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RESEARCH ARTICLE

Optimizing Technical and Economic Aspects of Off-Grid Hybrid Renewable Systems: A Case Study of Manoka Island, Cameroon

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ABSTRACT The lack of accessible and reliable electrical energy in Cameroon has become a pervasive obstacle to the nation's progress, with energy availability, quality, and cost identified as key hindrances to development over the past 15 years. Conventional solutions that rely on combustion engines and electrochemical storage systems have proven to be cost-prohibitive, limited in power output, and constrained in capacity. The dependence on traditional diesel generators has perpetuated maintenance challenges and a continuous demand for fuel supply, while the accompanying noise and pollution have restricted their use in residential areas. Recognizing the imperative of reducing dependence on fossil fuels and curbing greenhouse gas emissions, the need for clean and sustainable energy sources has emerged as a critical concern for the advancement of civilization. Against this backdrop, this research endeavors to identify the most cost-effective and efficient blend of renewable energy sources capable of meeting the power requirements of three small communities on Manoka Island, a district of Douala, Cameroon. Through a comprehensive technical, environmental, and economic analysis, this study addresses the substantial energy needs of 334 households, with an average daily power consumption of 1082.90 kWh and a peak electrical load of 183.99 kW. Leveraging the Hybrid Optimization Model for Electric Renewables (HOMER) program, this investigation assesses the feasibility of implementing Hybrid Renewable Energy Systems (HRES) to meet the region's energy demands. The research highlights the most optimal scenario integrating solar panels, wind turbines, battery cells, fuel cell generators, biogas, and an electrolyzer within an off-grid HRES system. Notably, the study demonstrated an absence of idle load, resulting in remarkably low unit energy costs of $0.1981 and a compelling net present value of $2,209,741. The cost-effective arrangement featured 201 batteries, yielding a project profit of $57,387, with an impressive Internal Rate of Return (IRR) of 9.09%, Return on Investment (ROI) of 6.19%, and a payback period of 8.76 years over a 25-year term. In essence, the insights gleaned from this exploration of hybrid energy systems represent a pioneering case study in sustainable electricity provision. This research significantly contributes to the knowledge base on renewable energy within the nation, underscoring its tremendous potential for sustainable development and energy security.

INDEX TERMS Hybrid renewable energy, off grid, optimization, techno-economic.

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NOMENCLATURE

A Rotor swept area (m^2).
A_g Fuel consumption coefficient (l/kW).

B_g	Fuel consumption coefficient (l/kW).
$C_{ann,tot}$	Total annual cost ($/yr).
C_{NPC}	Net present cost ($).
C_I	Internal capacitance (F).
E	Nernst voltage (V).
E_o	FC's open-circuit voltage (V).
E_l	Load demand (kWh).
E_g	Energy generation (kWh).
E_b	Battery state of charge (kWh).
E_{gen}	Energy generation (kWh).
$E_{gen_{MG}}$	Energy generated by the microgrid (kWh).
$E_{gen_{grid}}$	Energy generated by grid (kWh).
f	Inflation rate (%).
F	Faraday constant.
F_{dg}	Fuel consumption of diesel generator (l/h).
f_{PV}	Derating factor of PV module (%).
$\bar{G}_T$	Solar irradiation (kW/m^2).
$\bar{G}_{T,STC}$	Solar irradiation at STC (kW/m^2).
i	Actual interest rate (%).
i'	Nominal interest rate (%).
I	Electrolyzer current (A).
I_{FC}	FC's output current (A).
N	Number of FCs in series.
N_g	Generator efficiency (%).
N_b	Gear efficiency (%).
N_H	Hydrogen consumption (kg/h).
N_s	Number of series-connected cells.
N_{tank}	Mass of gas in the tank (moles).
P	Power for Hydrogen compression (kW).
P_1	Inlet pressure (kPa).
P_2	Discharged pressure (kPa).
P_{dg}	Rated power of diesel generator (kW).
P_{dg-out}	Power output of diesel generator (kW).
P_m	Wind turbine output power (kW).
P_{PV}	Solar PV output power (kW).
P_{output}	Power going out of the converter (kW).
P_{input}	Power going into the converter (kW).
P_{tank}	Amount of hydrogen in the tank (kg).
q	Hydrogen generation rate (kg/h).
R	Universal gas constant (kJ/kg.K).
R_{proj}	Duration of the project (yr).
T	Temperature (K).
T_C	PV cell temperature (°).
$T_{C,STC}$	PV cell temperature under standard test conditions (°).
v	Wind speed (m/s).
V	Volume of gas in the tank (m3).
V_T	Terminal voltage (V).
V_{CI}	Voltage generated by the internal capacitance (V).
V_{Loss}	FC's resistive loss (V).
y_{PV}	Rated PV power (kW).

Greek symbols

α_P	Temperature coefficient of power (%/°).
η_{comp}	Compression efficiency (%).
Υ	Polytropic effect.
η_f	Faraday efficiency (%).
ρ	Air density (kg/m^3).
σ	Battery self-discharge rate (%).
η_{cnv}	Converter efficiency (%).
η_{BC}	Battery charging efficiency (%).
η_{BD}	Battery discharging efficiency (%).
ρ_{h2}	Partial pressure of hydrogen (atm).
$\rho_{o2}^{0.5}$	Partial pressure of oxygen (atm).
ρ_{h2o}	Partial pressure of water (atm).

Abbreviations

AC	Alternating current (A).
BEAC	Bank of central African states.
COE	Cost of energy ($/kWh).
CRF	Capital recovery factor.
CHP	Combined heat and power.
CCHP	Combined cooling heating and power.
DC	Direct current (A).
FC	Fuel cell.
LCOE	Levelized cost of energy ($/kWh).
HRES	Hybrid renewable energy system.
HOMER	Hybrid Optimization Model for Electric Renewables.
IEA	International Energy Agency.
IRR	Internal rate of return (%).
NPC	Net present cost ($).
PV	Photovoltaic.
ROI	Return of investment (%).
WT	Wind turbine.

I. INTRODUCTION

A. BACKGROUND, MOTIVATION AND LITERATURE REVIEW

Energy is an important factor that characterizes the lifestyle and standard of living of a population. It is a fundamental requirement for the economy of a country and the most important condition for the continuity of civilization [1]. The global population is continuously growing, leading to ever-growing energy demand [2]. In developing countries, energy is a vital resource for the development of remote areas [3]. Conventional resources are insufficient to provide this energy uninterruptedly. Recently, an overview of the world has presented a rise in energy crises. Therefore, the use of renewables as a means to cope with today's challenges is now an economically viable option [4]. The world abounds with tremendous renewable energy sources of different natures in all countries. Despite their animosity, all of Cameroon's regions are good candidates for expanding access to renewable energy. In this regard, Cameroon has a wide variety of potential sources of renewable power. The nature of these sources differs and depends on the geographical region.

It is also possible to hybridize them by combining different renewable energy sources from different regions for optimum efficiency. Generating electricity from renewable sources is cheaper, cleaner, and more environmentally friendly in the long run. To achieve this goal, good and durable infrastructure that provides uninterrupted power at an affordable price is required. Decentralized energy systems that make use of renewable sources provide feasible answers to the problem of electricity in Sub-Saharan Africa due to their environmental benefits, decreasing costs, and accessibility. According to a 2017 analysis from the International Energies Agency (IEA), decentralized renewable energy sources are the most economical means to give power access to 70% of the world's population that presently lacks it by 2030 [5].

Solar and wind power, for example, are in infinite supply. But their features, like sun intensity and wind velocity, may change dramatically from day to day. This variability introduces significant uncertainties that impact the reliability and stability of energy systems, particularly when substantial investments are made in these systems. The uncertainties stemming from the variability of renewable energy sources necessitate the need for backup units, which in turn increases production costs [6]. Therefore, measuring quantitative data for renewable energy sources reduces uncertainty. In this context, effective planning, management, and efficient operation of electrical energy and power generation systems necessitate a sub-requirement. The key answer to the unpredictable nature of renewable energy sources is the use of HRES, which combine different renewable energy sources. By incorporating multiple energy sources into an electrical system, it becomes possible to generate the required energy at the desired time and season, while also reducing costs compared to relying solely on a single renewable energy source. However, difficulties arise when trying to ascertain the best way to size such systems to accommodate the amount of load needed at different places and times. These challenges arise from the variability of energy sources, the complexity of calculating an efficient cost model, and the time-consuming nature of the process [7]. HOMER, RETScreen, Hybrid2, TRNSYS, RAPSIM, and INSEL are only some of the optimization software packages that have been presented in the literature. Hybrid Optimization Model for Electric Renewables (HOMER) is one of the most important of these. This software enables the evaluation of different combinations in a more efficient and accurate manner, making it a crucial tool in the field [6]. Different studies employ HOMER software to obtain the best operating conditions for microgrid optimization in both on-grid and off-grid HRES. The literature review was conducted to find similar work done by other researchers, as shown below.

The study [8] assesses the economic, technical, and environmental performance of hybrid renewable energy systems in 21 Turkish provinces. It uses HOMER PRO software to compare costs, net present costs, greenhouse gas emissions, and renewable fraction. The optimal configurations are Grid/PV/WT and PV/WT/DG/BESS. The study also found that NPC values decrease with increasing solar radiation and wind speed. In [9], authors introduce third-generation perovskite solar cells (PSCs) for improving the efficiency of off-shore oil ships. A hybrid renewable energy system (HRES) incorporating PSCs, batteries, and a diesel engine was developed and analyzed using HOMER software. The model successfully reduced pollutants and greenhouse gases during the ship's journey from Dalian to Hurghada. The study advocates for the adoption of advanced solar cell technologies for cost-effective and environmentally friendly energy solutions in off-shore oil ships. The study [10] focuses on designing a hybrid microgrid system for sustainable power in the remote Doddipalli village of Chittoor, Andhra Pradesh, India. The system integrates a hydrogen tank and loads, enhancing energy management strategies. The optimal configuration (PV/WT/Grid) has a low levelized cost of energy, minimum net present cost, and high renewable energy fraction (97.8%). The system includes solar PV panels, four wind turbines, a hydrogen tank, a 700 kW electrolyzer, and a 94kW power converter. The research emphasizes the system's economic viability and reliability. In authors [11] evaluates battery depth of discharge (DOD) for various battery technologies in the cement industry in Pakistan. It focuses on lead-acid, lithium-ion, vanadium redox, and nickel-iron battery technologies. Four hybrid energy generation models are proposed using HOMER pro software. A multi-criteria decision analysis is conducted to maximize COF while minimizing net present cost, levelized cost of energy, and greenhouse gas emissions. The study finds that vanadium redox is the most suitable battery technology, achieving a 10% DOD and significant reductions.

