ELECTRICAL ENGINEERING AND ENERGY

Feasibility Analysis of Hybrid Green Power Generation System for Healthcare Institutions

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Abstract: Reliable and sustainable electricity supply is essential for healthcare facilities, where power interruptions can compromise critical medical services and patient safety. This study evaluates the techno-economic and environmental feasibility of a grid-connected hybrid green power generation system for healthcare institutions using the HOMER Pro optimization software. The proposed configuration comprises a 50 kW solar photovoltaic (PV) array, a 50 kW biogas generator, a 10 kW fuel cell integrated with a 10 kW electrolyzer and a 10 kg hydrogen storage tank, a 50 kW power converter, and grid connectivity. Simulation results demonstrate that the optimal hybrid system is both economically and technically viable, achieving an NPC of $168,314 and a COE of $0.156/kWh. The system generated sufficient electricity to export approximately 128,194 kWh/year of surplus power to the utility grid while purchasing only 19,239 kWh/year, indicating high energy generation capability, operational flexibility, and reduced dependence on grid electricity. Environmental assessment further revealed a renewable energy fraction of 93.2% with significantly reduced CO_2 emissions, highlighting the system's potential to mitigate environmental impacts. Sensitivity analysis confirmed that the proposed configuration remains economically attractive under a wide range of technical and financial uncertainties, demonstrating its robustness and resilience.

Keywords Feasibility, Hybrid Green Power, Techno-economic Analysis, Environmental, Healthcare

1. Introduction

The growing concerns over climate change, environmental degradation, and energy security have accelerated the global transition toward sustainable and low-carbon energy systems. Developing countries, including Ghana, are increasingly investing in renewable energy technologies to reduce dependence on fossil fuels and improve energy accessibility (Maka & Alabid, 2022; Fang et al., 2022). Despite these efforts, challenges related to energy reliability, affordability, and sustainability persist, particularly in critical sectors such as healthcare. Ghana's energy mix has historically depended on fossil fuels and hydropower, which, although instrumental to economic development, present challenges such as greenhouse gas emissions and vulnerability to climate variability (Kipkoech et al., 2022; Chen et al., 2023). Although the deployment of renewable energy technologies such as solar and wind power has increased, frequent grid outages and unstable electricity supply remain major concerns, especially in rural and semi-urban areas (Agyekum et al., 2021). According to Nyasapoh et al. (2022), Ghana continues to experience electricity reliability challenges despite progress in generation capacity expansion, highlighting the urgent need for decentralized and resilient energy systems.

The healthcare sector is particularly vulnerable to unreliable electricity supply because hospitals and clinics require continuous power for essential services such as surgical procedures, diagnostics, vaccine preservation, and emergency response systems. However, many healthcare facilities in Ghana rely heavily on diesel generators as backup power sources, which are associated with high fuel costs, operational inefficiencies, and environmental pollution (Nhamo et al., 2020). Lammers et al. (2024) further indicated that inconsistent electricity supply significantly undermines healthcare delivery, particularly in rural areas, thereby reinforcing the need for sustainable and reliable energy alternatives.

Extensive research has been conducted on hybrid renewable energy systems integrating solar, wind, diesel generators, and battery storage, with a primary focus on system sizing, optimization, and techno-economic feasibility for rural electrification (Rehman et al., 2020; Aziz et al., 2018; Rinaldi et al., 2021). In addition, advanced optimization techniques such as fuzzy logic control and particle swarm optimization have been explored to enhance system performance and operational efficiency (Zahedi & Moeini-Aghtaie, 2022). While these studies demonstrate the viability of hybrid systems across diverse geographical contexts (Siyoucef et al., 2021), they largely overlook healthcare-specific energy requirements, system resilience under fluctuating operating conditions, and the integration of locally available biomass resources.

Moreover, limited research has focused on real-world applications of hybrid energy systems within the Ghanaian context, particularly those utilizing biogas derived from hospital waste streams. According to Nyasapoh et al. (2022), Ghana possesses significant yet underutilized biomass potential within its renewable energy mix, especially for decentralized energy applications. This gap underscores the need for integrated hybrid energy solutions that combine technical performance, economic feasibility, and environmental sustainability, specifically tailored to healthcare institutions.

To address this research gap, this study investigates the feasibility of a hybrid green power generation system for Kokofu General Hospital in Ghana. The proposed system integrates solar photovoltaic (PV), biogas generation, fuel cells, battery storage, and grid connectivity, and is modeled using HOMER software (Rehman, 2021). The study aims to design and optimize a hybrid renewable energy system suitable for healthcare applications, evaluate its performance in terms of energy reliability and energy production, assess its techno-economic viability using metrics such as cost of energy (COE) and net present cost (NPC), and analyze its environmental benefits in terms of emission reduction. The key contributions of this study include the utilization of hospital-generated biomass for biogas energy production, a real-case techno-economic evaluation using site-specific data from Kokofu General Hospital, and the development of a sustainable and reliable hybrid energy framework applicable to healthcare institutions in developing countries.

2. Materials and Method

2.1 Description of the Healthcare institution and site

Kokofu Hospital, originally established in 1953 as a leprosarium, holds a unique historical significance in the healthcare landscape of Ghana. Kokofu General Hospital is situated within the town of Kokofu, which is likely a mix of rural communities in Ashanti region of Ghana (6°29.9N and 1°31.4W). The hospital complex comprised various buildings, including inpatient wards, outpatient clinics, administrative offices, and support facilities. Depending on its capacity, the hospital has specialized departments such as maternity, surgery, pediatrics, and emergency services as represented in Figure 1.

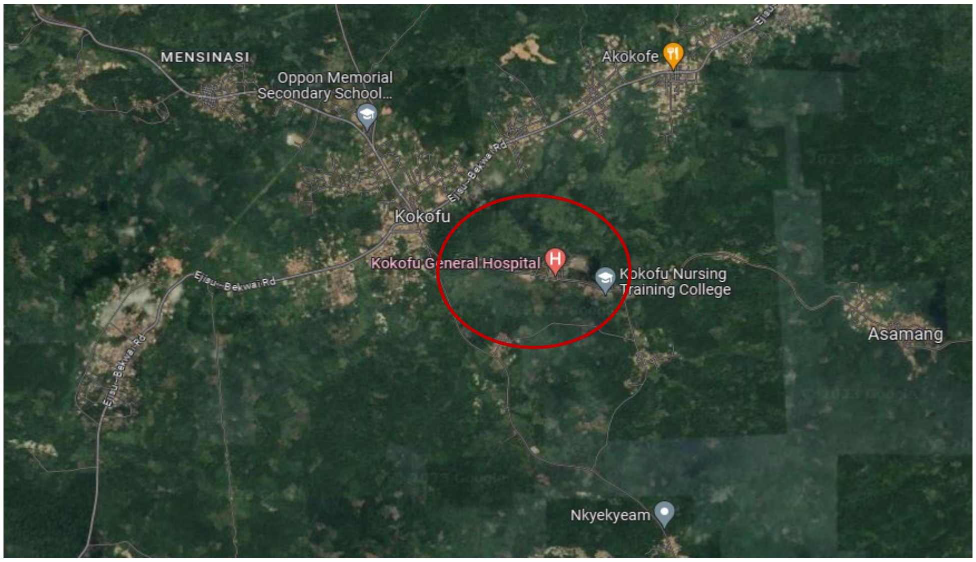

Figure 1 Geographical area of the Healthcare Institution

2.2 Energy accessibility within the health institution

Although Kokofu General Hospital and the Nursing Training College are connected to the national grid, they experience frequent and unreliable power supply interruptions that negatively affect essential healthcare services and training activities. Consequently, the institutions depend on four primary energy sources: grid electricity, diesel generators, uninterruptible power supply (UPS) units, and flashlight/torch lighting to ensure operational continuity.

2.3 Data Survey of the selected Health institution.

A comprehensive understanding of the electricity demand of a healthcare facility is essential for the effective design and implementation of an electrification system. The annual electricity consumption data for Kokofu General Hospital and the Nursing Training College were obtained from the administrator responsible for infrastructure operations and maintenance. As publicly owned institutions, the hospital and nursing training college receive financial support from the government to cover their electricity expenses. The total annual electricity consumption of the facilities was estimated at 141,792 kWh during the period from January to December. Due to the unavailability of some Electricity Company of Ghana (ECG) meter bills, portions of the historical electricity consumption data were estimated using available utility records, observed load patterns, and prevailing electricity demand trends.

2.4 Load Data Collection and Processing

Electricity consumption data for Kokofu General Hospital and the Nursing Training College were obtained from the Electricity Company of Ghana (ECG) energy meters installed at the respective facilities. Historical electricity consumption records were collected from the hospital and nursing training college administrations and verified using the available metering information. Due to the unavailability of some ECG electricity meter bills, portions of the historical electricity consumption data were estimated using available utility records, observed consumption patterns, and prevailing electricity demand trends. The combined annual electricity consumption of the hospital and nursing training college was determined to be 141,792 kWh/year.

To develop a representative load profile for the HOMER Pro simulations, the measured electricity consumption data were analyzed alongside the operational schedules of major electrical loads in both facilities. For the hospital, the load demand comprised lighting systems, refrigeration units, laboratory and diagnostic equipment, administrative office appliances, water pumping systems, and other healthcare-related electrical devices. The nursing training college load demand included classroom lighting, computer laboratories, administrative offices, hostel facilities, lecture halls, water pumping systems, and other educational and residential electrical appliances.

The collected electricity consumption data from both institutions were organized, validated for consistency, and processed to establish the hourly variation in electricity demand over a typical day. The resulting integrated load profile was subsequently used as the input demand profile in HOMER Pro for the techno-economic optimization and performance evaluation of the proposed hybrid renewable energy system.

2.5 Load Profile

Figure 2 presents the estimated hourly load profile of the combined Kokofu General Hospital and Nursing Training College with a total daily energy consumption of 421.2 kWh/day. The load profile exhibits a continuous demand throughout the 24-hour period, reflecting the critical nature of healthcare facilities that require uninterrupted electricity for medical equipment, lighting, refrigeration, and other essential services.

During the night (00:00–05:00), the load remains relatively stable between 11.5 and 12.5 kW, representing the hospital's base load required for essential operations. As daytime activities commence, the demand increases steadily from 15.0 kW at 06:00 to approximately 25.0 kW by 10:00, driven by increased clinical services, administrative activities, and occupancy within both the hospital and nursing training college.

