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Research Article

Optimization of a Hybrid Off-Grid Solar PV—Hydro Power Systems for Rural Electrification in Cameroon

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The use of decentralized renewable energy systems will continue to play a significant role in electricity generation especially in developing countries where grid expansion to most remote areas is uneconomical. The income levels of these off-grid communities are often low, such that there is a need for the delivery of cost-effective energy solutions through optimum control and sizing of energy system components. This paper aims at minimizing the net present cost (NPC) and the levelised cost of energy (LCOE). The study presents a hybrid power system involving a hydroelectric, solar photovoltaic (PV), and battery system for a rural community in Cameroon. The optimization of the system was done using HOMER Pro and validated using a metaheuristic algorithm known as genetic algorithm (GA). The GA approach was programmed using the MATLAB software. After the HOMER simulation, the optimal power capacity of 3 kW solar PV, 334.89 Ah battery, and 32.2 kW microhydropower was used to meet the load. The village load profile had a daily energy usage of 431.32 kWh/day and a peak power demand of 38.49 kW. The optimized results showed an NPC and LCOE of $90,469.16 and 0.0453 $/kWh, respectively. The system configuration was tested against an increase in hydropower capacity, and it was observed that increasing the hydropower capacity has the ability to significantly reduce the LCOE as well as the battery and solar PV size. A comparative analysis of the two approaches showed that the optimization using GA was more cost-effective than HOMER Pro with the least LCOE of 0.0344 $/kWh and NPC of $86,990.94 as well as a loss of power supply probability (LPSP) of 0.99%. In addition, the GA method gave more hydropower generation than HOMER Pro. This supports the fact that stochastic methods are more realistic and economically viable. They also accurately predict system operation than deterministic methods.

1. Introduction

There has been a rising global attention on power supply policies with the aim of establishing sustainable strategies to meet the ever-growing demand. These strategies emphasize three quintessential goals surrounding the energy challenge: power supply security, power affordability, and environmental sustainability. This is a serious concern especially in developing countries. About 17% of people do not have access to electricity globally, out of which 85% reside in rural areas; with a greater percentage from sub-Sahara Africa [1]. Most rural households use different sources of energy, with a huge reliance on biomass for cooking/heating and backup diesel generators for lighting, as well as candles and kerosene for lighting by those who cannot afford a diesel generator. The consumption of these energy sources has known alarming consequences such as the fact that biomass and fossil fuel combustion emit poisonous chemicals which are harmful to the environment. Renewable energy (RE) is increasingly being used in reducing the deficit between power demand and supply [2]. Other induced drivers are the environmental concerns of fossil fuel usage and climate change challenges [3]. Renewables such as wind, hydro, and solar energy are essential for developing sustainable power systems for communities deprived of access to power. The solar PV technology, among other renewables, has a lot of prospects because of its availability and environmental friendliness [4], but variations in solar irradiance limit the ability to reliably supply appliances without hybridizing with other energy sources. The RE systems when coupled in a hybrid configuration are more reliable in the delivery of electricity [3]. Microhydroelectric facilities are renewables with the potential to resolve the low rural electrification issue in off-grid communities. The implementation of a microhydropower is shown to have a relatively less environmental impact on aquatic life such as fish. This is more evident with the advancement in technology. For instance, there is an evolving hydro turbine technology such as the Archimedean screw turbine which is friendly to aquatic species like fish [5].

As the solar PV penetration in the network increases, its impact on grid planning, system security, scheduling, and control becomes steadily more prominent [6]. There is a need for control mechanisms and adequate reserve capacity in the power system to mitigate these impacts. Interestingly, the hydropower system has the capability of rapidly regulating system variables especially peak regulation, modulating frequency, and system emergency standby [7]. These properties can be used in the compensation of the fluctuating solar PV output and hence, supply stable electricity to users.