Recioui and Dassa [12] proceed to the comparison of HOMER with metaheuristic techniques to show the benefits of the software. With the ability to reconstitute various energy sources, HOMER is used as an instrument to assess the electrical sites or standalone grids. Furthermore, HOMER also offers some other advantages. Indeed, it is useful for technical, economic, and environmental analysis [13]. Iten et al. [14] investigate the financial feasibility of the demand-supply balance of electrical energy in academic research in Bhopal. A combination of a fuzzy logic program for estimating component capital and replacement costs and HOMER for sizing hybrid system configurations is used in this paper. According to the data, the hybrid system generates about 24,570.72 kWh of electricity at a levelized price for electricity (LCOE) of \$0.203 / kWh. Using the HOMER program, Rajbongshi et al. [15] took on the difficult task of optimizing PV-biomass-diesel-grid hybrid energy systems. Daily mean values of insolation are used as initial climate data. Results showed using biomass gasification is cheaper than a photovoltaic system. Indonesian researchers studied and designed stand-alone power systems for government and municipal loads in three regions of Maluku, Indonesia. Putra et al. [16] surveyed three villages of Wairtan, Klishatu, and Leiting

Villages. For this study, HOMER Pro, PVsys, and PVsol software were utilized for management and co-loading purposes. The authors recommend using the study's results to boost Bright Indonesia and other rural electrification initiatives. Parida et al. [17] aim to address the persistent issue of severe power shortages resulting from long-term supply and demand imbalances. They suggest using a combination solar-wind system in conjunction with a viable energy cooperative. Distributing energy produced by this hybrid wind and solar system is recommended to address the power crisis. A cooperative scheme aimed at power loss control was suggested and developed through simulation analysis using Simulink and HOMER. The authors in [18] introduced a self-contained hybrid renewable energy system designed to fulfill the thermal and electrical demands of 40 homes. The study conducted simulations to evaluate various systems, using data acquired via the use of HOMER Software. The hybrid PV/WT renewable energy system in Nigeria was examined by the authors in reference [19]. It was disclosed that nations possessing comparable economic and climatic circumstances may get advantages from the implemented Hybrid Renewable Energy Systems (HRES). The impacts of incentives on residential areas were examined in [20] by the use of several scenarios including household renewable energy systems (HRES). The findings indicate that hybrid systems exhibit superior return on investment and a more expedited payback time in comparison to photovoltaic (PV) and wind turbine (WT) systems. The authors of [21] offered a techno-economic study of grid-tied solar photovoltaic (PV) systems. The findings indicate that the incorporation of photovoltaic (PV) systems inside residential apartment complexes in Saudi Arabia has noteworthy effects on energy management. The researchers in reference [22] conducted a study to examine the economic and environmental consequences of a Hybrid Renewable Energy System (HRES). The findings of the study demonstrated that the integration of wind energy and solar power resulted in a substantial rise in both carbon dioxide (CO_2) emissions and energy expenditures. The objective of the writers was to acquire the most economically efficient and practical resolution for fulfilling the household energy requirements in [23]. The research done by the authors in reference [24] aimed to examine the potential of households' real market performance. Based on the findings of the study conducted in various urban areas, it was seen that a hybrid renewable energy system (HRES) consisting of a photovoltaic (PV) array with a capacity ranging from 3 to 7 kW effectively met the energy requirements, which were contingent upon the levels of solar radiation. In a study conducted by [25], an assessment was made on the technical and economic viability of a grid-tied hybrid renewable energy system (HRES). Photovoltaic (PV) systems have shown efficacy in mitigating power expenses and curbing the release of greenhouse gas (GHG) emissions. The use of HOMER Pro software facilitated the design of hybrid renewable systems, both grid-connected and stand-alone, by leveraging home power consumption data. The primary objective of this endeavor was to meet the residential electricity demands [26]. The results indicated that the grid-tied hybrid renewable energy system (HRES) was a more cost-effective option for residential families when compared to the stand-alone HRES. The paper included a comprehensive examination of the feasibility and sensitivity studies conducted on residential loads across several geographical regions [27]. The optimal solution was impacted by several aspects, including load demand, weather conditions, and various geographies. In [28], a research was conducted to assess the viability of a hybrid energy system including photovoltaics (PV), distributed generation (DG), and battery energy storage systems (BESS). The study examined three distinct methodologies for the integration of these components. The results indicated that the combined dispatch approach exhibited superior optimization when compared to the load-following and cycle-charging methods. A study was conducted in several locations of Nigeria to analyze the performance of stand-alone hybrid renewable energy systems (HRES) that use photovoltaic (PV), wind turbines (WT), diesel generators (DG), and battery energy storage systems (BESS) [29]. The findings suggest that the most optimal hybrid system, based on regional analysis, was the combination of photovoltaic (PV), wind turbine (WT), diesel generator (DG), and battery energy storage system (BESS), or alternatively, the combination of PV, WT, and BESS.

In a different study, Azad et al. [30] undertake sensitivity analysis of suggested energy systems with an emphasis on renewable energy systems. For the purpose of reducing carbon emissions at the lowest possible cost, the HOMER program was used to determine the most efficient combination of renewable energy sources. A technical and economic examination of a system that combines wind and solar energy to power a single off-grid dwelling in rural Turkey was undertaken by Akan [31]. HOMER software was used for the study, and it was determined that a combined contribution of 61.8% via solar power and 38.2% from wind power was sufficient to meet the load requirement. Likewise, Rahmat et al. [32] reported on a hybrid system built with the aid of the HOMER program to provide the homes in Jhawani neighborhood, India, with power. The research demonstrates how well the hybrid system works to provide the town's energy needs. The research concluded that using a mix of solar panel/biomass/diesel system for off-grid operation in really out of the way settlements is both practical and secure. However, it is also pointed out that implementation is needed to understand the practical challenges of the proposed hybrid systems.

To address the unique conditions of the island of St. Martin in Bangladesh, Jaman [33] proposed a hybrid photovoltaic panel/fuel cell system. The research used the HOMER program to analyze and quantify both the technical and economic components of the system. The goal was to find the hybrid system's optimal setup for the given environment;

he observed a major decrease in the emission of carbon dioxide in the simulations and stated that the hydrogen-based hybrid system for rural areas may be feasible with a grid connection. In Newfoundland, Canada, Khan and Iqbal [34] integrated a power production system that uses hydrogen as its energy source. Multiple conventional and renewable energy solutions, as well as energy storage systems, were simulated and optimized using the HOMER software. The analysis found that the wind-diesel reserve system remains a viable option at present pricing, while the wind-fuel cell system would be more appealing if fuel cell prices dropped by 15%. Riayatsyah et al. [35] examined Zaferler village's 2020 electricity usage statistics to design off-grid wind turbines, solar panel generators, hybrid cell energy systems, and technical and economic analyses using HOMER software to meet the region's energy needs. Three different scenarios were applied using three different types of generator components used in the system design, namely biogas, fuel cell, and diesel. The techno-economic consequences of each scenario's variables are calculated and compared to get the best possible result for the system. The optimal result is then determined in with respect to the economy and environment. Appropriate design and system optimization is highlighted. An extensive technical and economic examination of a PV/biomass/battery microgrid system was undertaken by Verma et al. [36] in six different regions of India. The findings showed significant benefits for microgrid strategy and operations. Furthermore, the microgrid system's levelized cost of energy (LCOE) at these six sites was far lower than the LCOE provided by traditional power systems. Das et al. [37] investigated the feasibility of using rooftop solar panels, wind power plants, and tiny gas turbines as part of a hybrid independently system to supply the energy needs of a town in Australia. The study's primary objective was to determine whether or not the hybrid system could effectively serve the community's energy needs. Each system was optimized using a genetic algorithm with many objectives utilizing either dynamic or static energy management. The results showed that in comparison to the load monitoring strategy alternatives, the hybrid system using a cyclic charging method had the smallest energy cost but slightly more life cycle emissions. Among the different alternatives, the hybrid vanadium oxide flow solutions exhibited the lowest energy cost, ranging from \$0.126 to \$0.187 per kilowatt-hour (kWh), and the lowest life cycle emissions, ranging from 46,258 to 104,664 kilograms of CO_2-equivalent per year (kg CO_2-eq/yr). With the goals of accessibility, environmental sustainability, and social benefits in mind, Hassan et al. [38] presented a HRES social indicator built into its design criteria. The proposed hybrid system combines solar photovoltaic panels, wind turbines (WT), micro-hydro turbines, biogas generators, and vanadium redox flow batteries to meet the 951–1526 kWh daily energy demand of a rural community in Bangladesh. There were six different setups considered, and only one was found to be capable of meeting the need while also meeting all of the technical and dependability requirements. The optimum setup includes a 68 kW PV, 90 kW WT, 50 kW MHT, 50 kW BG, and 300 kWh VRF, as found by multi-objective dimensioning optimization using the non-dominant tri-genetic algorithm-II. This setup has the potential to create 0.7396 local employment, has a cost of energy (COE) of \$0.126 per kWh, and emits 60,116 kg of CO2 equivalent year. In a separate study, Hassan et al. [39] designed a self-contained energy system capable of supplying both electrical and thermal loads. By comparing a baseline scenario to three other ones, they discovered that recovering surplus energy (electric and thermal) and adding thermal storage increased the total renewable share and decreased the carbon footprint. In this case, the annual cost of electricity was \$0.166, and the annual carbon footprint was 25,220 kg. Das et al. [40] investigated the trade-offs between price, energy, and exergy in hybridized trigeneration and cogeneration systems. The efficiency of combined Micro Gas Turbine/PV systems was measured using a multi-objective optimization algorithm. For the same electric-to-thermal load ratio, the efficiency (h) of CHP systems rose to 51% while that of CCHP systems rose to 55%. When there were power outages in the heating and cooling systems, CCHP was less impacted. Independent solar-PV or solar-CHP systems were able to reach 50% and 70% renewable penetrations. The literature indicates that hybrid systems have been widely employed to address the electrification challenges of isolated sites while considering environmental concerns. However, the integration of fuel cells and biogas generators with PV/WT systems and their impacts on techno-economic and environmental feasibility have yet to be explored in certain developing countries like Cameroon.

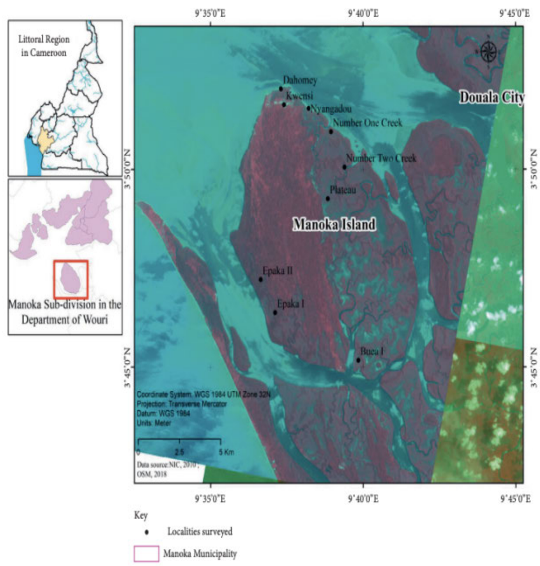

FIGURE 1. Location of Manoka Island.

B. RESEARCH GAPS, METHODOLOGY, AND CONTRIBUTIONS

This article focuses on addressing the energy supply gap in Cameroon through the implementation of a Hybrid

Renewable Energy System (HRES) and presents several key contributions across different aspects.