The load remains relatively high throughout the daytime, fluctuating between 21.5 and 25.0 kW, before reaching the daily peak of 25.5 kW at 18:00. This evening peak is attributed to the simultaneous operation of hospital services, residential activities within the training college, lighting systems, and other electrical equipment. After 19:00, the load gradually declines as non-essential activities reduce, returning to the overnight base demand by late evening.

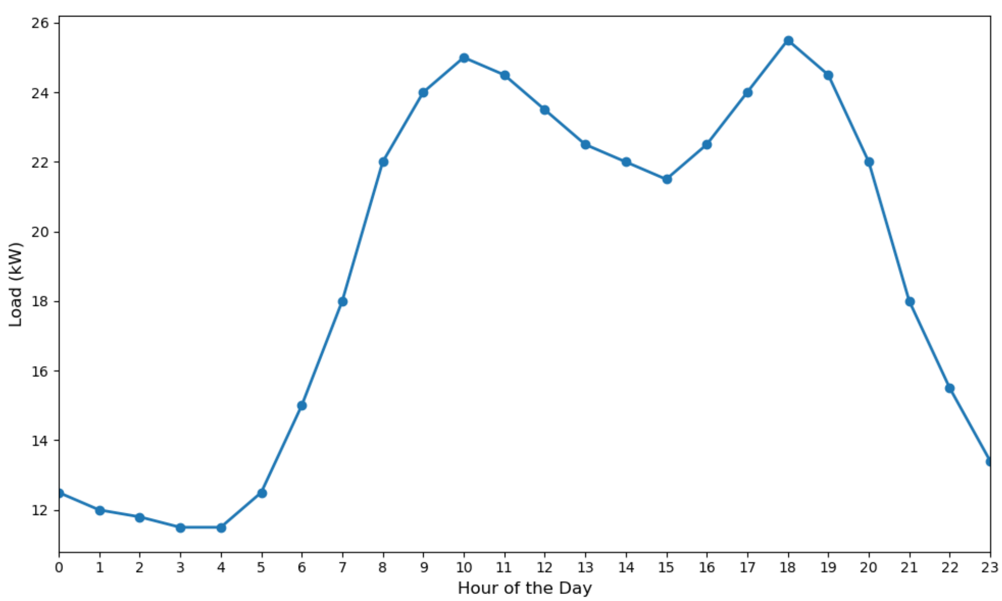

Figure 2 Hourly profile of the Healthcare institutions

2.6 Data collection

2.6.1 Solar Radiation Data collection

Accurate solar resource characterization is essential for the reliable design and optimization of hybrid renewable energy systems. Özbeyaz (2025) demonstrated that incorporating meteorological data and environmental parameters significantly improves solar power prediction accuracy and system performance evaluation. Although the present study employed HOMER Pro simulations rather than machine learning techniques, both approaches highlight the importance of accurate solar resource assessment for achieving reliable techno-economic analyses. The monthly solar radiation given by HOMER software is depicted in Figure 3 below.

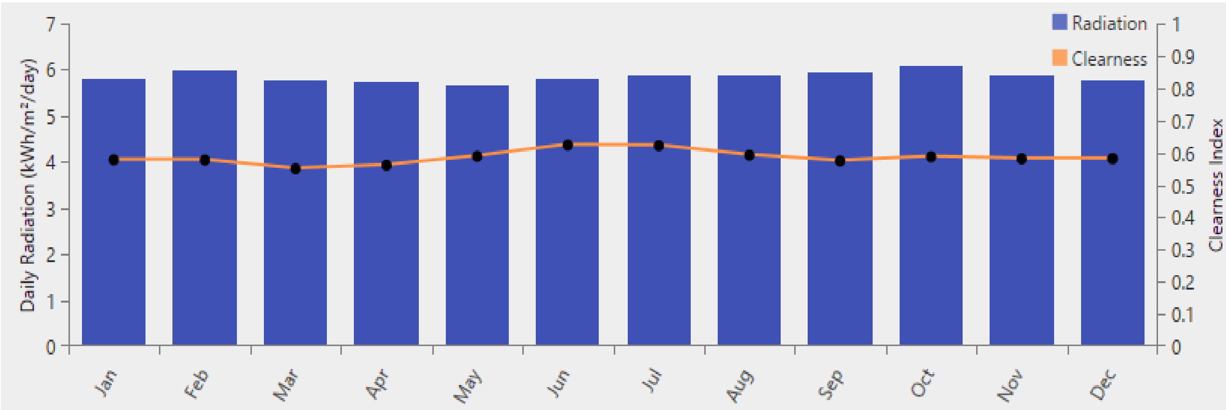

Figure 3 Monthly solar radiation given by HOMER software.

The annual mean solar global horizontal irradiance (GHI) within the Kokofu geographical region is estimated to be 5.85 kWh/m^2/day using data taken from the NASA database. Additionally, the data shows that Kokofu has the highest recorded GHI, which impressively reaches 6.08 kWh/m^2/day. These numbers show a sizable and potential resource for photovoltaic (PV) cell-based power generation.

2.6.2 Biomass Data Collection

Biomass is one of the oldest energy resources utilized by humans and continues to play a significant role in the transition toward sustainable and renewable energy systems. In this study, the potential for electricity generation from biomass resources available at Kokofu General Hospital, the Nursing Training College, and the surrounding Kokofu community was assessed. The biomass feedstocks considered included human excreta, hospital wastewater sludge, food waste generated within the hospital and training college, as well as supplementary organic waste from the surrounding community, including market waste and livestock manure as indicated in Table 1.

Primary data on population, waste generation characteristics, and waste management practices were collected through consultations with hospital administrators, energy managers, waste management personnel, representatives of the Nursing Training College, and stakeholders within the Kokofu community. Biomass availability was estimated based on the total population or waste source, average daily biomass generation rates, and the corresponding recovery efficiencies for each feedstock. The assessment indicated that approximately 8,839.5 kg of recoverable biomass could be generated daily from the combined waste streams, demonstrating substantial potential for biogas production and renewable electricity generation.

The average daily biomass generation rates and recovery efficiencies adopted in this study were obtained from published literature on municipal organic waste, wastewater sludge, and anaerobic digestion systems (Rose et al., 2015; Surendra et al., 2014; Weiland, 2010). Recovery efficiencies ranging from 80% to 95% were assumed to account for collection, handling, transportation, and processing losses prior to anaerobic digestion. These assumptions are consistent with values commonly reported in the literature for evaluating the technical feasibility of biomass-based energy systems and provide a realistic basis for estimating the recoverable biomass available for electricity generation.

$$H_{Bio} = \sum A_{\frac{DEP}{P}} \times P_T \times \eta_{rec} \tag{1}$$

H_{Bio} is sum of biomass of human excreta (Kg/day), $A_{DEP/P}$ is average daily excreta production per person (Kg/person/day), η_{rec} is recovery efficiency and P_T is total population.

Table 1 Availability of Biomass

Description of Biomass	Population/Source	Average Daily Production (kg/person/day)	Recovery Efficiency (%)	Biomass (kg/day)
Human excreta (hospital)	1,500	0.40	90	540
Hospital wastewater sludge	1,500	1.20	85	1,530
Food waste (hospital kitchen)	1,500	0.50	95	721.5
Community food/market waste	5,000	0.45	85	1,148
Cattle manure	500 cattle	10.0 kg/cattle/day	80	4,000
Poultry manure	10,000 birds	0.10 kg/bird/day	90	900
Total	—	—	—	8,839.5 kg/day

2.7 Data Modelling of Components for Hybrid Green Power Systems

2.7.1 Homer Software

The HOMER software is a tool used to assess designs for grid-connected and standalone power systems. It conducts simulations, performs sensitivity analyses, and showcases cost-optimized system configurations as shown in Figure 4. The software uses various input variables, including components, energy resource availability, temperature data, wind speed, solar radiation, and cost variations. The most optimized system is determined based on the project's net present cost and economic outcomes.

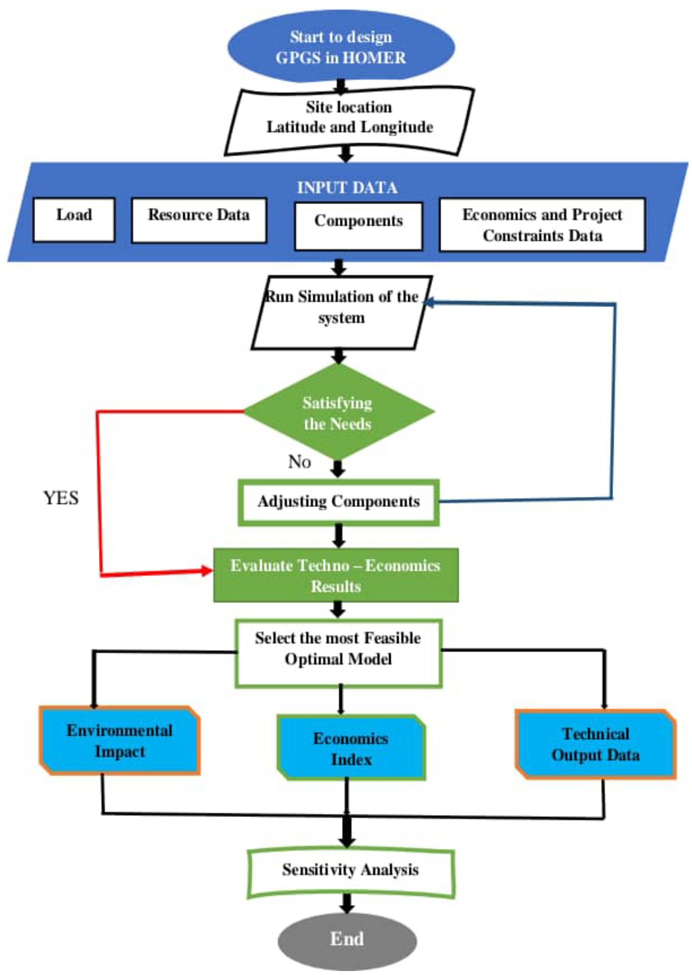

Figure 4 Homer flow chart

2.7.2 Hybrid Green Energy System Model

The hybrid system combines three energy sources: PV panels, biogas, and a fuel cell for backup power. The battery and hydrogen system are designed to provide power during periods of excess demand. The surplus electricity from the PV system is stored in the battery, while the remaining excess is channeled into the grid. In contrast, the standalone green energy system efficiently stores excess energy in the battery. An electrolyzer and fuel tank are used for hydrogen production and storage, which is then used for electricity generation. A converter is integrated into the system to convert DC and AC energy sources as depicted in Figure 5 and Figure 6.