Cameroon's location around the equator in West Africa and its tropical climate expose it to sufficient global solar insolation with a GHI ranging between 4.9 kWh/m^2/day and 5.8 kWh/m^2/day [8]. The mean annual daily global solar irradiation is about 5.2 kWh/m^2/day with peak sun hours of about 5 h per day thus, making solar energy a promising energy source. Cameroon has many small-scale to large-scale rivers with the potential for power production especially in remote areas [9]. It is reported that Cameroon has the third largest hydropower potential in Africa, after Congo-Kinshasa and Ethiopia, with a possible exploitable potential of 103 TWh per year [9]. However, available data for small rivers in Cameroon are scarce, and this necessitates the need for the government to ease the acquisition of this information for scholars. Research on the subject of hydro-based hybrid system optimization is limited, especially for Cameroon. As of 2019, Cameroon's rural electrification rate was 32% while the national electricity access rate was 63% [10]. Previously, the electrification of rural areas was mainly through grid extension but this option has been quite slow, as shown by the progress in rural electrification. There are challenges in the energy sector in Cameroon such as low clean energy access, rising energy demand, high grid extension costs, and regular power outages [11]. Grid extension to remote areas is often challenged by the high cost and rugged nature of off-grid communities such that pursuing this choice becomes uneconomical [3]. Worst is that, some of these remote locations are sparsely populated, making them less attractive for investors and technically challenging for developers [3]. Sparsely populated areas promote power losses through the distant distribution of electricity among users. This shows that off-grid systems are therefore highly favorable for supporting these locations.

While the government's effort has been previously on grid extension and recently on the installation of standalone thermal plants, some nongovernmental organizations (NGOs) have installed off-grid renewable energy systems in some rural areas. The off-grid thermal plants installed by the energy of Cameroon (ENEO)—power utility company—have some issues such as environmental pollution, high fuel costs, and high operation and maintenance (O & M) cost. In 2018, the government began, through ENEO, a program to hybridize these off-grid thermal plants with renewable power sources, mainly using solar PV [12]. Currently, there is a pilot hybrid solar PV—thermal power plant in Djoum with a 369 kWp solar PV plant. The off-grid systems installed by NGOs are not properly optimized. No comprehensive study has been done to determine the reliability, performance, and sustainability of the hybrid power stations in the Cameroonian context. Moreover, the Tongou hydropower station installed by an NGO suffered from acute power outages owing to poor system design [11]. There was a situation of complete disappearance of the river hosting the microhydroelectric station, causing periods of no power production. This is a serious problem as most of these NGO-financed power projects are either loans or donations to the villages with the potential of acting as a barrier to the uptake of renewables by reducing the confidence on these systems. This study contributes to the existing gap regarding hybrid off-grid systems in Cameroon by assessing their feasibility and sustainability in solving the rural electrification challenge, as well as illustrating how the cost of energy could be drastically reduced with the generation of power from more small hydroelectric plants. Also, a grid extension analysis is conducted to determine the point at which grid extension is cost-optimal and deduce which option (standalone system or grid extension) is best for the community. Promoting rural mini-grids by conducting in-depth technical study of system reliability, performance, and investment indicators is fundamental as it helps developers to ensure that the systems are technically and financially sustainable. This study will assist in reinforcing the implementation of ENEO's hybridization program and NGO-financed off-grid systems in the country. Moreover, this study will provide information on mini-grids as a suitable solution to improve rural electricity access. These data are needed to stimulate the upscaling of the hybrid systems in Cameroon as well as methods of hybrid system optimization.

This study focuses on the optimization of a hybrid solar PV and microhydro system with a battery storage to be deployed in a rural community in Menchum District, Cameroon. This community is off-grid. The system is designed in a way which ensures that the loads are reliably met by the system. The HOMER Pro software and genetic algorithm (GA) were used in the study. A comparative study at the economic level showed that regulating the hydropower capacity was capable of reducing the system LCOE and reconfiguring the entire architecture.

1.1. Literature on Hybrid Renewable Optimization. Hybrid system optimization is challenging because of aspects such as variability in power demand, nonlinearity of RE components, numerous parameters, and the interdependence of the control strategy and the optimum configuration [3]. The optimization of the system is important as it helps ensure the least investment while fully utilizing the resources and system components. The reliability of the energy system to meet the load and the lifetime system cost are major targets of the optimization.