1) THEORETICAL CONTRIBUTION

The article begins by highlighting the existing energy supply challenges in Cameroon, particularly the developmental hindrances caused by the lack of electrical energy. It sheds light on the limitations of conventional energy solutions like combustion engines and electrochemical storage systems in terms of cost, technical capacity, and power. The study aims to bridge this gap by proposing a new approach that combines various renewable energy sources to fulfill the power needs of communities.

2) PRACTICAL CONTRIBUTION

The practical implications of the research are discussed next. The proposed HRES is identified as a cost-effective and efficient solution for powering three communities on Manoka Island. Notable benefits of this system include decreased reliance on fossil fuels, reduced greenhouse gas emissions, and increased access to clean and reliable energy sources, thereby promoting sustainable development. Moreover, the study's findings have the potential to guide energy planning and decision-making not only within the studied region but also as a model applicable to similar contexts in Cameroon or beyond.

3) METHODOLOGICAL CONTRIBUTION

The article introduces the methodology employed for analysis and optimization – the Hybrid Optimization Model for Electric Renewables (HOMER) program. It emphasizes the thorough technical, environmental, and economic analysis carried out in the research, showcasing a comprehensive evaluation of the proposed system's feasibility.

4) INNOVATIVE SOLUTION

A novel solution is presented through the chosen off-grid HRES scenario involving a combination of solar panels, wind turbines, battery cells, fuel cell generators, biogas, and an electrolyzer. This innovative approach is designed to address the specific energy requirements of the region while maximizing both cost-effectiveness and efficiency.

5) EVIDENCE OF POTENTIAL

The introduction culminates by underlining the research's contribution to the significant potential of hybrid energy systems in advancing sustainable electricity solutions. It mentions that the study enriches the understanding of renewable energy within Cameroon and beyond, offering a practical demonstration of the effective utilization of such systems.

By encompassing these contributions within the introduction, the article not only contextualizes the research but also demonstrates its value in terms of theoretical insights and practical applications within the realm of renewable energy.

The fundamental purpose of this research is to encourage the use of clean and sustainable energy solutions in an effort to reduce the effects of climate change and increase energy security. Developing resilient and environmentally conscious energy systems for performing such projects in electrified regions like Manoka Island may benefit greatly from the methods and conclusions given in this study.

C. OUTLINE OF THE PAPER

The remainder of the paper consists of the following sections: The materials and techniques used are described in Section II, followed by a discussion of HRES modeling in Section III, a presentation of the problem formulation in Section IV, and an illustration of the findings and comments in Section V. Finally, the study's findings and implications are presented in Section VI.

II. MATERIALS AND METHODS

A. AREA UNDER STUDY

To satisfy the energy needs of the headquarter in the recently constructed Douala VI district of Manoka (3°51'19''N, 9°36.53′ E), a technical and financial evaluation of the hybrid system was conducted for this research. Douala, the city where this neighborhood is situated, sits on the coast of Cameroon. Manoka Island has a total size of 10,031 hectares and is inhabited by 3,371 people. There are perhaps 10% native Cameroonians living among a majority of West African immigrants. For the precise position of Manoka Island, see Fig. 1 [41]. This district has neither potable water nor electrification. The study focuses on 3 villages namely Dahomey, Kwensi, and Nyangadou with approximately 334 households.

B. ELECTRICAL LOAD ESTIMATION AT THE SELECTED AREA

Manoka Island in Douala, Cameroon, is located on the shore, and its electrical needs are met by a HRES that has been specifically developed and optimized to meet those needs. Household use in the study region was used to determine the load statistics shown in Table 1. The daily average consumption is 1,082.90 kWh, estimated according to the needs (lighting, ventilation, television, etc.) of these consumers. Fig. 2 illustrates the hourly load profile, showcasing an average load of 56 kW. On the other hand, Fig. 3 presents the average monthly load for the specified area.

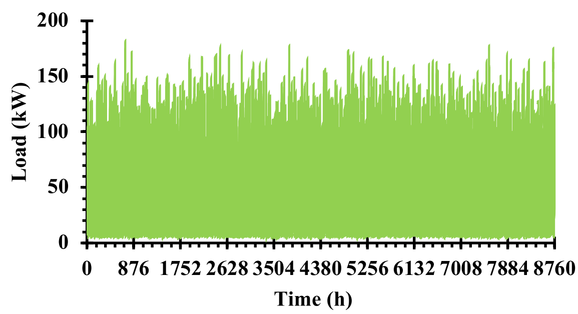

FIGURE 2. Hourly electricity consumption patterns in the research area.

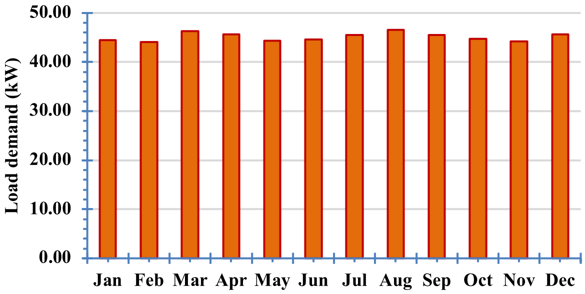

FIGURE 3. Monthly mean electricity consumption for the region.

C. ASSESSMENT OF RENEWABLE ENERGY SOURCES IN THE SPECIFIED REGION

1) POTENTIAL SOLAR ENERGY RESOURCES

NASA's Surface Meteorology and Solar Energy Database is the source of the meteorological data used in HOMER, and the study's analysis of the sites reveals a significant solar energy potential, especially during the dry season months of October to March. However, the sun's energy potential decreases during the rainfall-prone months of April to September. Hourly mean profiles of solar radiation and site transparency index collected in 2020 are shown in Fig. 4. The yearly average solar radiation on Manoka Island is 4.41 kWh/m^2/day. In January, solar radiation is at its maximum, at 5.41 kWh/m^2/day, while in August, it is at its lowest, at 3.45 kWh/m^2/day. Typical monthly transparency index averages range from 0.34 in August (very cloudy) to 0.561 in January (very sunny), indicating a relatively high potential for solar power utilization in the study. Fig. 5 shows the study area has 2675 hours of solar irradiation above 0.20 kW/m^2.

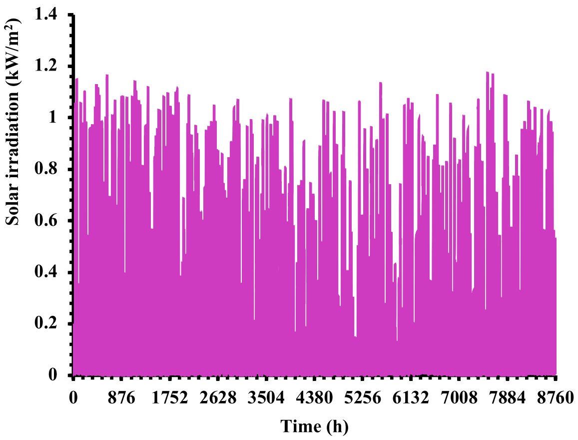

FIGURE 4. Hourly solar irradiation data for the study area.

2) WIND ENERGY RESOURCE POTENTIAL

A wind speed profile in the area was obtained from NASA. According to this data, the average wind speed in this region will be 3.0 m/s. The hourly distribution of wind speed frequency in the region is presents in Fig.6. Wind energy will be a complementary source of energy in cases where solar

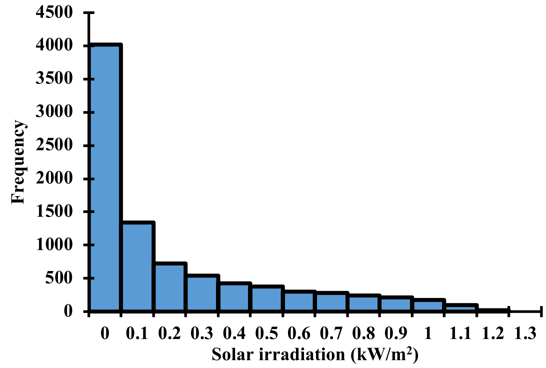

FIGURE 5. Distribution of solar irradiation frequency in the study region.

energy is insufficient. This is why it has become the most widely used energy source in hybrid systems.

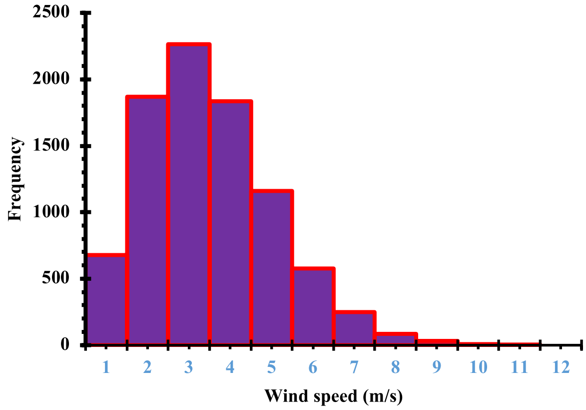

FIGURE 6. Distribution of wind speed frequency for the study region.

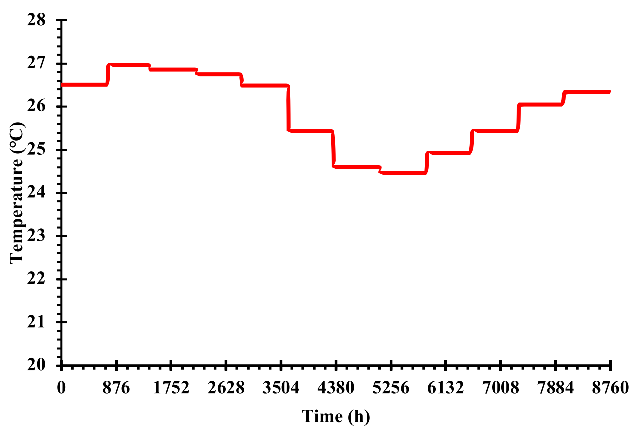

FIGURE 7. Hourly ambient temperature measurement data for the study area.

3) TEMPERATURE

The temperature plays a significant role in influencing the output power and efficiency of a PV system. The productivity of the photovoltaic array and, by extension, its power production, might suffer in warmer environments. An average annual temperature in the study area of 25.89° was observed. The daily temperature values of the region according to the months are presented in Fig. 7.

TABLE 1. Load consumption estimation for location.