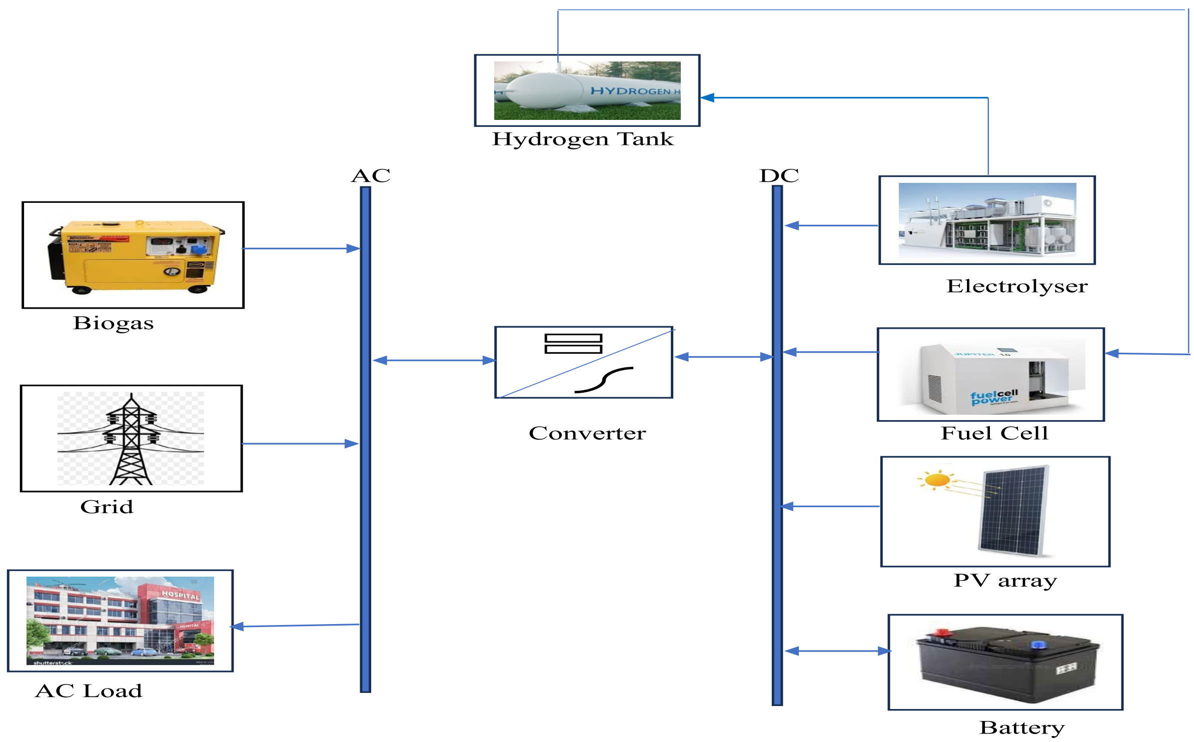

Figure 5 Proposed System

2.7.3 Modeling solar PV

The performance of a photovoltaic (PV) system is influenced by environmental conditions, particularly solar irradiance. The hourly power output of the PV array is estimated based on the incident solar radiation using Equation (1).

$$P_{PV} = Y_{PV} f_{pv} x \left(\frac{G_T}{G_{T,STC}}\right) x \left[1 + \alpha_P \left(T_C - T_{C,STC}\right)\right] \quad (1)$$

Where, P_{PV} is output power of the PV array (kW), f_{pv} rated capacity of the PV array under standard test conditions (kW), Y_{PV} is PV derating factor (%), $G_T$solar irradiance incident on the PV surface (kW/m²),$G_{T,STC}$ solar irradiance at standard test conditions (1 kW/m²), α_P is temperature coefficient of PV power (%/°C), T_C is operating temperature of the PV cell (°C) and $T_{C,STC}$ is PV cell temperature at standard test conditions (25°C).

Also, Temperature Correction is adjusting panel efficiency based on temperature.

$$\eta = \eta_{ref}\left[1 - \beta\left(T - T_{ref}\right)\right] \quad (2)$$

where, η is PV module efficiency at operating temperature (%), η_{ref} is module efficiency at reference temperature (%), β is temperature coefficient of efficiency (°C^{-1}), T is operating temperature of the PV module (°C) and T_{ref} is reference temperature (°C).

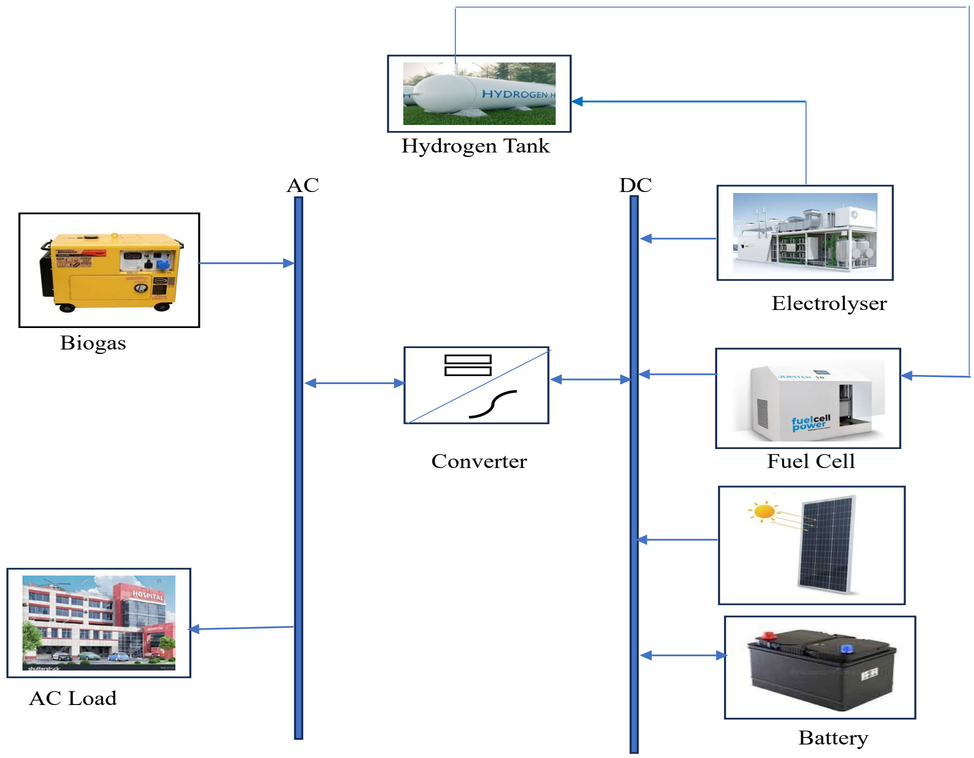

Figure 6 Compared System

In the ideal equivalent circuit of PV cell, a current source is connected in parallel with diode. Connected PV cell with load, voltage, and current equation of cell which is calculated by

$$I = I_{ph} - I_o[exp\left(\frac{qV}{KT}\right) - 1] \quad (3)$$

where, I is PV output current (A), I_{ph} is photocurrent generated by solar radiation (A), I_o is diode reverse saturation current (A), q is electron charge (1.6 $\times$ 10^{-19} C), V is PV cell voltage (V), K is Boltzmann constant (1.38$\times$ 10^{-23} J/K) and T is cell operating temperature (K)

2.7.4 Modelling of Digester

Digester is the component for the biogas production. The biological material is supplied to the digester with proper mixing of the water. The size of the digester depends on the retention time and substrate input of daily supply. The amount of substrate input in the sum of water and the biomass in cubic meter as expressed in Equation (4). The size of the digester depends on the retention time and substrate input of daily supply. The amount of substrate input in the sum of water and the biomass in cubic meter as expressed in Equation (3).

$$r = \mu(\frac{S}{K_S + S})X \quad (4)$$

where, r is substrate consumption rate (kg/m^3·day), μ is specific microbial growth rate (day^{-1}), S is substrate concentration (kg/m^3), K_S is half-saturation constant (kg/m^3) and X is microorganism concentration (kg/m^3)

2.7.5 Modelling Biogas

The biogas system consists of a biodigester and a genset, converting untreated biological materials into biogas for electrical energy generation. Kokofu General Hospital uses 5% carbon-composing waste, with an energy value of 5.5 MJ/kg and also with density of 0.720 Kg/m³. To determine the required biogas flow per hour, based on the biogas generator's operational capacity, this specific Equation (5) is used;

$$F_{bg} = \frac{P_{bg}}{\eta_{bg} LHV_{bg}} \tag{5}$$

where, F_{bg} is biogas consumption rate (m³/h), P_{bg} is electrical output power of the biogas generator (kW), η_{bg} is electrical conversion efficiency of the biogas generator (%) and LHV_{bg} is lower heating value of biogas (MJ/m³).

2.7.6 Modelling of Fuel cell

Fuel cells operate through electrochemical reactions. Depending on the type of fuel cell (e.g., proton exchange membrane (PEM), solid oxide (SOFC) and molten carbonate (MCFC), the specific reactions will differ. The Nernst equation helps model the voltage of the fuel cell based on the concentrations of reactants and products. The Nernst equation can be expressed as:

$$E = E^{O} + \frac{RT}{nF} In(\frac{P_{H_2} P_{O_2}^{1/2}}{P_{H_2O}}) \tag{6}$$

where, E is fuel cell operating voltage (V), E^{O} is standard cell voltage (V), R is universal gas constant (8.314 J/mol·K), T is operating temperature (K), n is number of electrons transferred, F Faraday constant (96485 C/mol), P_{H_2} is partial pressure of hydrogen (atm), P_{O_2} is partial pressure of oxygen (atm) and P_{H_2O} is partial pressure of water vapour (atm).

Also, the fuel slope establishes the quantity of fuel consumed by the generator for electricity generation. HOMER views the fuel slope as a linear relationship. The generator's FCG (Fuel Consumption Rate) is computed utilizing the Equation (7).

$$FCG = \propto P_{rated} + \beta P_{out} \tag{7}$$

where, FCG is generator fuel consumption rate (L/h), $\propto$ is fuel curve intercept coefficient (L/h/kW), P_{rated} is rated generator capacity (kW), β is fuel curve slope coefficient (L/h/kW) and $P_{out}$is generator electrical output power (kW).

