but the battery SOC is less than the maximum. The excess energy is used to charge the battery. The scenario is represented by Equation (27) as:

$$E_{demand}(t) = [\eta_{inv} \cdot E_{ren}(t)] - \frac{E_{BSS}}{\eta_{rec}(t)} \quad (27)$$

The energy deposited in the battery storage system is represented by ( $E_{BSS}$ ) through the rectifiers unit of an efficiency ( $\eta_{rec}$ ).

Scenario IV:  $[E_{Demand}(t) > E_{generated}(t), SOC > SOC_{min}]$

The energy generated from renewable sources is not sufficient to meet the energy demand; this situation represent an energy deficit. In the case of a positive net load (+ve net load) and the battery state of charge ( $SOC$ ) is not at its minimum, the deficit energy is taken care of by battery storage ( $E_{BSS}$ ) as shown in Equation (28):

$$E_{demand}(t) = \eta_{inv} \cdot [(E_{ren}(t) + E_{BSS}(t))] \quad (28)$$

Scenario V:  $[E_{Demand}(t) > E_{generated}(t), SOC \leq SOC_{min}]$ , and excess energy forecast in an hour ( $t$ ) to ( $t + 6$ )

This scenario shows that the generated output energy of the renewable sources is not sufficient to meet the energy demand, and the battery SOC is below the set point or minimum threshold. Also, the load demand forecast after 6 h indicates an excess energy production. The algorithm, therefore, makes a smart decision to meet the load at hour  $t$  using load-following dispatch while holding battery charging till the forecasted surplus renewable energy production in hour ( $t + 6$ ). So the Biogen is fully run and generates energy ( $E_{BGG}$ ) to meet the net load at time  $t$ , pending the anticipated surplus energy as depicted in Equations (29) and (30):

$$\sum_t^{t+6} E_{Demand}(t) - \sum_t^{t+6} E_{ren}(t) < 0; excessenergyforecasted. \quad (29)$$

$$E_{Demand}(t) = [\eta_{inv} \cdot E_{ren}(t)] + E_{BGG} \quad (30)$$

Scenario VI:  $[E_{Demand}(t) > E_{generated}(t), SOC \geq SOC_{min}]$ , and deficit energy forecast in an hour ( $t$ ) to ( $t + 6$ )

Conversely, if the generated output of the renewable source is not sufficient to meet the energy demand, the battery state of charge ( $SOC$ ) is above the set point or minimum threshold, and the forecast load in hour ( $t + 6$ ) shows a positive net load, that is, the projected energy output is less than the energy demand (energy deficit). The algorithm at this stage switches to a cycle charging strategy and uses the biogen to meet the net load and charges the battery storage system. This strategy ensures the battery is fully charged in anticipation of a forecasted deficit in hours ( $t + 6$ ), and the probability of using the backup diesel gen is reduced as shown in Equations (31) and (32).

$$\sum_t^{t+6} E_{Demand}(t) - \sum_t^{t+6} E_{ren}(t) < 0 \quad (31)$$

Deficit energy forecasted.

$$E_{Demand}(t) = \eta_{inv} \cdot E_{ren}(t) + E_{BGG}(t) - \frac{E_{BSS}}{\eta_{rec}} \quad (32)$$

## Results And Discussion

The HOMER Pro optimizer was used to simulate the system, and the simulation result was carefully analyzed and discussed in the next subsection.