Many studies have been conducted on off-grid renewable solutions for communities. In order to determine the feasibility of off-grid renewable energy supply to touristic sites in Australia, studies by [13] used the NPC, faction of renewable, and payback period as factors to base their decision on choosing the best option. In Cameroon, the scholars in [14] conducted studies on the simulation of standalone systems for rural communities with power needs ranging from 0 to 50 kW. Their aim was to find a suitable way of supplying electrical energy to these localities. The scholars in [15] simulated a hybrid microhydro PV system in Batocha-Cameroon using the HOMER software. Similar studies were conducted by [14] on an off-grid energy system in Cameroon using HOMER with consideration of combinations involving hydro-diesel generator-solar-LPG-battery. They all used a hypothetical load profile with no aspect of productive use of energy considered. Also, a diesel generator (DG) was part of the optimal system selected which does not currently fit into the government's plans of phasing out all thermal plants. Similar studies in Cameroon by [16] using the particle swarm optimization (PSO) to design a hybrid off-grid power system were conducted. The study presented the battery-PV-DG as the optimum configuration at an LCOE and NPC of 0.132 $/kWh and $38,817.7, respectively. The PSO and differential evolution (DE) were used in the optimization of a hybrid battery/PV/hydro system, and the results obtained were an optimum NPC and LCOE of $93,958.07 and 0.06192 $/kWh, respectively [17]. Still in Cameroon, a study by [18] using the HOMER software to design an optimum microhydro/DG/PV/battery architecture with an LCOE of 0.443 $/kWh. The feasibility of an off-grid hybrid Hydro/PV/Wind in six sites [19] was assessed in Ethiopia with the aim of supplying cost-effective power to rural communities. The researchers used HOMER Energy for optimization and obtained diverse system configurations with LCOE less than 0.16 $/kWh. Studies by [20] reported that the PV/wind/diesel/battery hybrid system was a feasible option for off-grid supply of electricity to rural areas in Pakistan. The HOMER results indicated that the hybrid system was attractive with a renewable energy penetration of 84%, an LCOE of 0.45 $/kWh, and a 69% reduction in greenhouse gas (GHG) emissions. Another study has been done in 10 rural villages in Iran, comprising a hybrid PV/DG/battery system using HOMER [21]. The LCOE obtained from the various options was in the range of $0.615 to $0.722. Techno-economic analysis on a hybrid PV/DG/battery was conducted by [22] on a university campus in Delhi using HOMER. They obtained an optimal system with an NPC of $170,348 and an LCOE of 0.090 $/kWh. Still on campus in Delhi, a techno-economic analysis of off-grid PV/DG/battery was conducted by [23] using HOMER, where the optimal system gave an NPC and LCOE of $639,981 and 0.34 $/kWh, respectively.

A metaheuristic bonobo optimizer (BO) was used in the optimization of an off-grid hybrid wind-DG-PV-battery in a rural area in Saudi Arabia [24]. Their objective was the minimization of the annualized system cost (ASC), and the algorithm found a least ASC of $149,977.2. In [25], the PSO and Monte Carlo techniques were used to optimally size a PV–wind–battery with minimization of the total annual cost (TAC) as an objective function. In [26], a genetic algorithm (GA) was used for the optimum sizing of a PV-wind-battery-solar collector system with the minimization of NPC as an objective function. These metaheuristic algorithm-based research studies for off-grid rural electrification are focused on parameters like ASC, NPC, LCOE, and loss of power supply probability (LPSP). without a justification on whether these systems need to be deployed as off-grid systems or if there's need for extension of the existing grid. This is pertinent in the context of rural electrification where policies need to be backed by compelling and established research on which options are much better and why. There is a need for a grid extension analysis where stakeholders are provided with information on whether the standalone option is worth pursuing even if the other economic indicators are promising. However, the scholars in [27, 28] agree that the PSO and GA are amongst the most promising optimization methods used to solve the energy system optimization problem, and this is corroborated by several publications. Generally, the inferences drawn from the works in [27, 28] are that the GA is scalable, independent of the initial solution, and can easily be merged with other techniques. For the PSO, the algorithm evades the complex model and high computational burden of the GA, and its implementation is simpler. Nonetheless, the downside of PSO is that it is not robust, especially when the dimensions of the problem are large. Genetic algorithms are well-suited for complex optimization problems with a large search space, making them particularly effective for sizing decisions that involve multiple parameters and interdependencies. GA employs a population-based search strategy that enables exploration of the solution space concurrently. This feature is advantageous when dealing with renewable energy systems, where the optimal sizing may not follow a direct path and needs exploration of various configurations [3]. Therefore, this study will use the GA for validating the results obtained from HOMER. The peculiarity of meta-heuristic approaches is that they can be adapted to several problems with no significant changes in the algorithms, hence the name meta. Table 1 provides a summary of other studies and limitations identified.