Time	Household load				Energy consumed (W.h)
	Types of appliances/ Rating power				
	Led lamp/10W	TV/ 100W	Fan/ 60W	Phone Charger/ 5W	
01:00	2	-	-	5	45
02:00	2	-	-	5	45
03:00	2	-	-	5	45
04:00	2	-	-	-	20
05:00	2	-	-	-	20
06:00	2	1	-	-	120
07:00	-	1	-	-	100
08:00	-	1	-	-	100
09:00	-	1	-	-	100
10:00	-	1	2	-	220
11:00	-	1	2	-	220
12:00	-	1	-	-	100
13:00	-	1	-	-	100
14:00	-	1	-	-	100
15:00	-	1	-	-	100
16:00	-	1	-	-	100
17:00	-	1	2	-	220
18:00	7	1	2	-	290
19:00	7	1	2	-	290
20:00	7	1	2	-	290
21:00	7	1	2	-	290
22:00	7	1	-	-	170
23:00	7	-	-	5	95
00:00	2	-	-	5	45
Total (Wh/day)					**3,245**

4) HOMER (HYBRID OPTIMIZATION MODEL FOR ELECTRIC RENEWABLES)

HOMER is an optimization program developed by the NREL that focuses on microgrid and micropower systems. It is a versatile software tool used for analyzing and optimizing the design and operation of hybrid renewable energy systems. HOMER is the world's most advanced modeling software in the world [42], [43]. This program determines the physical operation of the system, the lifetime cost, which is the sum of operating and installed costs, and the cost per unit (COE) of various combinations. Additionally, it helps to understand the changes and uncertainties when modeling the system. HOMER can model on-grid and off-grid systems with wind turbines, photovoltaic panels, hydroelectric power plants, fuel cells, piston generators, biomass energy, batteries, and hydrogen storage systems feeding loads [44]. There are many variables involved in system design. Designed to circumvent these design challenges, the HOMER software performs three basic tasks: sensitivity analysis, simulation, and optimization. In the sensitivity analysis part, the HOMER program performs a large number of optimization operations to measure the effects of input changes and uncertainties on the system. The optimization process determines optimal values for all variables defined by the system designer. Sensitivity analysis is a valuable technique used to evaluate the influence of variables that are beyond an individual's control [45]. In the simulation phase, the HOMER program analyzes the performance of different system configurations on an hourly basis, providing insights into the technical feasibility and associated costs of each system. Fig. 8 illustrates the methodological process of HOMER software tool.

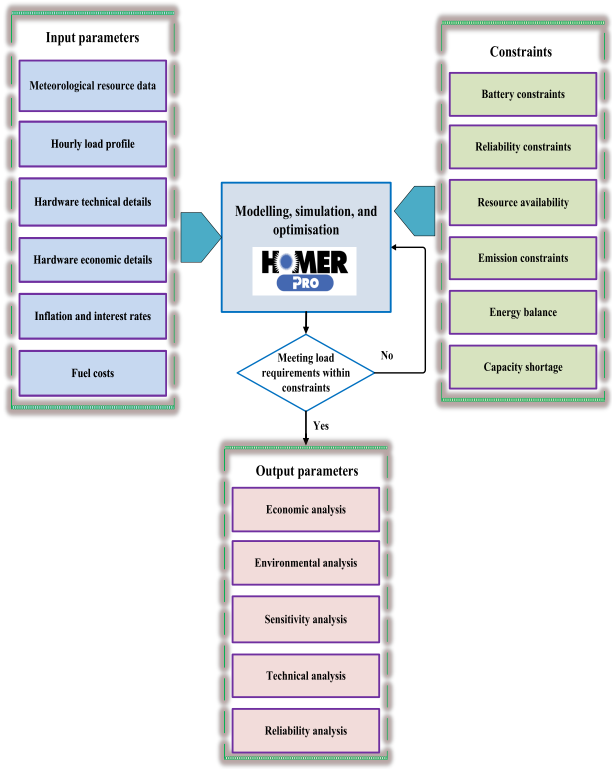

FIGURE 8. Methodology approach for determining optimal solution using HOMER software tool.

III. MODELING OF THE PROPOSED HRES COMPONENTS

The key components commonly found in systems are solar panels, wind turbines, fuel generators, fuel cells, biogas, converters, and batteries. The converters are used to change alternating current (AC) or direct current (DC) based on the desired electrical load. The system to be designed requires AC power. The system uses a fuel cell, wind turbines, and Solar panels to meet the needs. However, if these components are not enough to meet these energy needs, the fuel generator, and the biogas generator will be activated. All of these components are included in the system and the simulations are performed with the HOMER program. Three different simulations were performed to meet the needs of the region. Solar panels, wind turbines, diesel generators, batteries, and solar panels, wind turbines, fuel cells, biogas generators, and batteries are all modeled here. The HOMER diagram of these different scenarios is shown in Fig. 9.

A. SOLAR PANEL MODELING

The solar panel is a major element in the solar energy source. Photovoltaic cells in solar panels change the penetrating radiation directly into direct current. Solar power is a clean, sustainable option for meeting global energy needs [46]. Because of Cameroon's favorable climatic conditions, solar power is the clear front-runner among alternative energy sources [47]. HOMER uses the following (1) to express the power produced by solar panels in terms of solar heat and radiation effects [45]:

$$P_{PV} = y_{PV} \times f_{PV} \times \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}}\right) \times \left[1 + \alpha_P \left(T_C - T_{C,STC}\right)\right] \quad (1)$$

T_C is the cell temperature which is given by (2).

$$T_C = T_{amb} + (0.0256 \times G) \quad (2)$$

where, y_{PV} represents the rated output of PV generator under standard test conditions [kW], f_{PV} is the PV derating factor [%], $\bar{G}_T$ is the Solar radiation incident on the PV generator at current time step [kW/m^2], $\bar{G}_{T,STC}$ is the radiation under standard test conditions [1 kW/m^2], α_P is the temperature coefficient of power [%/^{0}C], T_C is the PV cell temperature at current time step [^{0}C], $T_{C,STC}$) denotes the PV cell temperature under standard test conditions [^{0}C].

Peimar SGM360M panel was used in the system to be designed using the HOMER program. The duration of the panel used is 25 years. Panel cost to be used for 1 kW is $650, the renewal cost is $650, the operating and maintenance cost for one year is $20. To ensure that production losses due to factors like dirt, temperature, shadow, and age do not exceed 80%, the derating factor for the panel to be employed in the system is set at 80%. Technical specificities of the Peimar SG360M panel are illustrated in Table 2.

TABLE 2. Technical data of solar modules [48].

Component	ITEM	Value
Solar panel	Panel power rating (kW)	1
	Normal operating cell temperature (^{0}C)	25
	Derating factor (%)	80
	Efficiency at STC (%)	18.5
	Degradation factor (%)	80
	Ground reflectivity (%)	20
	Duration (years)	25

TABLE 3. The economic characteristics of the wind turbine [48].

Component	ITEM	Value
Wind turbine	Acquisition costs ($)	50.000
	Replacement costs ($)	50.000
	Operation and maintenances cost ($)	500
	Lifetime(years)	25

B. WIND TURBINE MODELING

One sustainable energy option is wind turbines, which use the wind's kinetic energy to generate electricity. Tower power plants, speed converters, circuits for electricity and electronics, and blades are the main components of wind turbines. The price of energy changes depending on the source used [49]. Wind turbines are a viable option for lowering utility bills. Since wind turbines have such high installation costs, low-capacity wind generators are generally disregarded. Nevertheless, 10 kW wind turbines were used for this research. This choice was selected to provide a reliable energy supply for the area at a low cost of installation. Choosing 10 kW wind farms may lower both initial investment and ongoing maintenance costs, making them a realistic option for the research site. The research assumes a 25-year lifespan for wind turbines and provides height estimates between 24 and 30 meters. Table 3 shows the financial benefits of using wind turbines. Wind turbine output power is given by (3) [49]:

$$P_m = 0.5 \rho A C_P v^3 \quad (3)$$

The swept area of the rotor (A), the wind speed (v), and the power output of the wind module (Pm) are the inputs into the efficiency equation (C_P). You may briefly describe the major factors in this equation as follows: One may double the wind generator's output by increasing the rotor's swept area, since the power output is proportional to the square of the swept area. (2) A wind turbine's output power is proportional to the cube of the wind speed, therefore even a little increase in wind speed may have a substantial impact on the turbine's output. The power equation for a sizable wind turbine, considering the significance of gear and generator efficiencies, can be formulated as follows (4):

$$P_m = 0.5 \rho A C_P v^3 N_g N_b \quad (4)$$

In this context, N_g represents the efficiency of the generator, while N_b denotes the efficiency of the gearbox.

C. BATTERY MODELING

When the amount of energy produced by renewable sources exceeds the amount of energy needed to run the system, batteries play a vital part in system modeling. Then, when the generated power is inadequate, they feed the system with the energy they have saved. These batteries store and transmit energy in the form of alternating current (AC) voltage.

Given the relatively high price of batteries, understanding how many you have in your system is crucial [50]. The

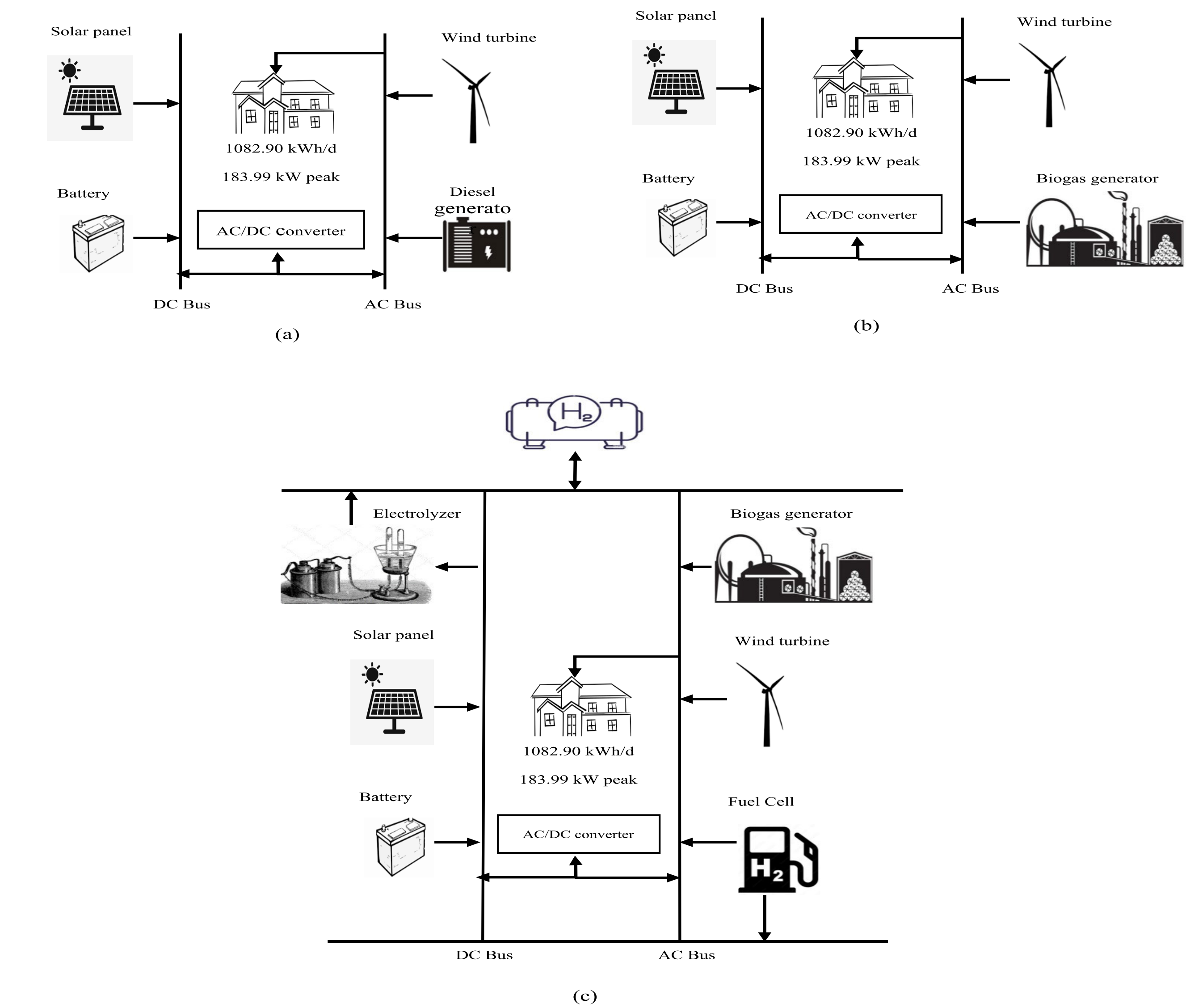

FIGURE 9. **Hybrid energy system (a) Scenario 1, (b) Scenario 2, and (c) Scenario 3.**

simulation accounts for around \$450 for 1 kWh of the batteries to be utilized in the system, \$450 every renewal, and \$20 per year for overall operation and maintenance. Between 15 and 25 years is what scientists think the battery will last. Additionally, the simulation's battery depth was 80%. Table 4 displays the used battery's technical parameters. Both (5) and (6) below [51] depict the charging status of a battery.