### How to cite this article:

Comparative economic analysis of CD vs CC

| Cost Component         | Combined Dispatch (CD) | Cycle Charging (CC) dispatch | Variance     |
|------------------------|------------------------|------------------------------|--------------|
| Capital Cost           | \$485,346              | \$388,444                    | +\$96,902    |
| Replacement Cost       | \$180,955              | \$228,665                    | -\$47,710    |
| O&M cost               | \$297,854              | \$679,039                    | -\$381,185   |
| Fuel cost              | \$4,220                | \$10,895                     | -\$6,675     |
| Salvage Cost           | \$31,528               | \$13,070                     | -\$18,458    |
| Net Present Cost (NPC) | \$936,846              | \$1,243,973                  | -\$307,127   |
| COE                    | \$0.267/kWh            | \$0.355/kWh                  | -\$0.088/kWh |

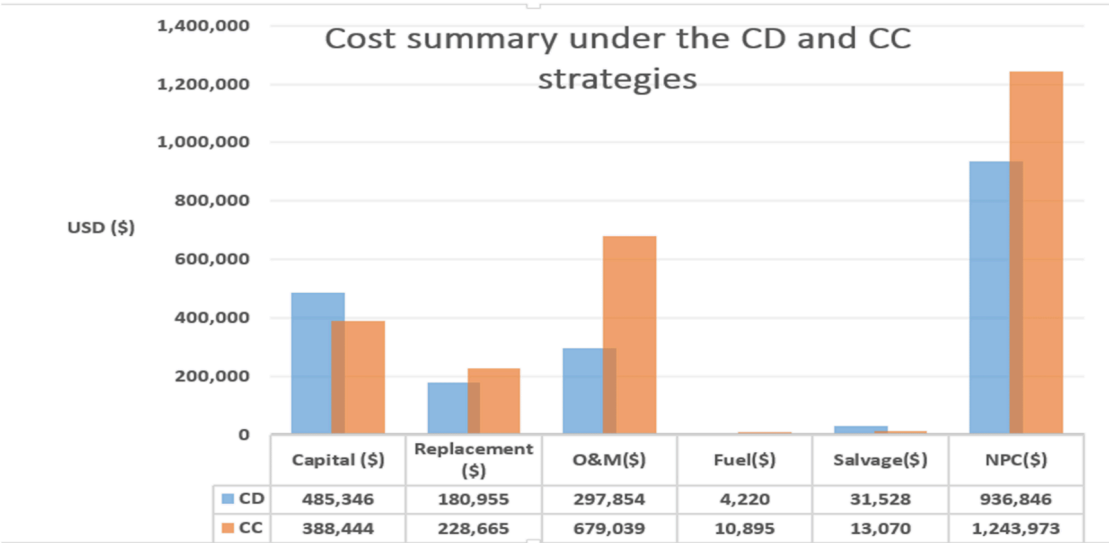
TABLE 6: Comparative economic analysis of CD vs CC

COE, Cost of Energy

Also, it is worth noting in Table 7 that while the CC strategy shows a slightly faster simple payback period, the CD strategy offers a significantly higher return on investment (ROI) and much lower overall COE. In Table 6, it is observed that the total net present cost saving is \$307,127 with CD, making the strategy more preferred for the abattoir when considering the project lifecycle. Figure 6 summarizes the cost implications under the two strategies.

| Metric                        | Combined Dispatch (CD) | Cycle Charging (CC) |
|-------------------------------|------------------------|---------------------|
| Present worth                 | \$35,850               | \$1,087,414         |
| Annual Worth                  | \$2,772                | \$84,116            |
| Return on Investment (ROI)    | 61.7%                  | 37.5%               |
| Internal Rate of Return (IRR) | 41.7%                  | 42.0%               |
| Simple Payback                | 2.73 years             | 2.46 years          |

TABLE 7: Investment and profitability metrics



**FIGURE 6: Cost summary of the hybrid energy system under CD and CC strategies**

CD, Combined Dispatch; CC, Cycle-Charging

These results confirm that the CD strategy balances cost and reliability more effectively than single-mode dispatch. This aligns with prior studies by authors [10,11], which demonstrated that CD strategies outperform single-mode approaches in hybrid systems. However, unlike those works, this study applies CD in a biogas-integrated agro-industrial context, filling a critical research gap.