1.2. Contribution and Paper Outline. Most of the studies on RE system optimization have been focused on optimal system configuration and cost minimization without highlighting the contributions of the subsystems to the cost-optimized function. Although most of the authors focused on techno-economic assessment, they fail to present a comprehensive route for validating the results obtained in a way that provides a clear contrast between optimization techniques. For example, in the studies that used more than one tool to conduct the optimization, the choice of tool was

Table 1: A summary of studies on energy optimization.

Country	Approach and major findings	Limitations	Author
Rural area, Cameroon	HOMER was used with an optimal system of 14 kW microhydro, a 15 kW LPG and 36 kWh of battery at an LCOE of 0.296 €/kWh and NPC of €153234. The breakeven grid extension distance was 15.4 km for microhydro/LPG system	No comparison with another tool, no consideration for systems LPSP	[14]
Rural area, Iran	The PSO and Monte Carlo technique were used to optimally size a PV–wind–battery with minimization of the total annual cost (TAC) as the only objective function. The optimal was wind/battery system with a TAC of $17183.11 which was lower than that of the other configurations such as PV/wind/battery and PV/battery)	Comparison with only stochastic tools, no grid extension analysis, TAC was the only parameter, no analysis of system reliability	[29]
Rural area, Cameroon	Simulation was done with HOMER. The optimum architecture was 5 kW PV, 2.12 kW hydro, 1 kW diesel; 125 battery, 6 kW inverter, and 6 kW rectifier. The microhydro-PV-diesel-battery system gave a total NPC of $70,042 and LCOE of 0.278 $/kWh	No assessment of grid extension, no comparison with another tool, the use of diesel which is polluting	[15]
Rural area, Saudi Arabia	Four metaheuristic algorithms (big-bang–big-crunch (BBBC), GA, crow search (CS), and the butterfly optimization algorithm (BOA)) were used to compare with the bonobo optimizer. The optimal hybrid wind-diesel-PV-battery gave a minimized annualized system cost (ASC) of $149,977.2	No assessment of grid extension, all tools used to compare were AI-based, use of diesel	[24]
Multimedia center, Cameroon	PSO was used. The optimum PV-battery-diesel system gave an LPSP, LCOE, NPC and emissions of 0.003%, 0.132 $/kWh, 38,817.7 $, and 2.2 kg/year, respectively	No grid extension analysis, no comparative analysis with another software, the use of DG	[16]
Rural area, Pakistan	Simulation was done with HOMER. The optimum configuration had 10 kW PV, 20 kW wind capacity, 30 kW diesel, 50 batteries, and a 50 kW converter. The feasible option had a renewable energy penetration of 84%, LCOE of 0.45 $/kWh and total NPC of $359,465	No grid extension analysis, no comparative analysis with another software, the use of DG	[20]
University campus, India	Simulation was done with HOMER. Techno-economic analysis on a hybrid PV/DG/battery. They obtained an optimal system with an NPC of $170,348 and an LCOE of 0.090 $/kWh	No grid extension analysis, no comparative analysis with another software, the use of diesel	[22]
Rural area, Cameroon	They used DE and PSO. The optimization of a hybrid battery/PV/hydro system and the results obtained were an optimum NPC and LCOE of $93,958.07 and 0.06192 $/kWh, respectively	No grid extension analysis, no comparative analysis with another software	[17]
Rural area, Iran	Simulation was done with HOMER for 10 rural villages with a system comprising PV/DG/battery system. The LCOE obtained in the various options were in the range of $0.615 to $0.722 $/kWh. Meymand village gave the best performance (NPC of $12053 and LCOE of 0.615 $/kWh) was the most appropriate option	No grid extension analysis, no comparative analysis with another software, the use of diesel	[21]
Rural area, Cameroon	Simulation was done with HOMER. The PV/diesel/small hydro/battery was found to be the most viable economic system for Southern Cameroon with a 0.443 $/kWh energy cost	No grid extension analysis, no comparative analysis with another software, the use of diesel	[18]
Rural area, Ethiopia	HOMER was used in the study. The optimum configuration was hydro/PV/wind with LCOE less than 0.16 $/kWh and an NPC of $246,787	No comparative analysis with another software, no grid extension analysis	[19]