$$E_b(t+1) = E_b(t) \times (1-\sigma) - \left(\frac{E_l(t)}{\eta_{cnv}} - E_g(t)\right) \times \eta_{BD} \tag{5}$$

$$E_b(t+1) = E_b(t) \times (1-\sigma) - \left(E_g(t) - \frac{E_l(t)}{\eta_{cnv}}\right) \times \eta_{BC} \tag{6}$$

In which the energy required $E_l(t)$ and the power produced $E_g(t)$ are given. The battery's discharge efficiency is given by η_{BD} and charge efficiency is given by η_{BC} respectively. Battery self-discharge is represented by the parameter. Efficiency of the converter is denoted by η_{cnv}.

TABLE 4. **Technical specificities of the battery [48].**

Component	ITEM	Value
Battery	Rated voltage (V)	6
	Rated capacity (kWh)	1
	Nominal capacity (A)	167
	SOC limits (%)	20-100
	Percentage of roundtrip efficiency (%)	90
	Maximum charging current (A)	167
	Lifetime (years)	15

D. DIESEL GENERATOR MODELING

A diesel generator is employed as part of the study's power infrastructure. The HOMER program specifications for an

Auto size Genset generator were followed, and a fuel-powered 180 kW generator was installed. Diesel generator renewal costs were also fixed at \$550 per kilowatt-hour. Simultaneously, operational and maintenance expenditures per hour were estimated at \$0.030. There is a 15,000-hour lifespan for the generator. 5.36 liters of diesel fuel are needed per hour to power the generator. Using the exchange rate from March 20, 2023 (\$1 = 608,59FCFA) set by the Bank of Central African States (BEAC), the cost of diesel for the diesel generator is \$1.18 per liter. To calculate how much fuel a diesel generator uses, we may use the following formula [47]:

$$F_{dg} = B_g \times P_{dg} + A_g \times P_{dg-out} \tag{7}$$

where P_{dg-out} represents a DG output power, P_{dg} represents the DG rated power, A_g and B_g are the fuel consumption constant coefficient constant which are approximately the values 0.246179 l/kW and 0.08415 l/kW respectively. Emissions and properties of fuel are shown in Table 5 below.

TABLE 5. Emissions and properties of diesel fuel.

Component	ITEM	Value
Diesel generator	Lower calorific value (milligrams/kilogram)	43.2
	Concentration (kilogram/meter cube)	820
	Carbon level (%)	88
	Sulphur level (%)	0.4
	Carbonic oxide (g/L fuel)	16.5
	Nitrogen oxides (grams/litre combustible)	15.5
	Uncombusted hydrocarbons (grams/litre combustible)	0.72
	Particle size (grams/litre combustible)	0.1
	Sulphur dioxide (%)	2.2

E. BIOGAS GENERATOR MODELING

The system also makes use of a biogas generator. Methane, which is found in biogas, may be used as a chemical energy source. The biogas is burned in a reactor at a sub-stoichiometric temperature to produce steam in a biogas generator. The steam is then piped into a turbine, where its rotational energy is transformed into mechanical power. A generator is linked to this turbine, allowing power to be produced. To ensure the feasibility of a biogas plant, it is important that the biogas is produced with a high concentration of methane, while keeping the carbon dioxide levels low. Additionally, the production process should be designed to maintain a high calorific value of the gas. Heating value of red pine pellets was included in the simulation at 17 MJ/kg. The red pine pellets for the biogas generator will be taken from the plant in the desired quantity. The cost of red pine pellets for 1 ton was calculated at \$50 and simulations were run. The cost of the preferred biogas generator for 1 kW is calculated at \$1000, the renewal cost is \$1000, and the operation and maintenance cost are calculated at \$0.30 per 1 hour. The biogas generator used in the system has a capacity of 30 kW. The generator has a life expectancy of 20,000 hours [20].

F. FUEL CELLS MODELING

A fuel cell is an electro-chemical system that makes use of hydrogen as a source and produces heat and electricity. The generic fuel cell defined in the HOMER program has been included in this system. Installation costs are \$3000 per kilowatt (kW), operating and maintenance costs are \$300 per kilowatt (kW), and replacement costs are \$2700 per kilowatt (kW) [52]. Terminal voltage (V_T) and hydrogen consumption (N_H) may be calculated statistically using the methods in (8) and (9) [53].

$$V_T = E - V_{CI} - V_{Loss} \tag{8}$$

$$N_H = \frac{I_{FC}}{C_I} \tag{9}$$

The preceding formula requires the values of E for the Nernst voltage formed internally, C_I, for the internal capacitance, V_{CI} for the voltage generated by the internal capacitance, V_{Loss} for the FC's resistive loss, I_{FC} for the FC's output current

Nernst voltage can be expressed mathematically as:

$$E = N\left[E_o + \frac{RT}{2C_I} log\left[\frac{\rho_{h2}\rho_{o2}^{0.5}}{\rho_{h2o}}\right]\right] \tag{10}$$

where N is the total number of FCs in series, E_o is the FC's open-circuit voltage, R is the universal gas constant, T is the temperature, ρ_{h2} is the partial pressure of hydrogen in atmospheres, $\rho_{o2}^{0.5}$ is the partial pressure of oxygen in atmospheres, and ρ_{h2o}. is the partial pressure of water in atmospheres.

G. ELECTROLYZER MODELING

The component of the system that carries out the electrolysis process and ensures the production of hydrogen at the end of the process is called the electrolyzer. The electrolyzer used in the system is a generic electrolyzer defined in the HOMER program. It has an 85% success rate and a duration of 15 years. The total power of the electrolyzer is up to 100 kW. Economic characteristics of electrolyzers are evaluated as follows: installation price \$2000/kW, cost of operation and maintenance \$200/kW, and renewal cost \$1800/kW [54]. In (11) [55], the rate at which hydrogen is generated by the electrolyzer, q, is represented as follows:

$$q = \eta_f \frac{N_s I}{2F} \tag{11}$$

Here, η_f, stands for Faraday efficiency, N_s, for the number of series-connected cells, I for the electrolyzer current, and F for the Faraday constant.

H. HYDROGEN TANK MODELING

The simplest method for storage of the hydrogen obtained in this electrolyzer as compressed gas is the use of hydrogen tanks. According to this study, this tank costs between \$1000 and $1600 for 1kg [56]. The economic data of the hydrogen tank was selected as follows: installation cost $1500/kg, operation, and maintenance cost $150/year, renewal cost $1350/kg, and lifetime 25 years [57]. The hydrogen tank with economic data is included in the system as a generic hydrogen tank defined in the HOMER program. The size of the hydrogen tank was chosen as 0 kg, 100 kg, and 200 kg and simulations were performed. The reason why three different tank sizes were defined for the system is to find the most appropriate tank size. The power needed to compress P is expressed with the formula in (12) [55]:

$$P = \frac{\Upsilon}{\Upsilon - 1} R \frac{T}{\eta_{comp}} \left[\left(\frac{P_2}{P_1} \right)^{\frac{\Upsilon}{\Upsilon-1}} - 1 \right] \tag{12}$$

The coefficient stands for the polytropic effect, R for the gas constant, T for the input temperature, comp for the compression efficiency, P_1 for the inlet pressure, and P_2 for the discharged pressure in this equation.

To determine how much hydrogen is in the tank, we may use the following (13).

$$P_{tank} = \frac{RT}{V} N_{tank} \tag{13}$$

where V is the total volume of gas in the tank and N_{tank} is the total mass of gas in the tank (in moles).

I. CONVERTER

A power merger is needed to ease the flow of energy between AC and DC buses. In HOMER, this is accomplished through a converter that reverses alternating current (AC) back into direct current (DC). During the simulation, a HOMER-defined generic converter was used. The converter's efficacy is found by solving for (14) [58].

$$\eta_{cnv} = \frac{P_{output}}{P_{input}} \tag{14}$$

where P_{output} is the power going out of the converter and P_{input} is the power going into it. The integrated converter has a 95% efficiency rate, a 25-year lifespan, and a cost of $985 per kilowatt-hour (kW-h) for installation and $887 for replacement. Every year, $92 is spent on upkeep and repair [59].

IV. PROBLEM FORMULATION

HOMER models the search space to determine the best grid arrangement and then simulates the resulting systems. Initially, an optimization problem is formulated in which the objective function is specified.

A. OBJECTIVE FUNCTION

The objective of this study is to compute the NPC and COE associated with (15) and (18) respectively with reliability constrained Integrated Renewable Energy.

B. SYSTEM RELIABILITY

The dependability of a system is measured by how well it performs in the face of intermittent power losses lasting no more than a few hours. There may be numerous of these interruptions every year. Resilience is the ability to continue functioning despite interruptions in service. If the power goes out, the system may keep running if it has energy storage or a backup generator. The LPSP method is also used to evaluate the system's dependability.

C. NET PRESENT COST (NPC)

The NPC of a component is the difference between its current level of payment during the life of a project and its current level of revenue during the same period. It can be evaluated by (15) as follows [60], [61]:

$$C_{NPC} = \frac{C_{ann,tot}}{CRF\left(i, R_{proj}\right)} \tag{15}$$

where $C_{ann,tot}$ [$/year] is the overall cost over a year, which includes the cost of ownership, the cost of replacement, the cost of O&M, the cost of emissions, and the cost of fuel for the generator. $CRF\left(i, R_{proj}\right)$ is a function that delivers the return on capital (CRF). The annual effective discount rate [%], and the duration of the project R_{proj} [year] is determined by (16) [60], [62], [63]:

$$CRF\left(i, R_{proj}\right) = \frac{i\,(1+i)^{\tau}}{(1+i)^{\tau} - 1} \tag{16}$$

where τ represents the plant's expected lifespan (in this case 25 years).