**Technical performance analysis of CD vs CC**

The result of the technical evaluation reveals that the CD strategy significantly optimizes renewable resource utilization and extends the lifespan of the equipment compared to the CC strategy. The electrical production profile demonstrates that the CD has a high affinity for solar energy integration, allowing it to contribute the majority of the energy mix, as depicted in Tables 7 and 8. However, while both strategies meet the load demand with zero unmet load, the CC results in more wasted energy, about twice as much. This occurs because the CC strategy forces the generator to charge batteries to a high SOC, leaving no room for incoming solar energy, which is subsequently wasted.

**How to cite this article:**

| Parameter           | Combined Dispatch (CD) |         | Cycle Charging (CC) |         |
|---------------------|------------------------|---------|---------------------|---------|
|                     | kWh/yr                 | Percent | kWh/yr              | Percent |
| PV production       | 2,31,901               | 68.7    | 159,493             | 37.1    |
| Biogen production   | 1,05,597               | 31.3    | 270,662             | 62.9    |
| Primary load served | 2,71,196               |         | 271,196             |         |
| Excess electricity  | 48,861                 | 14.5    | 53,714              | 35.7    |

**TABLE 8: Comparative analysis of electrical production of CD and CC strategy**  
PV, Photovoltaic

The biogas generator's operational integrity is impacted by the choice of strategy, the mechanical health, and the fuel requirements. Under the CD, the biogas generator operated for fewer hours (1,194 h/yr), resulting in a projected life of 16.8 years. Contrarily, the CC strategy overworks the generator (3,178 h/yr), reducing its life to just 6.29 years. Looking at the maintenance profile, the CD strategy offers slightly more frequent starts (478) than the CC strategy (410). The reduction in total run-time lowers the long-term operation and maintenance burden on the generator. Noticeably, the biomass feedstock as a resource is efficiently utilized, which makes the CD strategy the ideal choice for environmental fitness and sustainability (Table 9).

| Feedstock metric        | Combined Dispatch (CD) | Cycle Charging (CC) |
|-------------------------|------------------------|---------------------|
| Total Annual Feedstock  | 326 tons/yr            | 843 tons/yr         |
| Average daily Feedstock | 0.894 tons/day         | 2.3 tons/day        |
| Hourly Feedstock rate   | 0.0373 tons/hr         | 0.0962 tons/hr      |

**TABLE 9: Biomass feedstock sustainability**

**Comparative performance analysis of battery storage under CD and CC**

The analysis of battery energy storage systems (BSS) reveals that CD utilizes the storage capacity far more effectively than CC. While the battery systems maintain a 10-year expected life, the depth and efficiency of energy throughput vary significantly. Table 10 summarizes the operational performance of the battery storage under the two strategies.

| Battery Storage     | Units  | CD      | CC      |
|---------------------|--------|---------|---------|
| Autonomy            | Hr     | 15      | 0.98    |
| Lifetime throughput | kWh    | 374,999 | 112,029 |
| Expected life       | Year   | 10      | 10      |
| Energy in           | kWh/yr | 41,892  | 12,525  |
| Energy out          | kWh/yr | 33,541  | 10,020  |
| Storage depletion   | kWh/yr | 30.1    | 0.456   |
| Losses              | kWh/yr | 8,382   | 2,505   |
| Annual throughput   | kWh/yr | 37,500  | 11.20   |

**TABLE 10: Comparative battery storage data under CD and CC strategies**

CD, Combined Dispatch; CC, Cycle-Charging

The key technical insights reveal that system autonomy is an advantage when the CD strategy is used (15 h) against the CC strategy, which is 0.98 h. The cumulative energy processed by the battery under the CD strategy is 374,999 kWh, which is more than that of the CC. The CD strategy uses the battery chemical potential to shift energy, whereas the CC leaves the battery underutilized. CD proves to be superior in energy management logic for battery integration, which offers a robust buffer against power interruptions (15-h autonomy).