all from a particular category such as all meta-heuristics. This study attempts to compare the soundness and robustness of a commercial tool like HOMER Pro and an AI-based algorithm like the GA so that inferences could be made from the results obtained. A summary of the novel insights and contribution is presented as follows:

(i) This study uniquely demonstrates, through a sensitivity assessment, how the increase in hydropower capacity can affect the optimal system configuration as well as the LCOE. This will have policy implications in Cameroon which has a longstanding history of supporting large hydropower installations while ignoring microhydropower development.

(ii) Application of a multiobjective GA and HOMER Pro software is used to solve the sizing and cost optimization of a hybrid off-grid hydropower—solar renewable energy system. By comparing HOMER with GA results, the study aims to bridge the gap between a widely adopted commercial tool and a machine learning-based approach, providing insights into the applicability, advantages, and limitations of both.

(iii) It explores the design of a hybrid power system while upholding the technical sustainability and cost tradeoff through manual calculation, an aspect which is still a black box to energy experts.

(iv) It identifies the best rural electrification option through exploiting HOMER's grid extension assessment database where cost-optimized analysis is conducted between the off-grid system and the nearest grid-connected community.

(v) Instead of focusing on designing a single energy system as is common in most tools, the study exploits HOMER's ability to flexibly suggest several electrification options while selecting the optimal alternative based on the elimination criteria.

Comparative studies on 68 tools for renewable energy system analysis indicated that HOMER was one of the most appropriate tools for conducting optimization of both off-grid and on-grid systems [30]. This was further supported by [31], who pointed out that HOMER was a widely used and popular software. The HOMER software is widely used for the design of RE systems and will be used in this study to optimize the hybrid PV-hydro RE system alongside the GA method for validation of the findings. HOMER has an intuitive user interface, it is consistent in its energy system design, and is reliable. Therefore, it has been used in this study. Cameroon has relatively exploitable amounts of solar irradiation by virtue of its location near the equator and satisfactory hydroelectric potential in several communities. This implies that the country's precarious rural electricity access situation could be addressed through hybrid system combinations particularly in those locations where these resources are present. This research examines the feasibility of using an off-grid solar/microhydro renewable energy system for affordable electricity generation to meet the power demand of a rural area in Cameroon. Here, the system is sized in line with the solar/microhydro resources and the power demand of the location. Then, an economic analysis is done on the hybrid system while comparing it with other supply options such as grid extension or a standalone system. In addition, a sensitivity assessment is conducted to explore the influence of increasing the hydropower capacity on the system configuration and LCOE.

The initial part of the study is an introduction which is followed by a review of the literature on RE optimization. Moreover, the methodology is presented with an elaboration of the modeling of system components. The results and discussion are equally presented with the major findings of the study. Finally, the study ends with a summary of the results.

2. Materials and Methods

The research paper used the HOMER Pro software to simulate data collected in order to determine the feasibility of electrifying a remote community in Cameroon, and the results were validated using computational GA. HOMER Pro is a unique energy modeling application which has a worldwide database of resources such as solar irradiation, wind, temperature, as well as the RE system components. The simulation will involve several constraints and data such as the solar/hydro resource of the site, load profile, and other economic considerations. The study used several combinations of energy resources (solar, microhydro, and batteries) while monitoring system performance factors such as the LCOE, NPC, storage capacity, and system reliability.