2.7.7 Modelling of Electrolyzer

An electrolyzer uses electrical energy to drive the electrolysis of water into hydrogen and oxygen gases. The main components of an electrolyzer model include the electrochemical reaction kinetics and the transport of ions and gases.

Anode (oxidation): $H_2 \rightarrow 2H^{+} + 2e^{-}$ (8)

Cathode (reduction): $\frac{1}{2} O_2 + 2H^{+} + 2e^{-} \rightarrow H_2O$ (9)

2.7.8 Modelling of battery storage

The green energy system's battery capacity fluctuates due to unpredictable renewable energy patterns and weather conditions. Its capacity is influenced by previous state of charge, energy generated, and system load demand, charging when needed. During this phase, the battery's charging capacity can be characterized as follows:

$$E_{bat}(t) = E_{bat}(t-1) \times (1-\sigma) + \left(E_{ren}(t) - \frac{L(t)}{\eta_{inv}}\right) \eta_{bat} \tag{10}$$

where, $E_{bat}\ (t)$ is battery energy at time t (kWh), $E_{bat}(t-1)$ is battery energy during previous time step (kWh), σ is battery self-discharge rate (%), E_{ren} is renewable energy generated at time t (kWh)$L(t)$ is load demand at time t (kWh), η_{inv} is inverter efficiency (%) and η_{bat} is battery charging efficiency (%).

In a broad sense, whenever the combined power output from the renewable energy sources falls short of satisfying the load requirements, the battery bank enters a discharge state. As a result, the standard battery capacity and the amount of charge within the battery bank during this timeframe can be represented as follows:

$$C_{bat} = \frac{E_d \times N_a}{DoD} \tag{11}$$

where, C_{bat} is required battery bank capacity (kWh), E_d is daily energy demand (kWh/day), N_a is number of autonomy days and DoD is allowable depth of discharge (%).

The total number of batteries required is calculated in the given Equation (12);

$$N_b = C_{bat}.(C_{single})^{-1} \tag{12}$$

where, N_b is total number of batteries required, C_{bat} is required battery bank capacity (kWh) and C_{single} is capacity of a single battery (kWh).

The total number of strings required is calculated according to the given Equation (13);

$$N_s = N_b V_b (V_{DC})^{-1} \tag{13}$$

where, N_s is number of battery strings, N_b is total number of batteries, V_{DC} is DC bus voltage (V) and V_b is nominal battery voltage (V).

2.7.9 Modelling of charge Controller

A charge controller in a green energy system regulates battery bank charging and discharging to optimize energy flow and maintain system stability. The charging process in a simple charge controller might be:

$$P_{ch} = \eta_c (P_{ren} - P_L) \tag{14}$$

Where, P_{ch} is battery charging power (kW), η_c is charge controller efficiency (%), P_{ren} is renewable energy generation (kW) and P_L is load power demand (kW)

The charger controller reflects the balance between the power generate d by the renewable source, the power consumed by the load, and the power used to charge the battery. Taking into account factors such as battery state of charge, system demand, and available energy from the renewable sources.

2.7.10 Modeling of converter

A converter is a device that switches electrical power between DC and AC, and HOMER can simulate different types of converters. Inverters have a maximum AC power output, and their capacity affects the rectifier capacity. These devices are essential for optimizing energy flow in green energy systems by connecting various components like renewable sources, energy storage, and electrical loads.

$$V_o = \eta_{conv} V_i \tag{15}$$

where, V_o is converter output voltage (V), V_i is converter input voltage (V) and η_{conv} is converter efficiency (%).

2.8 Modeling of Economic Factors.

Economic factors encompass various phenomena, including net present cost, energy cost, anticipated payback duration, and profitability index.

2.8.1 Net Present Cost

The comprehensive net present cost (NPC) of a system reflects the current value of all expenses incurred over its lifespan minus the current value of earnings during that period. It includes capital, replacement, operation, maintenance, fuel, emissions penalties, and grid power procurement costs. In contrast, revenues comprise salvage value and income from selling power to the grid.

2.8.2 Total net present cost

The Total Net Present Cost (NPC) is a financial measure that calculates the overall cost of a project or system, considering the time value of money. It combines all expenses and income associated with the project over its lifetime, helping determine its economic feasibility and profitability.

$$NPC = \frac{C_{ann}}{CRF(i,N)} \quad (16)$$

where, NPC is total net present cost ($), $C_{ann}$is total annualized cost ($/year), CRF is capital recovery factor, i is annual real discount rate (%) and N is project lifetime (years).

$$CRF(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (17)$$

where 'i' is the annual actual interest rate and 'N' denotes the duration in years.

2.8.3 Cost of Energy

This represents the cost for each kWh of electricity generated within a system and can be calculated using the following formula.

$$COE = \frac{C_{ann}}{E_{prim} + E_{def} + E_{grid,sales}} \quad (18)$$

where, COE is cost of energy ($/kWh), C_{ann} is total annualized cost ($/year), E_{prim} is annual primary load served (kWh/year), E_{def} is annual deferrable load served (kWh/year) and $E_{grid,sales}$ is annual electricity sold to the grid (kWh/year).

2.9 Environmental Performance

The environmental performance of the proposed hybrid renewable energy system was evaluated using the emission analysis module available in HOMER Pro software. The software estimates the annual emissions of carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and unburned hydrocarbons (UHC) based on the operational characteristics of each system component, fuel consumption patterns, and the amount of electricity imported from or exported to the utility grid. The environmental assessment involved a comparative analysis between the proposed hybrid renewable energy system and a conventional grid-dependent electricity supply scenario to quantify the reduction in greenhouse gas emissions and atmospheric pollutants. The percentage reduction in emissions was calculated using Equation (19):

$$ER\% = \frac{E_{conv} - E_{prop}}{E_{conv}} \quad (19)$$

where $ER\%$ represents the percentage reduction in emissions, E_{conv} denotes the annual emissions associated with the conventional electricity supply system (kg/year), and E_{prop} represents the annual emissions produced by the proposed hybrid renewable energy system (kg/year). This approach provides a quantitative measure of the environmental benefits achieved through the integration of renewable energy technologies.

2.10 Energy Management Strategies

Effective control strategies and energy management systems are crucial in hybrid green power generation systems that utilize multiple energy sources like PV, Biomass, and Fuel Cells. These systems prioritize using renewable energy to meet energy demands and store excess energy in batteries. During peak load periods, the grid supplements power, but doesn't charge the batteries. The goal is to efficiently coordinate energy distribution among networks, considering operational conditions and economic constraints, while maintaining a secure and reliable power system operation.

2.11 Techno-economics Variables

HOMER Pro enables a thorough technical analysis of hybrid microgrid systems, considering losses and utilizing computer modeling. It also offers meteorological data for various regions and comprehensive information on system components from manufacturers.

2.11.1 Solar PV Specification

Generic flat plate PV was employed, the initial cost of a 1 kW panel is $820, with replacement costs amounting to $0.00, and O&M of 10 $/yr. These panels come with a 25-year lifespan and an 80% derating factor. Various capacities for the solar PV panels were explored, [0,50,100,150 kW]

Kokofu General Hospital is situated between Latitudes 6°29.9N and Longitudes 1°31.4W. Therefore, facing south at an angle of between -6 and 30 degrees is the best for solar panels. The tilt angle of 8.9^{o} from horizontal facing south was used for this investigation to minimize dust collection and assure efficient cleaning by rains.

2.11.2 Battery Specification

A generic 1 kWh Li-ion battery was considered in the analysis, with a capital cost of $300, a replacement cost of $250, and an annual operation and maintenance (O&M) cost of $10. Battery capacities of 50, 100, 150, and 200 units were evaluated in the optimization process.

2.11.3 Biogas-Fueled Generator Specification

Biogas is used as fuel by the generator set to generate electricity. The capital cost for a biogas system encompasses both the biodigester and generator costs is $300, also replacement is considered as $ 250 and O&M of 0.13 $/yr. The genset capabilities ranging were 0, 50, 100 and 150 kW.

2.11.4 Electrolyzer Specification

The Fuel Cell (FC) relies on a hydrogen source, primarily obtained through water electrolysis. We choose a DC-based electrolyzer to reduce power conversion losses. The cost parameters include an installation cost of $340 per kW, an estimated replacement cost of $340 per kW, and an annual operation and maintenance cost of $20 per year, with an efficiency of 85%.

2.11.5 Hydrogen tank Specification

To store hydrogen generated through electrolysis, a hydrogen tank is essential in a fuel cell-based system. The cost per kilogram of hydrogen capacity varies with tank size, averaging around $500 for smaller tanks. Replacement costs are estimated at $500 per kilogram, with O&M of $0.0. The study explores various tank sizes from 0 to 20 kilograms, assuming a 25-year lifespan for the hydrogen tank in the optimization design.

2.11.6 Fuel Cell Specification

The analysis focuses on Proton Exchange Membrane Fuel Cells (PEMFCs) for small-scale hybrid power generation. It considers a 5 kW PEMFC unit with an estimated cost of $600 for installation, $500 for replacement, and O&M is of $0.13 per hour. System sizes range from 5 kW to 25 kW and with a minimum load ratio of 25%,

2.11.7 Grid Specification

The grid serves as a secondary source of electricity for the hybrid green energy system, with HOMER used to assess its cost compared to the grid. The grid charges a fixed rate of $0.1 per kWh for both power supply and sellback, along with monthly demand charges of $0.50 per kW.

2.11.8 Converter Specification

A 10kW converter is integral to the hybrid system, facilitating AC to DC and DC to AC energy conversion. It costs $350/kW initially, has a $300/kW replacement cost, and a 15-year lifespan. With 95% inversion efficiency and 95% rectification efficiency, it operates alongside a diesel generator to maintain a consistent power supply, and different capacities (0, 50,100, 150 kW) are available to match the specified load.

2.11.9 Economic Inputs

The real interest rate, which considers the difference between inflation and nominal interest rates, is used in HOMER's calculations to convert capital costs into annual expenses over the component lifespan. This approach assumes a consistent price increase over the 25-year lifespan of the hybrid microgrid system. The annual real interest rate in Ghana was considered as 25% and expected nominal interest rate were 30%, 35% and 40% with an expected inflation rate [5,10,15, 20%].

2.11.10 Constraint Inputs

In power system design, constraints are predefined conditions that must be met for a feasible power generation scheme. HOMER can calculate the annual capacity shortfall, considering factors like excess electricity from renewable sources and fully charged batteries. The maximum annual capacity shortage can range from 0% to 10%, with a required operating reserve of 10% of the hourly load. The annual peak load can be 0%, and the operating reserve is determined as a 10% with renewable output, such as 80% for solar power.