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Comparative environmental impacts by CD and CC

| Emissions (kg/yr)     | CD    | CC   |
|-----------------------|-------|------|
| Carbon Dioxide        | 58.8  | 152  |
| Carbon Monoxide       | 0.653 | 1.69 |
| Unburned Hydrocarbons | 0     | 0    |
| Particulate Matter    | 0     | 0    |
| Sulfur Dioxides       | 0     | 0    |
| Nitrogen Oxides       | 0.408 | 1.05 |

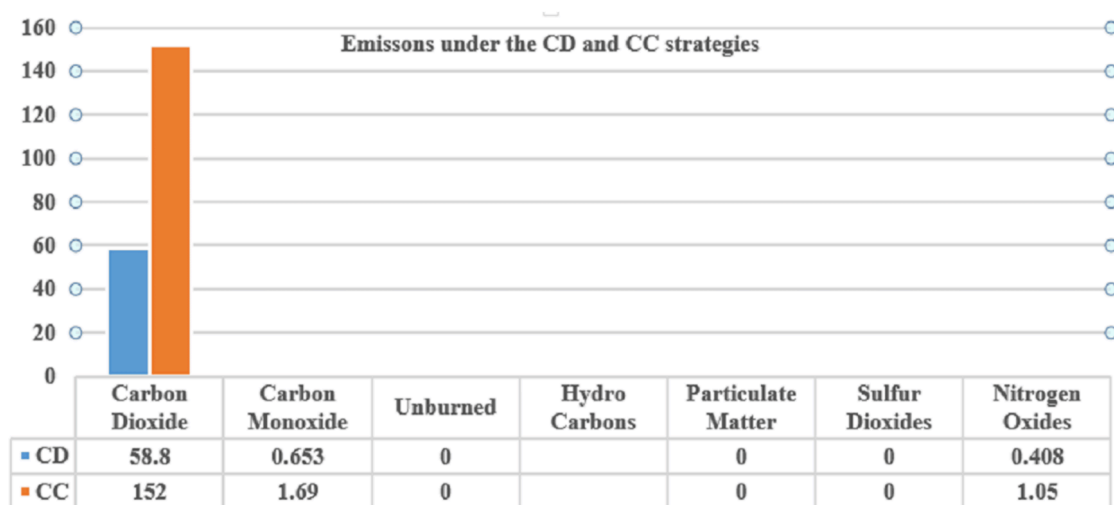
TABLE 11: Comparative analysis of emissions under CD and CC strategies

CD, Combined Dispatch; CC, Cycle-Charging

Table 11 provides insight into the superiority of a biogas generator over a diesel generator when used as a fuel in an internal combustion engine in a hybrid energy system. It shows that emissions in CD are substantially lower, at about 58.8 kg/yr, compared to the CC, which is about 152 kg/yr. The hydrocarbons and PM for both strategies indicate zero values (0) due to the clean-burning properties of the biogas internal combustion engine (ICE) model used by HOMER Pro. This also establishes the fact that CD is environmentally friendly as depicted in Figure 7.

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**FIGURE 7: Emission under CD and CC dispatch strategies**

CD, Combined Dispatch; CC, Cycle-Charging

#### Load forecast performance analysis by combined dispatch strategy

A CD strategy can manage the system response by forecasting the load ahead. Table 12 depicts the result of the energy management to the forecasted scenarios in Figures 8 and 9 for January and May.

| Day <sub>Hrs</sub> (t)            | E <sub>Gen.</sub> (kW) | E <sub>Load</sub> (kW) | Current Net Load | E <sub>Gen.</sub> forecast kW | E <sub>Load</sub> forecast kW | Future Net load | EMU <sub>Response</sub> |
|-----------------------------------|------------------------|------------------------|------------------|-------------------------------|-------------------------------|-----------------|-------------------------|
| Jan 1, 8:00 hr to Jan 1, 14:00 hr | 106                    | 102.67                 | Zero (0)         | 101.07                        | 82.41                         | Negative        | CC dispatch             |