2.1. Study Area. The location of interest is a small community called Munkep, situated in the North West Region of Cameroon. It lies between a latitude of 6.742 N and a longitude of 9.98 E with an elevation of 502.6 m above sea level [32]. This farming community is located about 23 km from the nearest electrified community. The map of the study area is shown in Figure 1. The community currently uses diesel generators, solar home systems (SHSs), batteries, firewood, candles, and kerosene lamps for lighting. In the community, most households rely on diesel generators to produce electricity at a relatively high cost, and there are no plans that the grid will be extended to this community within the medium or short term. Regrettably, low-income families who survive on barely less than a dollar per day can only use kerosene for lighting and most often, firewood for cooking and lighting. The negative effects of the kerosene and diesel generators include air pollution, health hazards, and environmental degradation. The loads of the Munkep community will be met by a hybrid energy system which is made up of a microhydro generator as the primary energy source coupled with a solar PV and a battery network.

2.2. Objective Function Formulation. The main objective is to minimize the NPC which will in turn minimize the LCOE. For a hybrid system, the NPC involves several cost

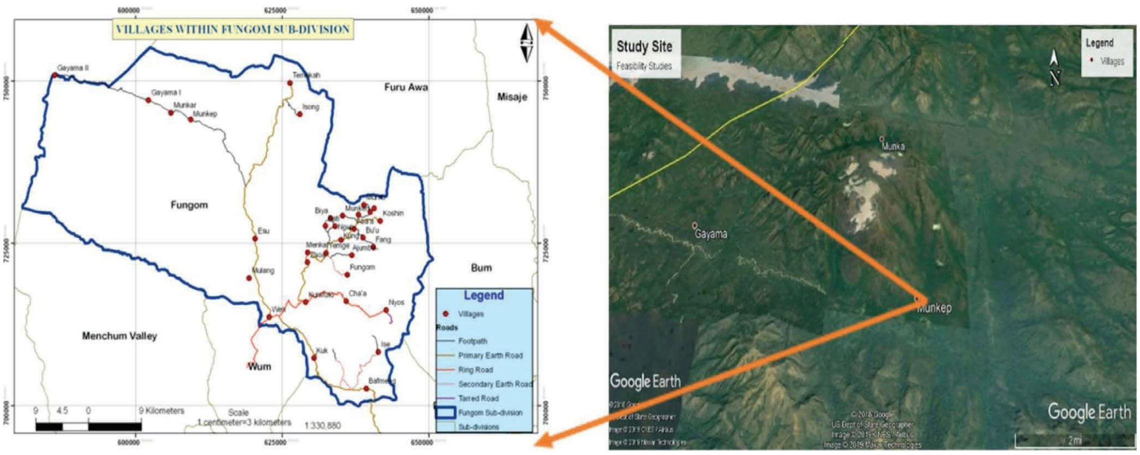

FIGURE 1: Location of the site [33].

components discounted with a discount rate to the present value using capital cost, replacement cost, maintenance, and operation cost. The NPC represents all the costs that occur within the project lifecycle, with future cash flows. The objective function is represented by the following equation [34]:

$$\text{Minimize NPC} = C_{\text{Cap}} + C_{O\&M} + C_R, \tag{1}$$

where C_{Cap} is the capital cost of the system, $C_{O\&M}$ is the system's operation and maintenance cost, and C_R is the system's replacement cost.

The economic assessment in HOMER is such that it seeks to reduce the system cost and identify the optimum configuration. The optimum hybrid system configuration is determined using the NPC, and it is also represented as in the following equation [34]:

$$\text{NPC} = \frac{\text{ASC}}{\text{CRF}}, \tag{2}$$

where ASC is the annualized system cost and CRF is a ratio to calculate the present value of the system components for a given time period taking into consideration the interest rate. It is calculated using the following equation [17]:

$$\text{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1}, \tag{3}$$

where i is the interest rate, n is the project life time.

The LCOE is equally a significant component of the system design and it indicates how economically profitable the system can be. It is calculated using the following equation [17]:

$$\text{LCOE} = \frac{\text{NPC}}{\sum_{t=1}^{t=8760} P_{\text{load}}} \times \text{CRF}, \tag{4}$$

where P_{load} is the load power.