2.11.11 HOMER Simulation Settings

The proposed hybrid renewable energy system was modeled and optimized using HOMER Pro software. Simulations were conducted using an hourly time-step over a 25-year project lifetime to evaluate the technical, economic, and environmental performance of various system configurations. The optimization process considered all feasible combinations of photovoltaic (PV), biogas generator, fuel cell, electrolyzer, hydrogen storage tank, battery storage, converter, and grid connection components.

The annual electrical load of Kokofu General Hospital and the Nursing Training College, estimated at 141,792 kWh/year (421.2 kWh/day), was used as the primary load input. Solar resource data were obtained from the NASA database integrated within HOMER Pro, with an average global horizontal irradiance of 5.85 kWh/m^2/day. Biomass resource availability was estimated at 8,839.5 kg/day from hospital waste, wastewater sludge, community organic waste, and livestock manure.

The component capacities considered during optimization included PV arrays (0–150 kW), biogas generators (0–150 kW), fuel cells (5–25 kW), battery storage systems (50–200 units), electrolyzers (0–20 kW), hydrogen storage tanks (0–20 kg), and converters (0–150 kW). Economic parameters included a project lifetime of 25 years, nominal discount rates ranging from 30% to 40%, and inflation rates varying from 5% to 20%. Grid electricity purchase and sellback prices were both set at $0.10/kWh.

To ensure reliable electricity supply for healthcare operations, the maximum annual capacity shortage was constrained to 0%, while an operating reserve equivalent to 10% of the hourly load demand was maintained. HOMER Pro automatically determined the optimal dispatch strategy and system configuration based on the minimization of the NPC.

2.11.12 Optimization Criteria and Selection of the Optimal Configuration

The optimal hybrid energy system configuration was selected using the optimization engine embedded in HOMER Pro. The software evaluates all feasible combinations of system components specified within the search space and performs hourly simulations over the entire project lifetime. For each configuration, HOMER calculates the technical, economic, and operational performance indicators, including NPC, COE, renewable energy fraction, excess electricity production, capacity shortage, and unmet load.

In this study, the primary optimization criterion was the minimization of the NPC, which represents the total life-cycle cost of the system, including capital, replacement, operation and maintenance, fuel, and grid electricity costs over the 25-year project lifetime. The COE was used as a secondary economic indicator to compare the unit cost of electricity produced by different system configurations.

During the optimization process, HOMER evaluated multiple combinations of PV capacities (0–150 kW), biogas generator capacities (0–150 kW), battery storage capacities (10–50 kWh), fuel cell capacities (5–

25kW), electrolyzer capacities, hydrogen tank capacities, converter sizes, and grid interaction options. All candidate systems were required to satisfy the healthcare institution's electrical demand while maintaining a maximum annual capacity shortage of 0% and the specified operating reserve constraints.

2.11.13 Justification of Modeling Assumptions and Component Sizing

The selection of system components and their capacities was based on the electricity demand characteristics of Kokofu General Hospital, local renewable energy resource availability, and HOMER Pro optimization results. The objective was to develop a technically reliable and economically viable hybrid energy system while maximizing renewable energy utilization.

The hospital's annual electricity consumption was 141,792 kWh/year, equivalent to an average daily demand of approximately 421 kWh/day. To ensure uninterrupted power supply for healthcare services, the system sizing considered peak demand, operating reserve requirements, seasonal resource variations, and future load growth. Therefore, a range of component capacities was evaluated in HOMER Pro, including PV (0–150 kW), biogas generator (0–150 kW), fuel cell (5–25 kW), battery storage (50–200 units), and converter capacities (0–150 kW).

The selection of a 50 kW PV system was justified by the high solar resource availability at the study location, with an average solar irradiance of 5.85 kWh/m²/day. The optimization results showed that this capacity provided an optimal balance between electricity generation, investment cost, and renewable energy penetration. Similarly, the 50 kW biogas generator was selected based on the estimated availability of approximately 8,839.5 kg/day of biomass resources from Kokofu General Hospital, the Nursing Training College, and the surrounding community, providing reliable dispatchable renewable power during periods of low solar generation.

The fuel cell capacity was limited to 10 kW because it primarily served as a backup power source to improve system reliability. Larger fuel cell capacities increased lifecycle costs without significant performance improvements. Likewise, the 50 kW converter capacity was selected to accommodate power exchange between the AC and DC subsystems efficiently. Battery storage and hydrogen production components were initially included in the optimization search space to evaluate the feasibility of fully renewable standalone operation.

2.11.14 Model Validation

The reliability of the proposed hybrid energy system model was verified through several validation procedures. First, the electrical load profile used in the HOMER Pro simulations was developed from actual electricity consumption data obtained from the Electricity Company of Ghana (ECG) and verified through field surveys conducted at Kokofu General Hospital and the Kokofu Nursing Training College. Where historical ECG meter records were unavailable, missing data were estimated using available consumption records and observed load patterns.

Second, the renewable energy resource data, including solar irradiance and biomass availability, were obtained from established databases and site-specific assessments and compared with published values reported for similar climatic and institutional conditions. Finally, the optimized system's technical and economic performance indicators were evaluated against findings from comparable studies. The close agreement between the simulation results and published literature demonstrates the reliability of the proposed hybrid energy system model for assessing sustainable electricity supply.

2.11.15 Limitations of the Study

This study has several limitations that should be acknowledged. First, the biomass resource assessment was based on estimated waste generation rates derived from population-based models and institutional records rather than long-term direct measurements of biomass production. Furthermore, due to the unavailability of some ECG electricity meter bills, portions of the historical electricity consumption data were estimated using available records and demand trends. Second, the analysis assumed the continuous availability of grid electricity and constant operational performance of all system components throughout the project lifetime. Third, potential future changes in component costs, electricity tariffs, government policies, financial incentives, and technological advancements were not explicitly incorporated beyond the sensitivity analyses conducted. In addition, operational factors such as equipment degradation, maintenance downtime, and seasonal variations in biomass generation were simplified within the HOMER Pro simulation environment. These assumptions may influence the accuracy of the technical and economic performance predictions. Therefore, future studies should incorporate long-term field measurements of biomass availability, comprehensive electricity consumption records, real-time operational monitoring, and experimental validation to improve the reliability and accuracy of the techno-economic assessment. Furthermore, integrating more detailed models of equipment degradation, maintenance scheduling, and policy and market uncertainties would provide a more realistic evaluation of hybrid renewable energy system performance over its operational lifetime.

3. Results and Discussion

3.1 Optimization Results Analysis

HOMER evaluated multiple hybrid renewable energy system configurations to determine the optimum solution based on the minimum COE, NPC, and maximum feasible renewable energy contribution, as presented in Table 2. Although several system configurations satisfied the electricity demand of the healthcare facility, the selected configuration achieved the most favourable balance between economic performance, renewable energy utilization, and supply reliability.

Table 2: Comparation of Optimized Result

Parameter	Compared System	Proposed Hybrid System
PV Capacity	50 kW	50 kW
Biogas Generator	50 kW	50 kW
Fuel Cell	10 kW	10 kW
Electrolyzer	10 kW	10 kW
Converter	50 kW	50 kW
Hydrogen Tank	10 Kg	10 Kg
Battery Storage	100 Strings	No
Grid Connection	No	Yes
COE	$0.362/kWh	$0.156/kWh
NPC	$213,458	$168,314
Initial Capital Cost	$192,000	$132,000
Annual Operating Cost	$5,596/year	$9,471/year
Renewable Energy Fraction	100%	93.2%

The optimized standalone configuration comprised a 50 kW PV array, a 50 kW biogas generator, a 10 kW fuel cell integrated with a 10 kW electrolyzer and a 10 kg hydrogen storage tank, a 50 kW converter, and a battery bank consisting of 100 battery strings. This configuration achieved a COE of $0.362/kWh, an NPC of $213,458, an initial capital cost of $192,000, an annual operating cost of $5,596, and a renewable energy fraction of 100%.

In contrast, the proposed hybrid system retained the same generation components but replaced battery storage with utility grid integration. The optimized configuration achieved a substantially lower COE of $0.156/kWh and NPC of $168,314, with an initial capital cost of $132,000 and an annual operating cost of $9,471 while maintaining a renewable energy fraction of 93.2%. Despite the slight reduction in renewable energy penetration, the system recorded zero unmet load and zero capacity shortage, confirming that reliable electricity supply was maintained throughout the simulation period. Overall, the proposed configuration reduced the COE by approximately 56.9% and the NPC by approximately 21.2% compared with the standalone system, demonstrating that utility grid integration provides the most cost-effective configuration without compromising system reliability.

The obtained results agree with recent studies on hybrid renewable energy systems for institutional and healthcare applications. Ali et al. (2025) reported that integrating photovoltaic and biomass resources with utility grid support significantly improves techno-economic performance by reducing lifecycle costs while maintaining high renewable energy utilization. Likewise, the proposed PV–biogas–fuel cell–grid configuration achieved a low COE of $0.156/kWh, an NPC of $168,314, and a renewable energy fraction of 93.2%. Ba-swaimi et al. (2025a) similarly demonstrated that hydrogen-assisted hybrid systems provide reliable electricity for healthcare facilities, although their dependence on extensive battery and hydrogen storage infrastructure increases system complexity and capital investment. In comparison, the present study shows that grid integration can achieve comparable reliability with a simpler and more economical system configuration. Furthermore, the findings of Hüner (2025) and Peirow et al. (2023) support the complementary role of dispatchable biogas generation in enhancing the reliability of solar PV-based hybrid systems.

The novelty of this study lies in integrating solar PV, biogas generation derived from hospital and community biomass resources, fuel cell technology, and utility grid connectivity within a single optimized framework for healthcare electrification. Unlike conventional PV–battery or PV–hydrogen systems, the proposed configuration achieves high renewable energy penetration without relying on large-scale battery storage, thereby offering a practical and economically sustainable solution for improving energy resilience in healthcare facilities across Ghana and other developing countries.

3.2 Techno-economics Analysis

3.2.1 Electric Power Output Analysis

Figures 7 and 8 present the annual electricity generation profiles of the standalone and proposed hybrid energy systems. In the standalone configuration, the PV subsystem generated 72,264 kWh/year, representing 42.9% of the total annual electricity production, whereas the biogas generator supplied 96,200 kWh/year, accounting for 57.1%. The fuel cell generated only 2.67 kWh/year (0.00158%), indicating that it was operated primarily during emergency conditions. Throughout the simulation period, the system completely satisfied the annual AC load demand of 153,764 kWh/year without experiencing unmet load or capacity shortages.