D. NET DISCOUNT RATE (I)

The actual interest rate employed in converting among annualized and in-time charges is what is known as the "net discount rate" in HOMER Pro. To get the effective interest rate, Homer uses the following (17) formula [60]:

$$i = \frac{i' - f}{1 + f} \tag{17}$$

The above expression represents the yearly percentage rate of inflation plus the nominal interest rate. The annual inflation rate in Cameroon in January 2023 is 3.25%, while the net discount rate is 4.20% [64].

E. COST OF ENERGY (COE)

The COE, additionally referred to as the leveled cost for electricity (LCOE), is the cost each kilowatt-hour of electricity produced at a plant. By dividing the annual cost of electricity generation by the total power demand, as shown in formula (18) above [58], we may get the COE.

$$COE = C_{NPC} \times CRF \Big/ \sum_{t=1}^{8760} E_{gen} \tag{18}$$

where E_{gen} electricity that comes from both the power grid and a microgrid combined (MG). It is obtained by the relation

(19).

$$E_{gen} = E_{gen_{MG}} + E_{gen_{grid}} \quad (19)$$

where $E_{gen_{MG}}$ stands for the energy generated by the micro-grid whereas $E_{gen_{grid}}$ is purely grid-based power.

Concerning stand-alone MG systems, energy generated by the grid is given by (20).

$$E_{gen_{grid}} = 0 \quad (20)$$

F. UNCOVERED LOAD

Equation (21) [65], [66] provides a definition for the uncovered load, which represents the ratio of the annual uncovered load to the total annual load.

$$Unmet\ Load = \frac{Annual\ Non-served\ Load}{Annual\ Entire\ Load} \quad (21)$$

V. RESULTS AND DISCUSSIONS

A. OPTIMIZATION RESULTS

In this study, the HOMER software was used to simulate and assess three different off-grid hybrid systems. The simulation was used to determine the unit energy costs and capital expenditures for three distinct scenarios. The outcomes of the ideal case scenario are shown in Table 7.

PV/WT/Battery/Generator systems are used in all optimization procedures. The distinguishing characteristics of the different hybrid systems include the diesel generator, biogas generator, and fuel cell generator. In the first, second, and third situations, respective power sources included diesel generators, biogas generators, and fuel cells and biogas generators. According to the study, Scenario 3—which uses PV, WT, FC, and biogas—offers more affordable alternatives, and by using load monitoring as part of the optimization process, the number of batteries needed by the systems may be decreased. Scenario 3's levelized cost per kilowatt-hour is $0.1981, and its net present value is $2,209,741. Due to the use of fuel cells, the system's net present cost and per-unit energy cost are substantially lower than those of other systems, which greatly lowers the need for PV panels.

In Scenario 2, the biogas generator combination was the answer, and as a result, the system's LCOE and NPC were higher than in Scenario 3. It was noted that Scenario 2 had a net present value of $4,110,257 and the lowest energy cost at $0.3685 per kilowatt-hour. The levelized cost for Scenario 1's PV panels, wind turbine, battery, and diesel generator were $0.323 per kilowatt-hour, with a net present value of $3,612,896. Comparatively speaking, this system is more lucrative than Scenario 2's system. Additionally, the findings showed that none of the setups under consideration had any unmet loads. Additionally, it was found that for Scenarios 2 and 3, the biogas generator was followed by PV modules, which made a considerable contribution to energy generation.

In Scenario 1, the diesel generator produced the most power, followed by PV modules.

Statistics on emissions for each scenario are included in Table 6. Table 6 demonstrates that, when compared to Scenarios 1 and 3, Scenario 2 has the greatest favorable effects on the environment. In Scenario 3, the system emits 21.069 kg/year of carbon dioxide as opposed to Scenarios 1 and 2's emissions of 76.203 kg/year and 0.291 kg/year, respectively. According to the outcomes shown in Table 6, a PV/WT/FC/Biogas system may have significant advantages even if its renewable energy factor and environmental emissions are significantly greater than those of Scenario 2.

TABLE 6. Emission values for all configuration.

Quantity	Value		
	Scenario 1	Scenario 2	Scenario 3
Carbonic oxide (kg/yr)	76,203	0.291	21,069
Carbonic acid (kg/yr)	480	0.0305	3.84
Natural gas (kg/yr)	21	0.013	0.0731
Micro particle (kg/yr)	2.91	0.00185	0.0102
Hydrogen sulphate (kg/yr)	187	0	0
Nitrous oxides (kg/yr)	451	0.0287	1.79

B. EFFECT OF THE WIND TURBINE ON THE SYSTEM

Fig. 10 depicts the average daily and seasonal wind turbine power production for the three distinct system designs used to create Scenario 3. The velocity of the wind and quantity of generation needed by the system will determine how much electricity wind turbines can produce in the chosen location.

The combined wind turbines generate 2,628 kWh/year when operated for 4,700 hours per year, as illustrated in Fig. 10.

The unit cost of the electrical energy produced is $1.04 kWh, the average power of the wind turbines will be 0.3 kW, and capacity factor will be 3%. As can be seen through a year, wind turbines were mostly used in June, July, and August. This is because wind turbines generate the necessary electrical energy during the rainy months when the solar panels cannot provide or are not sufficient on their own. Due to the location of the selected area, the amount of energy obtained from the solar panel will be the main energy source for this system.

C. EFFECT OF SOLAR PV ON THE SYSTEM

Fig. 11 illustrates power output values obtained from the solar panels used in Scenario 3 at different days and times of the year. Due to the location of the selected region, the energy obtained from solar panels will be the main energy source for the system. At the same time, the high capacity of the panels allows more energy to be produced in a short period. The solar panels selected for the system operate 4,397 hours per year and produce a total of 177,990 kWh/year of electrical energy. The module has an average daily production of 1,273 kW/h, a capacity factor of 14.5%, and the PV penetration is 45%. The maximum capacity of the solar panels integrated into the system is 140 kW. The unit cost of the electrical energy produced by the panel will be $0.0338/kWh.

TABLE 7. Summary of optimization results.

Item	Component	unit	Best hybrid system		
			Scenario 1	Scenario 2	Scenario 3
System configuration	Solar panels	kW	596	931	140
	Wind turbines	kW	10	10	10
	Batteries	Quantity	1,139	1,277	201
	Fuel cell	kW	-	-	30
	Electrolyzers	kW	-	-	100
	Hydrogen Tanks	kg	-	-	100
	Biogas generator	kW	-	210	210
	Diesel generator	kW	210	-	-
	Dispatch strategy	LF or CC	LF	LF	LF
Cost	LCOE	$/kWh	0.3239	0.3685	0.1981
	NPC	$	3,612,896	4,110,257	2,209,741
Energy generation	Solar panels	kWh/yr	758,481	1,185,065	177,990
	Wind turbines	kWh/yr	2,628	2,628	2,628
	Biogas generator	kWh/yr	-	12,279	240,821
	Diesel generator	kWh/yr	36,955	-	-
	Fuel cell	kWh/yr	-	-	51,664
	Unmet loads	kWh/yr	0	0	0

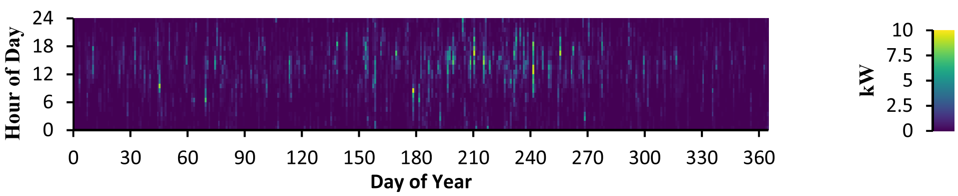

FIGURE 10. Wind turbine power output in scenario 3.

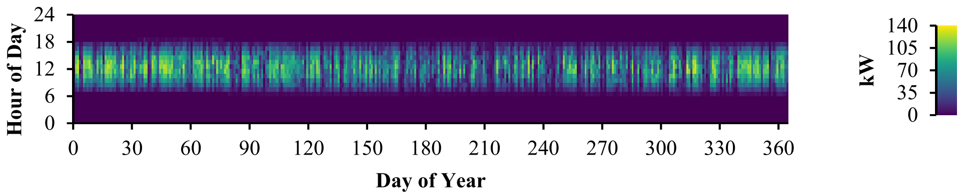

FIGURE 11. PV power output in scenario 3.

D. EFFECT OF THE BIOGAS GENERATOR ON THE SYSTEM

As shown in Fig. 12, the biogas generator produced the highest amount of energy at night. During this time, most of the production was supplied to the user during the rainy season. The biogas generator integrated into the system operated 966 times per year, 2,653 hours per year, and produced a total of 240,821 kWh of electrical energy. The fuel consumption rate of the generator is 0,295 kg per kWh and the annual fuel consumption is 102 tons.

E. EFFECT OF FUEL CELL GENERATOR ON THE SYSTEM

Fuel cell generators use hydrogen as fuel. The hydrogen to be used is generated by electrolyzing water in an electrolytic cell. The electrical power to be used for water electrolysis is provided by the surplus electrical power in the system. Hydrogen tanks are used to store the resulting hydrogen. In other words, these renewable power systems are integrated into energy storage and production systems. The results from the fuel cell generators are shown in Fig. 13.

In scenario 3, the additional power requirement for the electrolyzer is 4176.47 kW. The fuel cell generator's power production is shown in Fig. 13 during various times of the day and seasons. Over the course of a year, this system-integrated generator worked for 2,165 hours and produced 51,664 kWh of electricity. The fuel cell generator used 10,849 m^3 of hydrogen altogether, or 0.210 m^3/kWh, over this time period. The system's noon electrical supply was generated by the

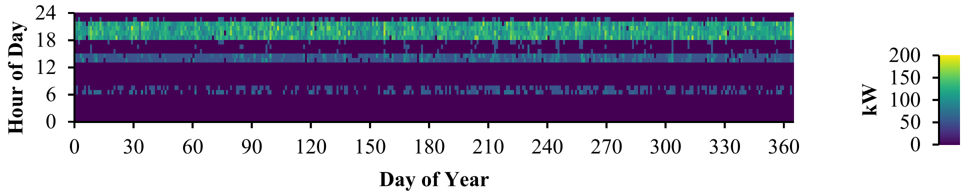

FIGURE 12. Power output from biogas generator in scenario 3.

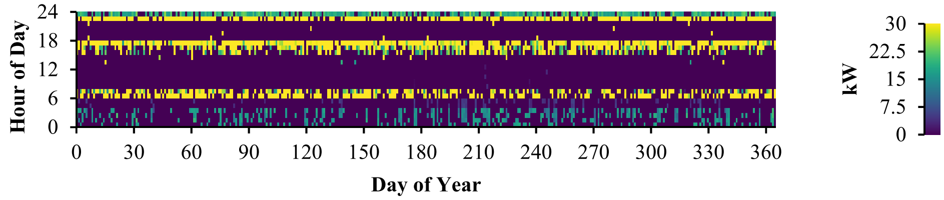

FIGURE 13. Fuel cell power output in scenario 3.

generator. It hardly moved at all. Typically, it would begin in the late afternoon and continue until the morning. This is because solar panels don't begin providing enough electricity until midday. The efficiency of the electrolyzer used to create hydrogen should also be assessed. Fig. 14 depicts the electrolyzer's monthly energy usage.