**TABLE 12: The combined dispatch algorithm' EMU response to forecasted scenario**

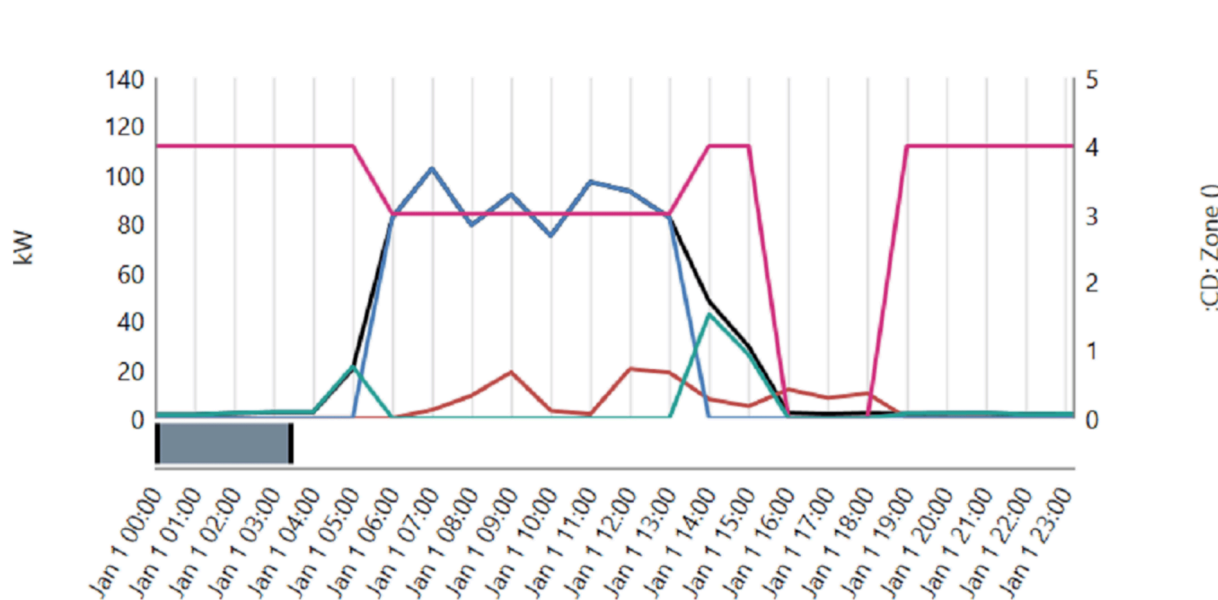
CC, Cycle-Charging; EMU, Energy Management Unit

The key insight in Table 12 shows that EMU acts as the brain of the HRES. It demonstrated the potential to forecast future load demand and make real-time decisions, such as when to charge or discharge the battery, when to switch the generator on/off, and how to balance renewable sources with biogas generation. Table 17 shows that CD makes decisions 6 h ahead by comparing the generated energy to the energy needed by the load:  $E_{gen}(t + 6) < E_{load}(t + 6)$ . The CD strategy ensures cost efficiency by suspending or adjusting battery charging depending on the forecasted net load. Figures 9 and 10 show hourly time series analysis of the CD strategy for January and May. On Jan 1 at 14:00 hrs, the EMU suspends charging due to a

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negative net load forecast. Also, on May 1 at 10:00 hrs, the EMU balances generator and battery operation to meet demand. The combined dispatch strategy has demonstrated that it can accurately forecast the load demand; it is smart and cost-efficient in its decisions for microgrid systems and effective in the coordination of battery storage and biogas generators to ensure reliability.