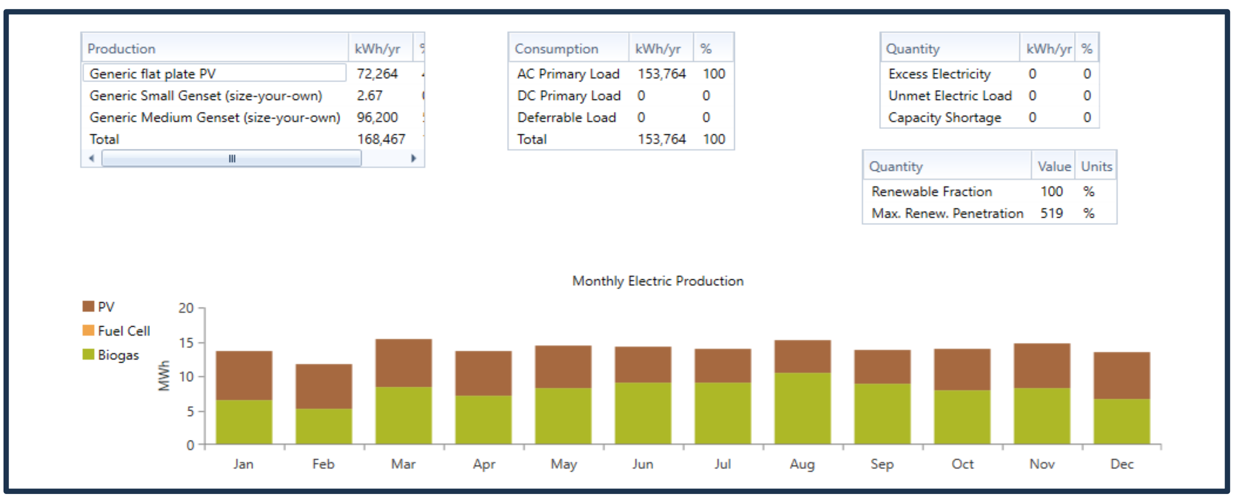

Figure 7 Electric output of the compared system

For the proposed grid-connected configuration, the annual electricity generation profile differed because the biogas generator became the principal energy source, producing 194,300 kWh/year, equivalent to 68.0% of the total electricity generated. The PV array maintained an annual production of 72,264 kWh/year, contributing 25.3%, while electricity purchased from the utility grid amounted to only 19,239 kWh/year

(6.73%). The system also exported 128,194 kWh/year of surplus electricity to the utility grid. Similar to the standalone system, the proposed configuration fully satisfied the annual electricity demand without recording unmet load or capacity shortages.

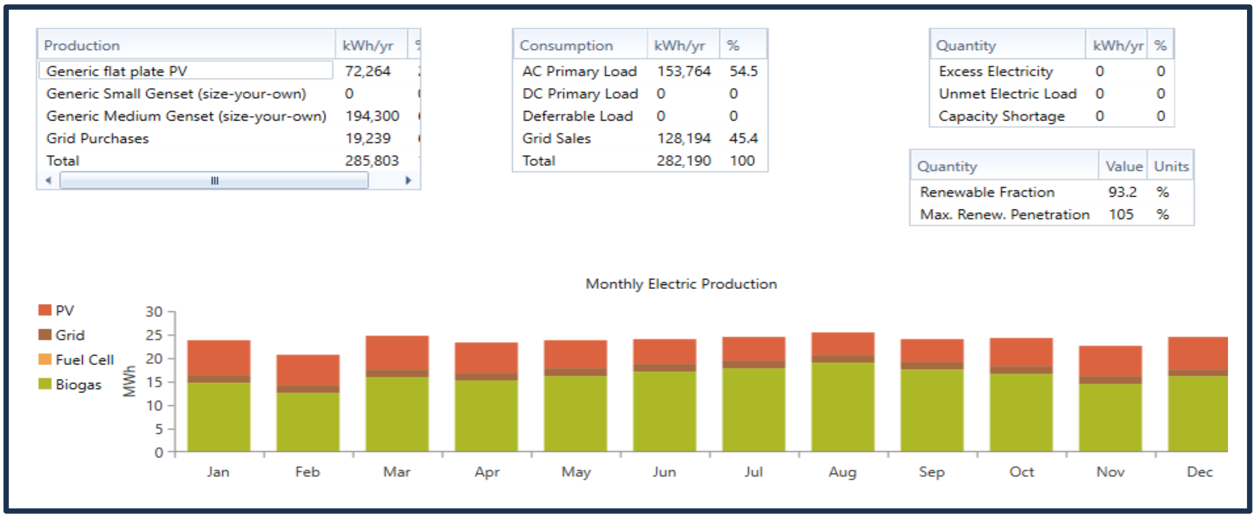

Figure 8 Electric output of the proposed system

These results demonstrate that both configurations were technically capable of supplying the healthcare facility's electricity demand throughout the year. However, the proposed configuration exhibited a more diversified energy supply by combining renewable generation with limited grid support. The implications of the electricity exchanged with the utility grid are examined in the subsequent section.

3.2.2 Grid Performance Analysis

Figure 9 illustrates the monthly electricity exchanged between the proposed hybrid renewable energy system and the utility grid. Throughout the year, electricity exported to the grid consistently exceeded electricity imported, indicating that the hybrid system generated surplus renewable electricity beyond the facility's demand. Monthly electricity purchases ranged from 1,525 kWh in September to 1,666 kWh in October, whereas electricity exports varied between 8,954 kWh in February and 11,510 kWh in August.

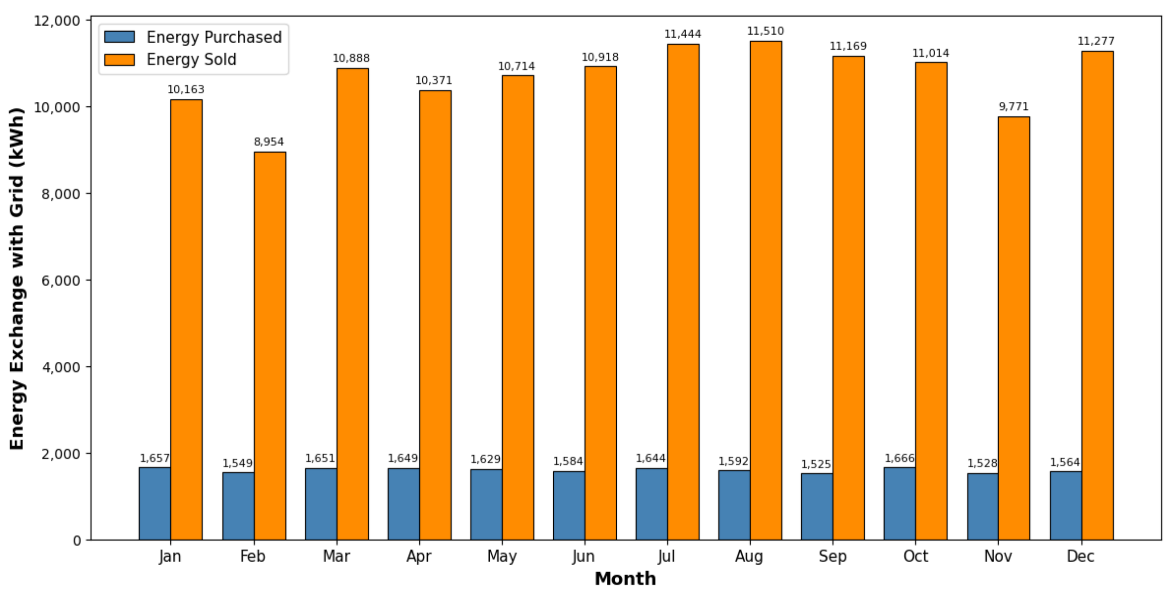

Figure 9 Grid performance

The higher electricity exports observed between July and September are attributable to favourable renewable energy generation conditions and effective system dispatch, while the comparatively lower exports recorded in February reflect seasonal variations in renewable resource availability. The results therefore indicate that the proposed hybrid system functions as a net electricity exporter, enabling productive utilization of excess renewable energy while reducing dependence on electricity purchased from the utility grid.

3.2.3 Economic Analysis

Figure 10 illustrates the cash-flow profile of the proposed hybrid renewable energy system over the 25-year project lifetime. The largest expenditure occurs during the initial investment stage, where approximately \$130,000 is required for the procurement and installation of the principal system components. Annual operating and replacement costs ranging between approximately \$25,000 and \$30,000 are subsequently incurred to maintain reliable system operation throughout the project lifetime.

At the end of the project, the system retains a positive salvage value of approximately \$45,000, reflecting the residual value of the installed components. The favourable cash-flow profile is consistent with the optimization results presented in Section 3.1, demonstrating that the selected configuration offers an economically sustainable solution over its operational lifetime. Although the project requires a relatively high initial capital investment, the combination of moderate operating costs and residual component value supports its long-term financial viability for healthcare electrification.

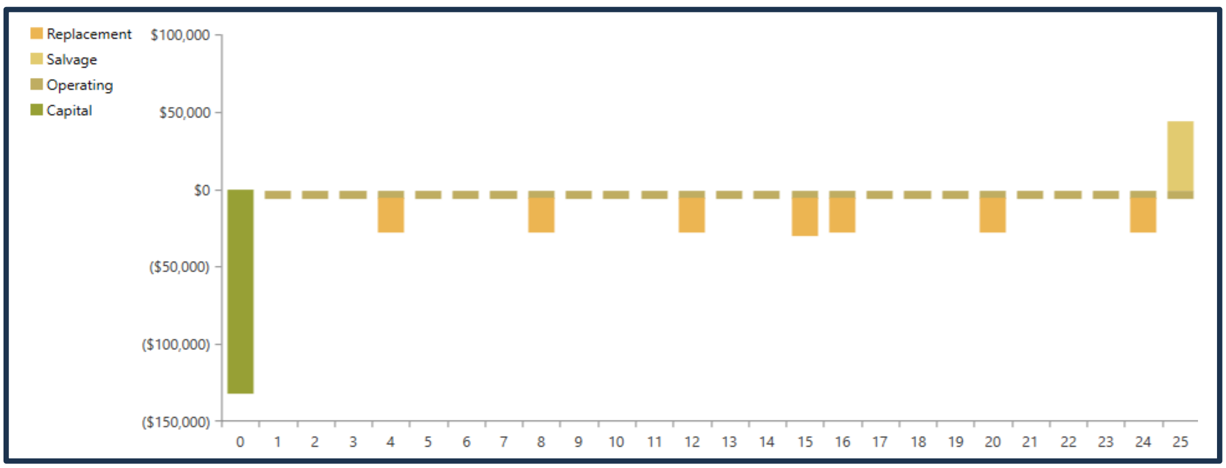

Figure 10 Cash flow distribution

3.3 Environmental Analysis

The environmental performance of the proposed hybrid green energy system was evaluated using the emission analysis module in HOMER Pro, which estimates atmospheric emissions based on electricity generation from each energy source and their corresponding emission factors. The integration of PV generation, biogas, and limited grid electricity significantly reduced greenhouse gas emissions, as PV systems produce negligible operational emissions while biogas is considered a low-carbon energy source due to its near carbon-neutral lifecycle.