The loss of power supply probability (LPSP) is a measure of system reliability index which represents the potential of the system's inability to meet the load demand. It is estimated by the percentage of the energy deficit of the total energy produced by the hybrid. The LPSP offers information on the hybrid system reliability and it is calculated using the following equation [35]:

$$\text{LPSP}(\%) = \frac{\sum_{t=1}^{T}\left[P_{\text{load}} - P_{\text{PV}} - P_{\text{Hydro}} - \left(E_{\text{Batt}}(t) - E_{\text{Batt\_\_min}}\right)\right]}{\sum_{t=1}^{T} P_{\text{load}}}, \tag{5}$$

where P_{load} is the total system load, P_{PV} is the total generated PV power, P_{Hydro} is the total generated hydroelectric power, $E_{\text{Batt(t)}}$ is the energy stored in the battery at a time t, and $E_{\text{Batt\_min}}$ is the minimum energy that can be stored in the battery.

An LPSP of 0% implies the load will be satisfied all the times and an LPSP of 100% implies that the load cannot be supplied at all.

2.2.1. Bound Constraints. There are constraints regulating the limits of the solar panels, hydro turbines, and the battery system. They are presented as follows:

$$\begin{aligned} &0 \le P_{\text{Hydro}} \le P_{\text{Hydro\_Max}}, \\ &0 \le N_{\text{Bat}} \le N_{\text{Bat\_Max}}, \\ &1 \le N_{\text{solar}} \le N_{\text{solar}_{\text{Max}}}, \end{aligned} \tag{6}$$

Table 2: Boundary limits of variables.

Variable	Minimum value (kW)	Maximum value (kW)
Hydro (P_{Hydro})	0	40
Solar PV (N_{solar})	1	15
Battery (N_{Bat})	1	25

P_{Hydro_Max} is the hydro turbine's maximum power, N_{Bat_Max} is the maximum number of batteries, and N_{solar_Max} is the maximum number of solar modules.

Table 2 shows the boundary limits of the constraints used in the simulation.

2.3. Resources Assessment. Cameroon has a fairly good solar radiation with global horizontal solar radiation fluctuating from 4.29 to 6 kWh/m^2 [36] and a huge potential for hydropower [14]. The solar resource data was obtained from NASA while the hydro resource was scaled from data used by [17] in a location with a similar rainfall pattern.

2.3.1. Solar Resource Assessment and Temperature. The solar resource information for the Munkep village was obtained from NASA (latitude of 6.742 N and longitude of 9.98E) and ranged from 4.015 kWh/m^2/day in August to 6.047 kWh/m^2/day in February, representing the period of the rainy and dry seasons in Cameroon [32]. It is the 22-year average insolation data. Sustainable power generation in a PV system occurs at a daily radiation greater than 3.5 kWh/m^2/day [37]. The daily solar radiation and the clearness index of Munkep village are shown in Figure 2.

Figure 2 shows that February is the sunniest month with a solar radiation of 6.047 kWh/m^2/day, while August has the least solar radiation of 4.015 kWh/m^2/day. The daily radiation reduced from February to August and later rose until December. The trend observed in the monthly solar resource is the reverse with the microhydro resource, enabling the complementary operation of the solar and hydro systems in the hybrid topology. The flow rate of the run-of-river falls when the solar radiation increases.

Solar module operation is greatly affected by the ambient temperature, and it is important to include the temperature effect in the model. The dry season has periods with one of the highest ambient temperatures, while the rainy season presents the lowest ambient temperature. HOMER Pro uses the ambient temperature to compute the solar PV output power. Figure 3 shows the site's monthly average ambient temperature.

The power output of the PV system is given by the following equation [38]:

$$P_{out\_pv} = P_{PV\_rated} \times \left(\frac{G}{G_{ref}}\right) \times \left[1 + K_T\left(T_c - T_{ref}\right)\right], \quad (7)$$

where P_{out_pv} is the output power of the PV system, P_{PV_rated} is the PV rated power, G is the solar radiation (W/m^2), G_{ref} is the solar radiation at reference conditions ($G_{ref} = 1000$ W/m^2), T_{ref} is the cell temperature at reference conditions ($T_{ref} = 25°$C), K_T is the temperature coefficient of the maximum power ($K_T = -3.7 \times 10^{-3}$/°C), and T_c is the cell temperature which is determined by the equation [38]:

$$T_c = T_{amb} + (0.0256 \times G), \quad (8)$$

T_{amb} is the ambient temperature.