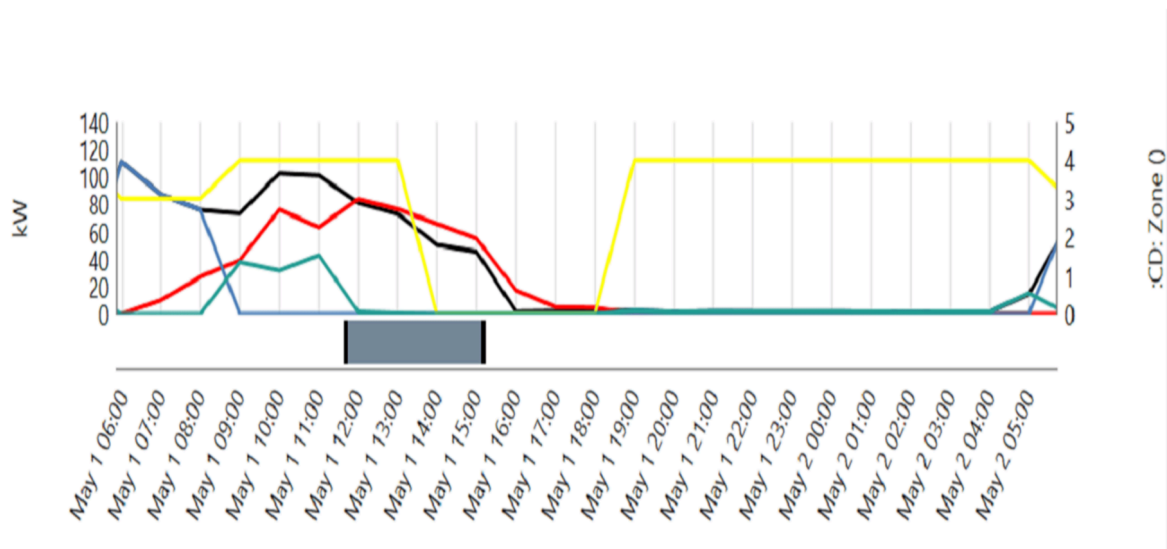


**FIGURE 8: January hourly time series detail analysis of the CD strategy**

CD, Combined Dispatch

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**FIGURE 9: May hourly time series detail analysis of the CD strategy**  
CD, Combined Dispatch

Conclusions

The research has successfully assessed the performance of a PV/biogas/battery hybrid energy system for a large-scale agro-industrial facility under a combined dispatch strategy. From the results of the study, the CD strategy has demonstrated superior economic viability to single-mode dispatch strategies, achieving a lower NPC of \$936,846 and a COE of \$0.267/kWh, alongside a significantly higher ROI of 61.7%. Technically, the CD strategy effectively manages energy flow by utilizing battery storage for 15 h of autonomy, compared to only 0.98 hours under the CC strategy. It also reduces the operational burden on the biogas generator, extending its projected life to 16.8 years by preventing excessive runtimes. Its environmental impact, by integrating waste-to-energy through biogas generation, reduces reliance on diesel, resulting in a cleaner energy profile with CO<sub>2</sub> emissions 61% lower than those produced under the CC strategy. Also, the CD approach minimizes wasted energy by ensuring that battery charging logic accounts for forecasted solar availability, reducing excess electricity production from 35.7% (under CC) to 14.5%. Generally, the study demonstrates that a combined dispatch strategy provides a robust framework for managing the intermittency of renewable energy while maximizing the economic and environmental benefits of waste-to-energy systems in the energy-intensive commercial sector. Future research incorporating advanced forecasting of load and biomass availability, as well as demand-side management, can further enhance system resilience. Policymakers and stakeholders should encourage hybrid renewable energy adoption in agro-industrial sectors to accelerate the energy transition and reduce environmental impacts.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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**Supervision:** Oluwatobi V. Olisa

## Disclosures

**Human subjects:** All authors have confirmed that this study did not involve human participants or tissue.

**Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue.

**Conflicts of interest:** In compliance with [the ICMJE uniform disclosure form](#), all authors declare the following:

- **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work.
- **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work.
- **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

## Data Availability Statements

Data will not be available due to the fact this study is an ongoing project with co-authors having interest in further analysis. It is therefore not wise to release data to the public yet.

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