The simulation results indicate that the proposed system emits approximately 12,188 kg/year of CO_2, 3.36 kg/year of SO_2, and 26.0 kg/year of NO_x, while achieving a renewable energy fraction of 93.2%. These results demonstrate that the high penetration of renewable energy substantially decreases dependence on grid electricity and conventional fossil-fuel generation, thereby reducing the environmental footprint of the healthcare facility.

The obtained results are consistent with recent studies on hybrid renewable energy systems. Ba-swaimi et al. (2025a) reported that integrating photovoltaic, hydrogen energy storage, and grid connectivity in healthcare facilities significantly reduces greenhouse gas emissions while improving renewable energy utilization and system sustainability. Similarly, Hüner (2025) demonstrated that incorporating biogas into hybrid renewable energy systems substantially lowers carbon emissions and enhances environmental sustainability compared with conventional electricity generation. These findings closely agree with the present study, where the combination of 50 kW PV and 50 kW biogas generation resulted in a high renewable energy contribution and relatively low annual emissions.

Recent evidence from healthcare facilities further supports the environmental and economic benefits of renewable energy integration. A study investigating the implementation of a solar photovoltaic system in a private hospital reported that the generation of 7,122,802.80 kWh of renewable electricity prevented approximately 3,148 metric tons of CO_2-equivalent emissions while reducing electricity costs by 72.3%, demonstrating the technical feasibility and economic advantages of renewable energy adoption in healthcare operations (Yorulmaz & Tas, 2025) These findings further validate the potential of renewable energy technologies to significantly reduce both operational costs and environmental impacts in energy-intensive healthcare institutions.

Comparable conclusions were also reported by Peirow et al. (2023), who found that hybrid renewable energy systems designed for hospital applications significantly reduce greenhouse gas emissions while ensuring reliable electricity supply for critical healthcare services. Overall, the environmental performance of the proposed PV-biogas-fuel cell-grid system demonstrates its suitability as a low-carbon electricity solution for healthcare institutions and supports the objectives of Ghana's Renewable Energy Master Plan (Energy Commission, 2019), which promotes renewable energy deployment to reduce greenhouse gas emissions and accelerate the country's transition toward sustainable energy systems.

3.4 Sensitivity Analysis

3.4.1 Effect of Grid Price on Cost of Energy and Net Present Cost

Figure 11 presents the sensitivity of the hybrid energy system to variations in grid electricity prices. The results indicate that increasing the grid electricity price from $0.10/kWh to $0.25/kWh leads to a reduction in the COE from $0.156/kWh to $0.103/kWh. This reduction occurs because higher grid electricity prices increase the economic value of electricity exported to the utility grid, thereby improving the overall economic performance of the hybrid system.

Conversely, the NPC exhibits a gradual increase from $168,314 to $174,021 as the grid price rises. The increase in NPC may be attributed to the greater economic valuation of system operations and associated lifecycle expenditures under higher electricity market prices. These findings demonstrate that the economic viability of the proposed hybrid renewable energy system improves significantly in regions characterized by high electricity tariffs, making grid-connected renewable systems increasingly attractive.

3.4.2 Effect of Solar PV Cost on Cost of Energy and Net Present Cost

Figure 12 illustrates the impact of variations in solar photovoltaic capital costs on the economic performance of the hybrid system. As the PV capital cost increases from $820/kW to $1,066/kW, the COE rises from $0.156/kWh to $0.167/kWh, while the NPC increases from $168,314 to $180,614. The results indicate a direct relationship between PV investment cost and the overall economic performance of the system.

The increase in both COE and NPC can be attributed to the significant contribution of solar PV technology to the hybrid energy system configuration. Higher PV installation costs increase the initial capital investment requirements, which subsequently elevate the lifecycle cost of electricity generation. Nevertheless, despite these increases, the hybrid system maintains economic feasibility, demonstrating its resilience against fluctuations in photovoltaic technology costs.

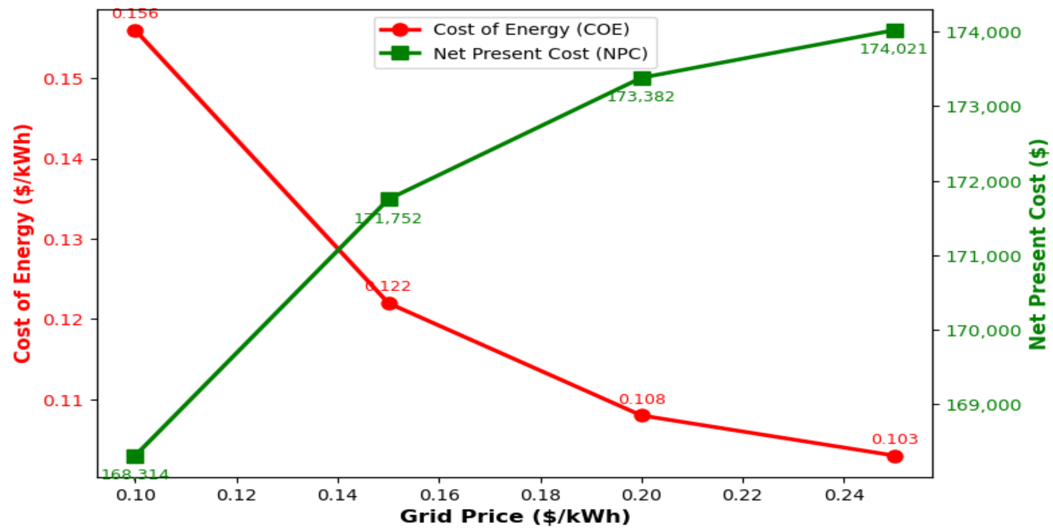

Figure 11 Effect of Grid Price on Cost of Energy and Net Present Cost

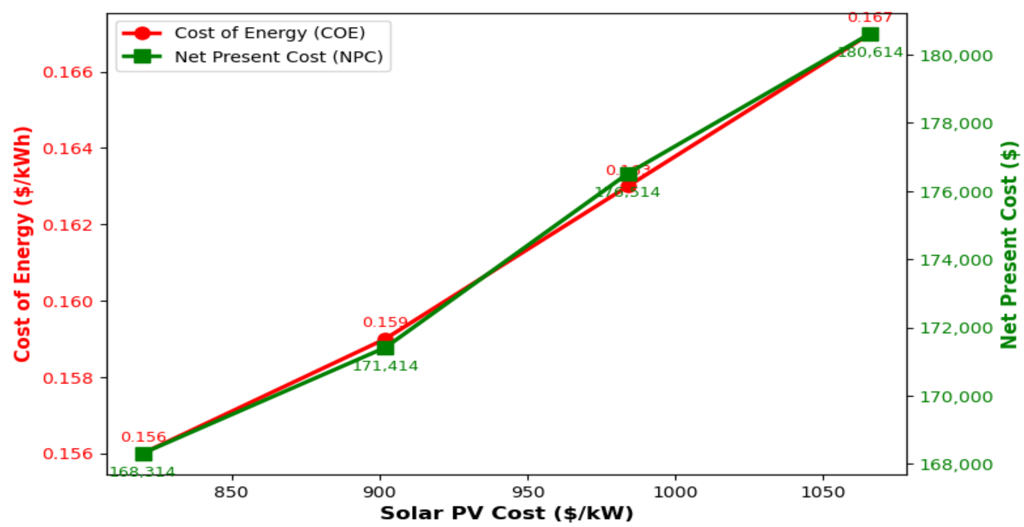

Figure 12 Effect of Solar PV Cost on Cost of Energy and Net Present Cost

3.4.3 Effect of Load Demand on Cost of Energy and Net Present Cost

Figure 13 presents the influence of increasing load demand on the economic indicators of the proposed hybrid energy system. As the average daily load increases from 421.27 kWh/day to 571.27 kWh/day, the COE decreases from $0.156/kWh to $0.120/kWh, whereas the NPC increases from $168,314 to $185,195.

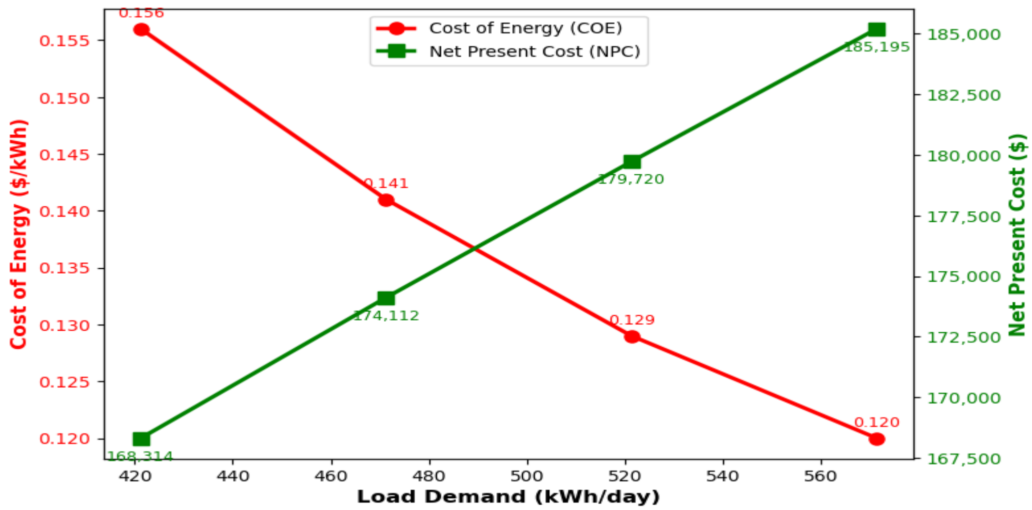

Figure 13 Effect of Load Demand on Cost of Energy and Net Present Cost

The reduction in COE with increasing load demand indicates the existence of economies of scale, whereby fixed capital and operational costs are distributed over a larger amount of electricity supplied. Conversely, the increase in NPC reflects the need for additional system investments and operating expenditures to satisfy higher electricity demand. These results suggest that the proposed hybrid system becomes increasingly cost-effective when deployed in facilities with higher energy consumption levels, such as hospitals and institutional buildings.