The electrolyzer is a device that is only manufactured in January, as shown in Fig. 14. This system's integrated electrolyzer generated 90 kg annually. The electrolyzer with a power output of 100 kW was used for the simulation. An electrolyzer producing 3–5 kW of electricity is suitable for this setup. The hydrogen tank is a part of the system that is used to store hydrogen until it is required.

Previously, 100 kilogram and 200 kg hydrogen tanks were available. Once 90 kg of hydrogen have been produced, they are placed in a storage tank. With these factors in mind, a 100-kilogram hydrogen tank should be plenty. The monthly quantity of hydrogen contained in the tank is seen in Fig. 15. In the app, 100 kilograms of hydrogen may be used to store 3,333 kilowatt-hours of power.

F. EFFECT OF USING BATTERY ON THE SYSTEM

The use of batteries in these systems significantly increased the system cost. Table 8 shows the net present values and unit energy prices of the systems for 3 scenarios, along with the number of batteries they contain.

TABLE 8. NPC and COE of the systeMS.

Scenario	Number of batteries	NPC ($)	COE($/kWh)
1	1,139	3,612,896	0.3239
2	1,277	4,110,257	0.3685
3	201	2,209,741	0.1981

In scenarios 1 and 2, with battery counts of 1,139 and 1,277 respectively, the higher costs can be attributed to the increased number of batteries compared to scenario 3. This difference in battery quantity directly influences the overall expense of these scenarios.

As can be seen, increasing the amount of batteries significantly increased the system cost. In scenario 2, where the number of batteries is 1,277, the energy cost is $0.3685, while scenario 3 with 201 batteries has a unit energy cost of $0.1981. Based on this information, unit energy cost and NPC decrease as the number of batteries in scenario 3. Fig. 16 displays the integrated battery's hourly charge level data over the course of a year.

G. ENERGY BALANCE OF THE SYSTEM

The assessment relies on the contribution of each of the components to overall output. The load is met by the interplay of the system's solar generator, turbine for wind power, biogas power source, and fuel cell while it is operational. If the total output falls short of the load requirement, the storing system is activated, as shown in Fig. 17. Fig. 17 shows the monthly energy produced by system components. As illustrated, power supply is mainly provided by Solar panels and biogas generators. According to the values shown in Fig. 17, solar panels followed by biogas generators account for a significant share of energy production. The fuel cell generator and wind turbines are less significant in energy production. Surplus electricity generation in the whole system is 61,234 kWh per year, the unmet electrical load is 0 kWh per year as shown in Fig. 18. The capacity deficit is 0 kWh per year.

Fig. 19 shows the power generated by each source and the total electrical load served for a defined period of 250 hours of the year. This helps with a better understanding of how the system operates.

H. COST-BENEFITS ANALYSIS

The results presented in Table 9 and Fig. 20 show that the project has the potential to provide long-term advantages with a payback time of 8.76 years throughout the project's

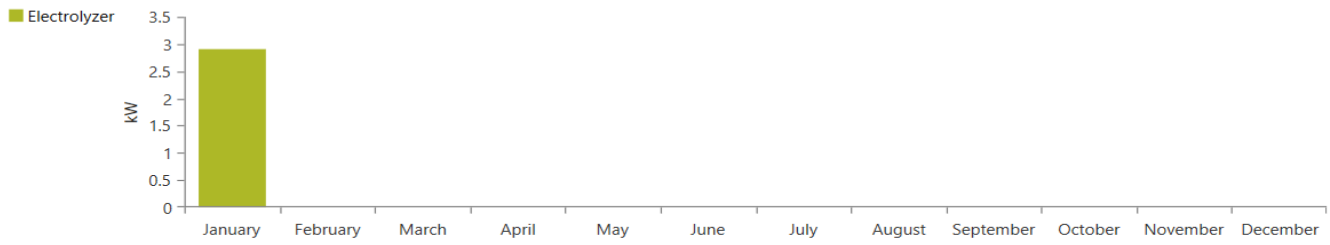

FIGURE 14. Average energy use in the integrated electrolyzer.

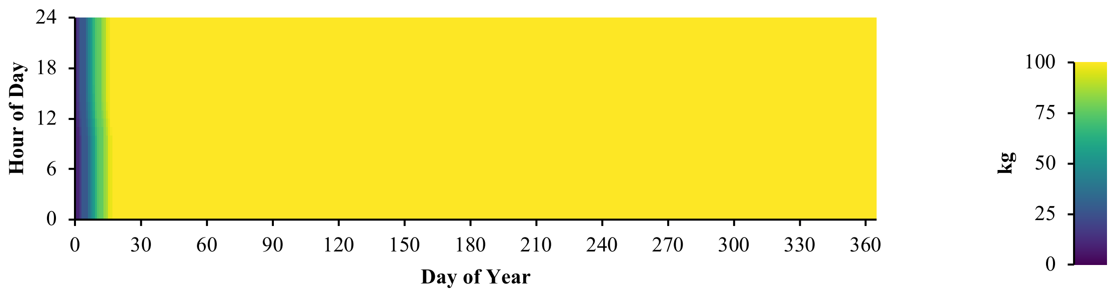

FIGURE 15. Monthly amount of hydrogen stored by the hydrogen tank integrated in the system.

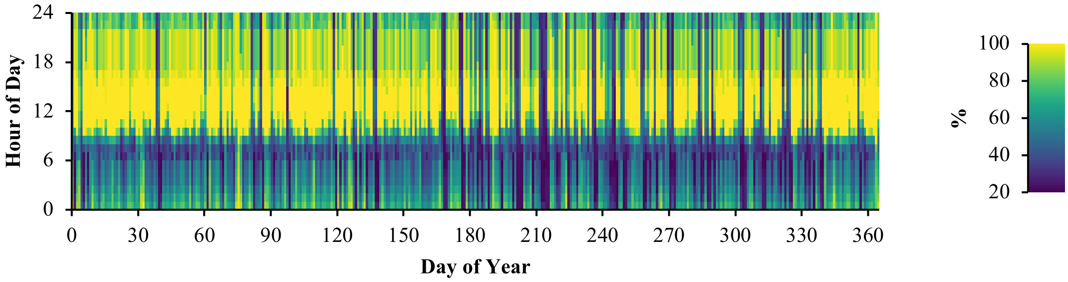

FIGURE 16. Battery charge status during the year.

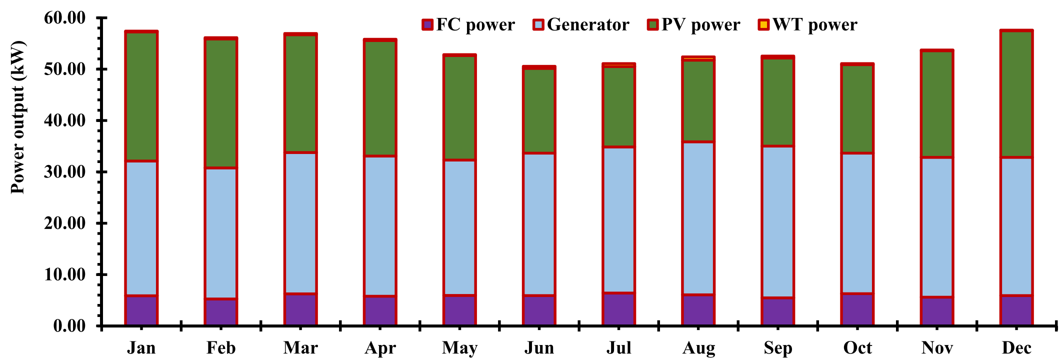

FIGURE 17. Monthly average electricity production for optimal HRES in scenario 3

25-year life and little outlay of funds. However, technological and material developments make it possible for solar cells to have a lifespan greater than 25 years. Thus, using solar PV modules with a lifespan of up to 40–50 years can help the project even more. Additionally, the number of batteries used in the simulation was taken into account as a comparison criterion, and the HOMER simulation revealed that the most cost-effective arrangement had 201 batteries. For an electricity cost of \$0.1981/kWh, an internal rate of return (IRR) of 9.09%, and a return on investment (ROI) of 6.19%, the

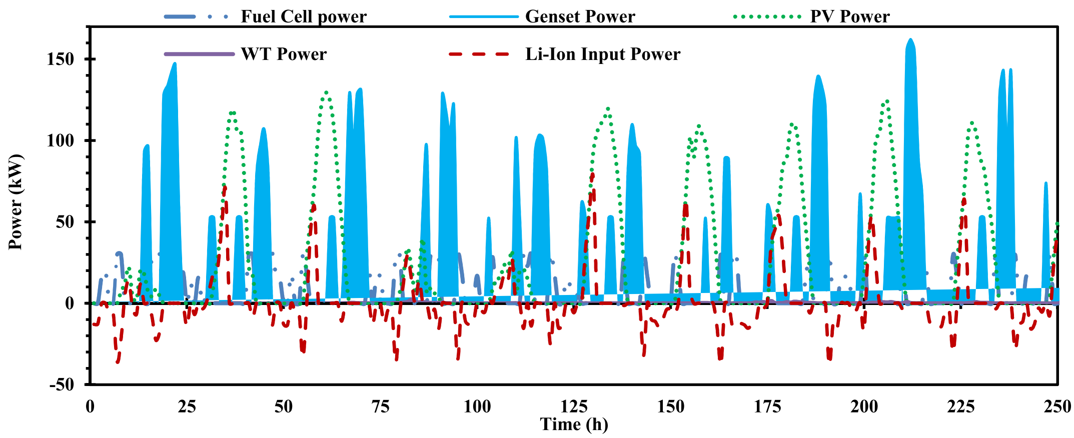

FIGURE 18. Time series data for electrical unmet load, excess electricity and renewable power

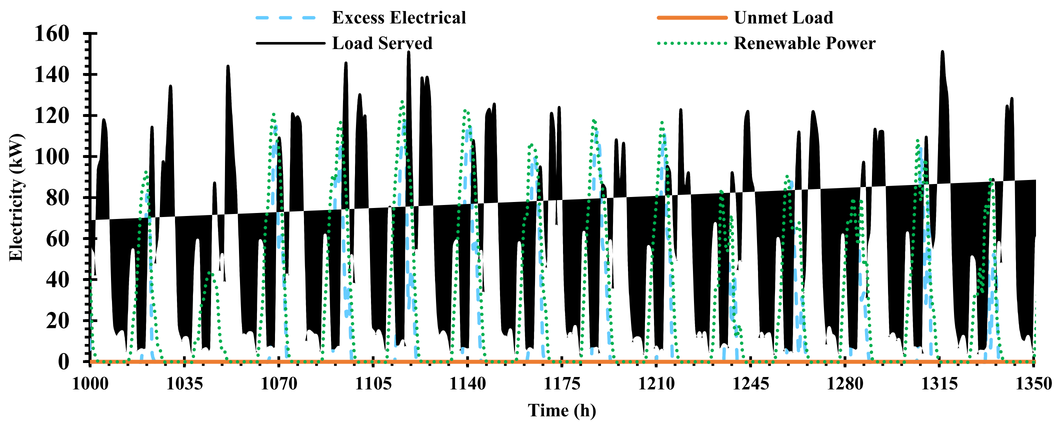

FIGURE 19. Time series data for electricity production from different power

project profit over 25 years in this case is $57,387. These storage systems also have a positive impact on the economic calculations, especially the reduction of payback time.