3.4.4 Effect of Nominal Discount Rate on Cost of Energy and Net Present Cost

Figure 14 shows the effect of varying the nominal discount rate on the economic performance of the hybrid energy system. As the nominal discount rate increases from 25% to 40%, the COE rises significantly from $0.156/kWh to $0.218/kWh, while the NPC decreases from $168,314 to $153,708.

The increase in COE reflects the higher cost of capital associated with increased discount rates, which raises the effective cost of electricity generation over the project lifetime. In contrast, the reduction in NPC occurs because future operating and replacement costs are discounted more heavily at higher discount rates, resulting in lower present-value costs. These findings highlight the importance of financial assumptions in determining the economic feasibility of renewable energy projects and demonstrate the sensitivity of lifecycle cost analyses to discount rate selection.

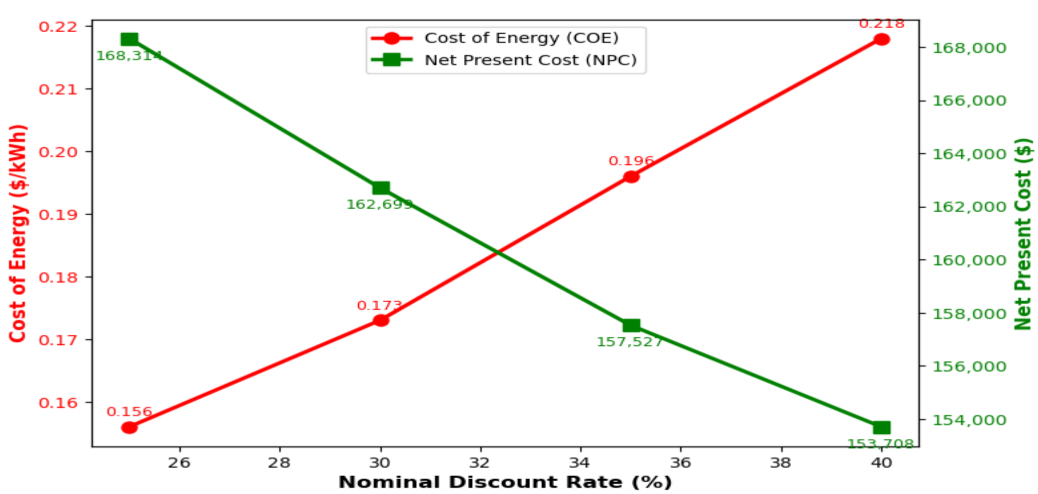

Figure 14 Effect of Nominal Discount Rate on Cost of Energy and Net Present Cost

3.4.5 Effect of Expected Discount Rate on Cost of Energy and Net Present Cost

Figure 15 illustrates the impact of changes in the expected discount (inflation) rate on the economic performance of the proposed hybrid system. The results indicate that increasing the expected discount rate from 5% to 20% increases the COE from $0.0685/kWh to $0.130/kWh, while the NPC decreases from $262,163 to $180,829.

The increase in COE is primarily due to the influence of inflation on future investment, operation, and maintenance costs, which ultimately raises the unit cost of electricity generation. Conversely, the reduction in NPC can be explained by the decreasing present value of future expenditures under higher expected discount rates. The results demonstrate that the economic performance of hybrid renewable energy systems is strongly influenced by macroeconomic parameters and that accurate estimation of discount and inflation rates is essential for reliable techno-economic assessment.

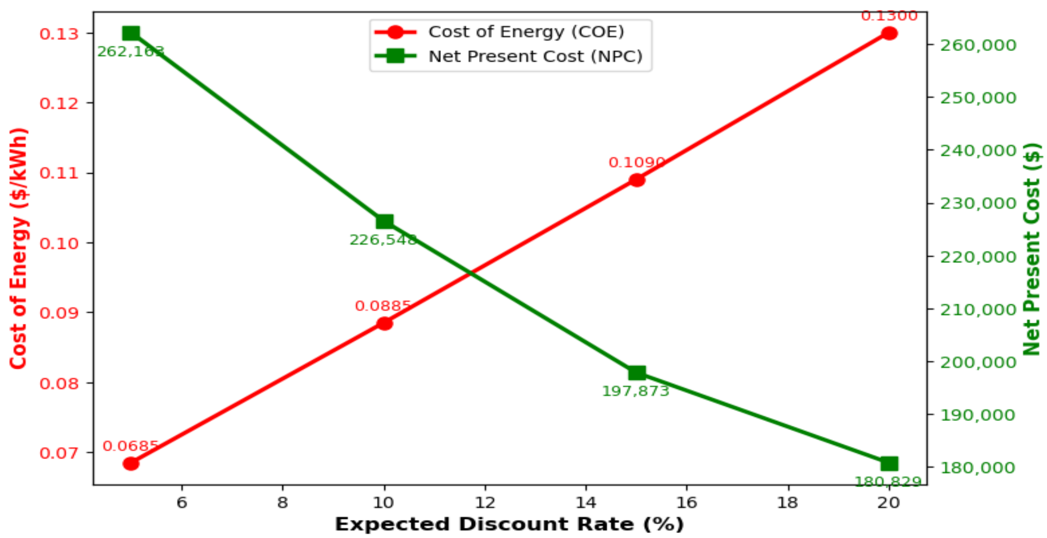

Figure 15 Effect of Expected Discount Rate on Cost of Energy and Net Present Cost

Moreover, the sensitivity analysis confirms that the proposed grid-connected hybrid energy system remains economically viable under a wide range of technical and financial conditions. Among the investigated parameters, the nominal discount rate and load demand exhibit the strongest influence on system economics, while variations in solar PV costs and grid electricity prices have comparatively moderate effects.

3.5 Practical Applicability of the Proposed System

The proposed hybrid renewable energy system demonstrates strong potential for practical implementation in healthcare facilities in Ghana and other developing countries experiencing unreliable electricity supply. The integration of solar photovoltaic generation, biogas energy, fuel cell backup, and utility grid connectivity provides a reliable, sustainable, and economically viable solution for critical healthcare operations. The high renewable energy fraction (93.2%), low cost of energy ($0.156/kWh), and zero unmet load achieved in this study demonstrate the system's suitability for hospitals and other essential public institutions.

Recent studies have similarly confirmed the practical feasibility of renewable energy technologies in healthcare applications. Ba-swaimi et al. (2025a) reported that grid-connected hybrid renewable systems significantly improve energy reliability and sustainability in healthcare facilities, while Peirow et al. (2023) demonstrated that hybrid renewable energy systems provide reliable and environmentally sustainable electricity for hospitals. Furthermore, Özbeyaz (2025) reported that implementing a solar photovoltaic system in a private hospital reduced electricity costs by 72.3% and prevented approximately 3,148 metric tons of CO_2-equivalent emissions. These findings support the practical applicability of the proposed PV-biogas-fuel cell-grid system and highlight its potential to contribute to sustainable healthcare electrification and Ghana's renewable energy development goals.

4 Conclusion

This study evaluated the techno-economic and environmental feasibility of a hybrid green power generation system for Kokofu General Hospital using HOMER Pro optimization software. The proposed configuration comprised a 50 kW photovoltaic (PV) array, a 50 kW biogas generator, a 10 kW fuel cell, a 50 kW converter, and utility grid connectivity. The optimization aimed to identify the most cost-effective system capable of providing reliable electricity while maximizing renewable energy utilization.

The optimization results demonstrated that the proposed hybrid system achieved a COE of $0.156/kWh and an NPC of $168,314, while maintaining a high renewable energy fraction of 93.2%. The system supplied the hospital's annual electricity demand without any unmet load or capacity shortage, confirming its capability to provide a reliable and uninterrupted power supply for critical healthcare services. The energy generation analysis further revealed that photovoltaic and biogas technologies supplied the majority of the annual electricity demand, with only limited reliance on utility grid electricity, thereby enhancing both energy security and operational flexibility.

The environmental assessment showed that the proposed system emitted only 12,188 kg/year of CO_2, 3.36 kg/year of SO_2, and 26.0 kg/year of NO_x, demonstrating that the high penetration of renewable energy substantially reduces greenhouse gas emissions and dependence on fossil fuel-based electricity. These findings highlight the environmental benefits of integrating solar PV and biogas generation in healthcare energy systems and support the transition toward low-carbon electricity generation.

Sensitivity analysis further confirmed the robustness of the proposed configuration under varying technical and economic conditions. Among the parameters investigated, the nominal discount rate and electricity demand exerted the greatest influence on the system's economic performance, whereas variations in PV capital cost and utility grid electricity prices had comparatively smaller impacts. This demonstrates that the proposed hybrid system remains economically viable across a wide range of future operating scenarios.

Overall, the findings demonstrate that integrating solar PV, biogas generation, fuel cell technology, and grid connectivity provides a reliable, economically competitive, and environmentally sustainable electricity solution for healthcare institutions. The proposed system offers a practical pathway for reducing operating costs, minimizing greenhouse gas emissions, and enhancing energy resilience in hospitals. Consequently, this framework can serve as a valuable reference for the design and deployment of hybrid renewable energy systems in healthcare facilities and other critical infrastructure across Ghana and similar developing countries, thereby supporting national renewable energy policies and global sustainable development objectives.

Declaration of Ethical Standards

The author confirms that this study was conducted in accordance with all applicable ethical standards and guidelines.

CRediT Authorship Contribution Statement

Paul Kusi: Conceptualization; Methodology; Investigation; Data curation; Formal analysis; Software; Validation; Visualization; Writing – original draft; Writing – review & editing; Project administration.

Declaration of Competing Interest

The author declares that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

The data supporting the findings of this study were obtained from Kokofu General Hospital and the NASA POWER database and were used within the HOMER Pro simulation environment. The datasets are available from the corresponding author upon reasonable request.

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