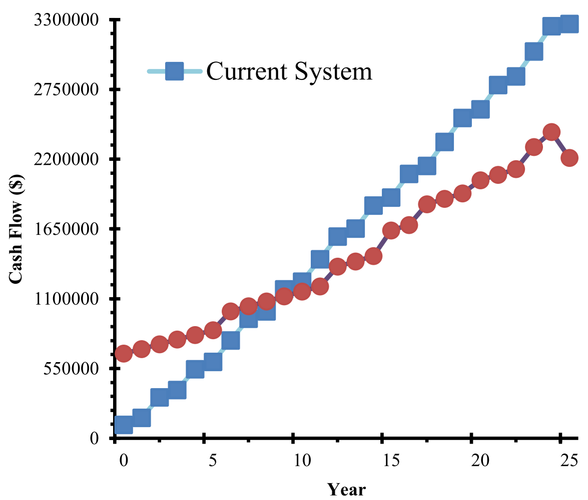

FIGURE 20. Cumulative cash flow over project lifetime

Fig. 21 shows the nominal cash flow of base case the most optimal plan for scenario 3 for the duration of 25 years. Minimum cash flow is maintained for the optimal plan throughout the project lifetime, while the cash flow for the base case is continuously increasing until it reaches the maximum value at the end of the entire project life.

TABLE 9. Financial evaluation of the projects.

Economic indicators	Values
Simple payback period	8.76 yr
Return on Investment	6.19 %
Internal Rate of Return	9.09 %
Net Present Value	$1.06M
Capital Investment	$562,824
Annualized Savings	$57,387

Table 10 presents a comparative analysis of the stand-alone hybrid renewable energy systems (HRES) investigated in this research, in relation to similar studies conducted in the residential sector as documented in the literature. Upon examination of Table 10, it becomes evident that the findings of the research in the existing literature exhibit variations both among themselves and in comparison, to the current HRES under investigation.

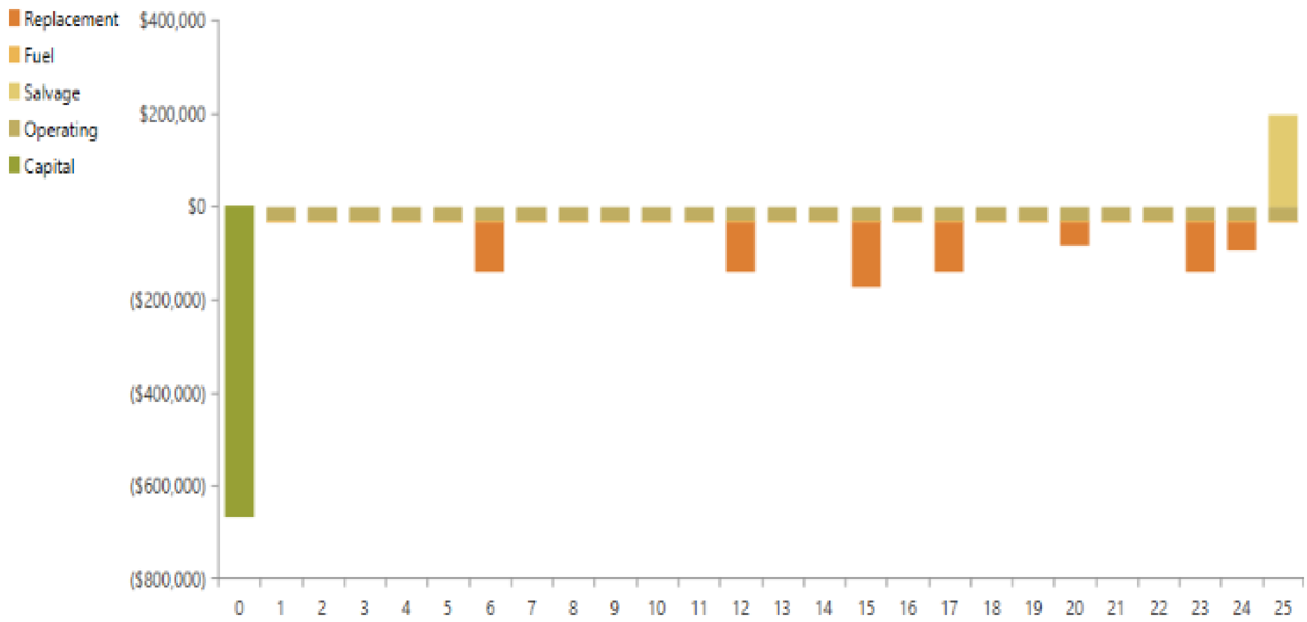

FIGURE 21. Nominal cash flow results.

TABLE 10. Comparison of the results of present HRES with other research studies.

System configuration	System component	COE ($/kWh)	NPC ($)	CO_2 (kg/yr)	RF (%)	Reference
Islanded	PV/WT/DG/BESS	0.198	643,647	264,55	64.5	[18]
GRID-TIED	GRID/PV/WT/BESS	UNKNOWN	1812	1804	UNKNOWN	[19]
GRID-TIED	GRID/PV	0 .0382	4378	UNKNOWN	UNKNOWN	[20]
Islanded	PV/WT/DG/BESS	0.137	722,356	84007	64	[21]
Islanded	PV/DG/BESS	0.430	286,315	63061	33	[22]
Islanded	WT/BESS	0.309	148,486	0	100	[23]
GRID-TIED	GRID/PV/BESS	0.27-0.5217	UNKNOWN	UNKNOWN	UNKNOWN	[24]
GRID-TIED	GRID/PV/BESS	0.071-0/092	6682-8819	52.7-1730	54-61	[25]
GRID-TIED	GRID/PV	UNKNOWN	1,366 .9	UNKNOWN	UNKNOWN	[26]
Islanded	PV/DG/BESS	UNKNOWN	9,159.6	44.5	UNKNOWN	
GRID-TIED	GRID/WT/PV/BESS	0.037-0219	1,627,833-3,589,056	40,959-614,386	53-96.8	[27]
Islanded	WT/PV/BESS	0.288-0.695	4,060,031-8,925,135	0	100	
Islanded	PV/DG/BESS	0.21	110,191	27,678	44.7	[28]
Islanded	PV/WT/DG/BESS	0.459-0.562	10,733-17,123	0-681	UNKNOWN	[29]
Islanded	PV/WT/DG/BESS	0.198-0348	23,372-40,858	182-503	91.20-96.60	[8]
Islanded	PV/WT/DG/FC/BG/BESS	0.1981	2,209,741	21,069	92.3	Present study

The variations in NPC, COE, RF, and CO_2 (carbon dioxide levels) shown a strong correlation with solar radiation, wind speed, load demand, and the geographical site where the investigation was carried out. Nevertheless, as a result of Cameroon's abundant solar radiation and wind speed, it often exhibits a lower levelized cost of electricity (NPC) and cost of energy (COE), a larger renewable fraction (RF), and lower carbon dioxide (CO_2) emissions in comparison to the studies cited in Table 10.

VI. CONCLUSION

Manoka Island is part of the Douala VI district in Cameroon's coastal area, and this research looked at how off-grid hybrid systems may help satisfy the island's electrical demands. The

HOMER program used the collected data to compare and simulate different systems. Three different scenarios were simulated in the HOMER program. While the wind turbine, solar panel, and batteries were used in all scenarios, the biogas generator was added in Scenario 1, the diesel generator in Scenario 2, and the fuel cell and biogas generator in Scenario 3. Based on the simulation results of all scenarios, Scenario 3 is the most appropriate hybrid system when considering unit energy cost and net present values. The energy cost, net NPV, installation, operation, and maintenance cost of Scenario 3 are calculated as $0.1981, $2,209,741, $667,824, and $54,634.20, respectively. The most cost-effective arrangement had 201 batteries, resulting in a project profit of $57,387 with an IRR of 9.09% and ROI of 6.19% and a payback period of 8.76 years for the 25-year.

Although the shares of the fuel cell and wind turbine in meeting total energy needs are small, they have met the required load when the solar panel, the second energy source, is not producing energy. In addition, one of the advantages of this system component is the abundance of biogas in the location for production. At the same time, because the system's fuel cell generator stores the extra energy in the form of hydrogen for further use when needed, the number of batteries in the system is quite small compared to other scenarios. This reduces the cost of scenario 3 and makes the system more advantageous. In these evaluations, solar panels, wind turbines, biogas generators, fuel cell generators, and battery systems are the most appropriate systems that can be installed in the selected region among the simulated systems.

However, understanding the practical difficulties of hybrid system configuration requires implementation. In the near future, the price per kWh of power supplied by hybrid power plants will be more advantageous than the unit cost of conventionally produced energy because of the decline in renewable energy elements due to technical advancement and the increase in costs owing to the degradation of fossil fuels. This research shows that an electrified region of Cameroon may benefit from an optimized PV/WT/FC/Biogas/Battery-based system in terms of economic and social growth, energy security, and the sustainable usage of existing renewable resources.

Looking forward, it is important to acknowledge the limitations of this study. Our research focused on a specific case study, and as such, the results may not be directly transferable to other geographical or socioeconomic contexts. Additionally, the sensitivity of our findings to variations in assumptions highlights the need for ongoing data collection and refinement of analytical models.

To pave the way for future research endeavors, it is recommended to explore the following directions:

- Further investigate the integration of emerging energy storage technologies and smart grid concepts into hybrid systems to enhance efficiency and adaptability.
- Conduct comprehensive environmental impact assessments to quantify the broader sustainability benefits of hybrid systems in reducing carbon emissions.
- Evaluate the social and behavioral factors influencing energy consumption patterns, which can guide user engagement strategies and enhance system adoption. In addition to that the utilization of excess energy generated by the hybrid system to meet the freshwater or heating demand warrants further investigation.

In closing, this study serves as a foundational step towards sustainable energy solutions for underserved regions. It is our hope that the insights gained here will inspire a broader dialogue and spur innovative research that contributes to a greener and more energy-secure future.

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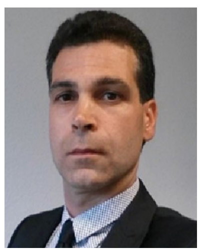

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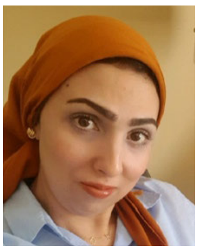

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