2.3.2. Hydro Resource Assessment. In general, a microhydroelectric plant would generate a few hundreds kilowatts of power usually through a run-of-river scheme. This technique is suitable in areas where the available hydro resource possesses a low discharge. The determination of flow rate using rainfall runoff patterns was not possible owing to the enormous data requirements which were not available at the time of the study. The site has several rivers whose stream flows were not measured. However, the annual flow used by [17] was scaled and used in the simulation. The monthly flow data is presented in Figure 4.

The net head used in the study was 3.2 m, and the design flow was 1000 l/s (1 m^3/s). The study considered a minimum flow ratio and a maximum flow ratio of 50% and 150%, respectively. A turbine efficiency of 80% was used in the study. The turbine transforms the moving water from the penstock into mechanical energy which is later converted into electrical energy by the generator. The power produced in the hydropower system is given by the following equation [17]:

$$P_H = \begin{cases} 0, & \text{for } Q < Q_{min}, \\ \rho \times g \times H_n \times \eta_{TG} Q, & \text{for } Q_{min} \le Q < Q_{max}, \\ \rho \times g \times H_n \times \eta_{TG} Q_{max}, & \text{for } Q \ge Q_{max}, \end{cases} \quad (9)$$

where P_H is the power produced by the hydro system in watts, ρ is the water density (1000 Kg/m^3), H_n is the net head in meters (m), Q is the flow rate (m^3/s), g is the acceleration due to gravity (9.8 m/s^2), η_{TG} is the product of the turbine and generator efficiency, and Q_{min} and Q_{max} are the turbine minimum and maximum stream flow.

The hydropower station has a limit to the power it can produce, and it is expressed as a function of the flow rate:

$$\begin{aligned} Q_{min} &\le Q \le Q_{max}, \\ P_{min} &\le P \le P_{max}. \end{aligned} \quad (10)$$

Table 3 shows the data used in the simulation of the hydroelectric system.

2.4. Electricity Usage of the Rural Community. The Munkep community needs electricity mostly for domestic appliances such as lamps, TVs, radios, cell phones, and refrigerators. There were some considerations for community loads such as iron and computers in schools, community halls, health posts, small-scale industrial activities, and rural commercial facilities such as small processing factories for cassava flour and soya bean flour, cold storage, and cottage industries. Table 3 represents the list of all connected loads to the system with their unit power rating in Watts. The demand has been

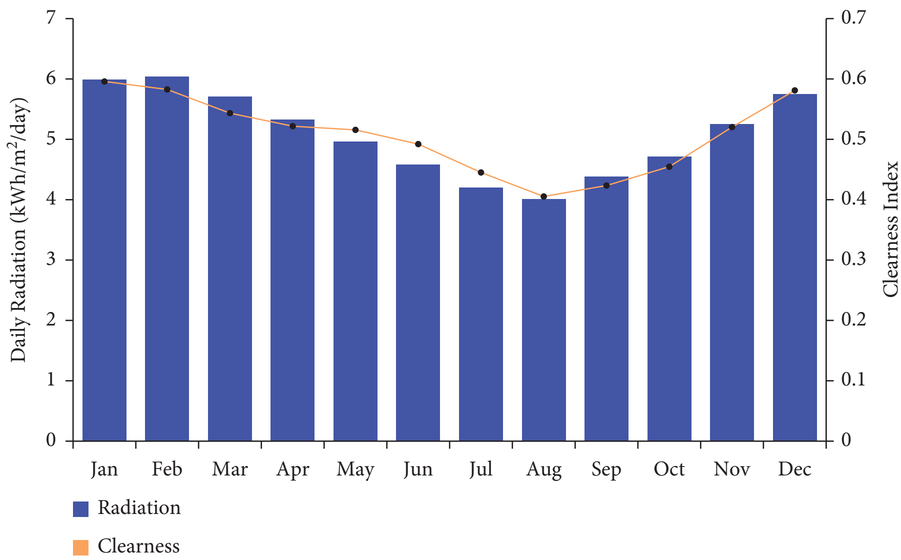

Figure 2: Monthly solar potential of Munkep.

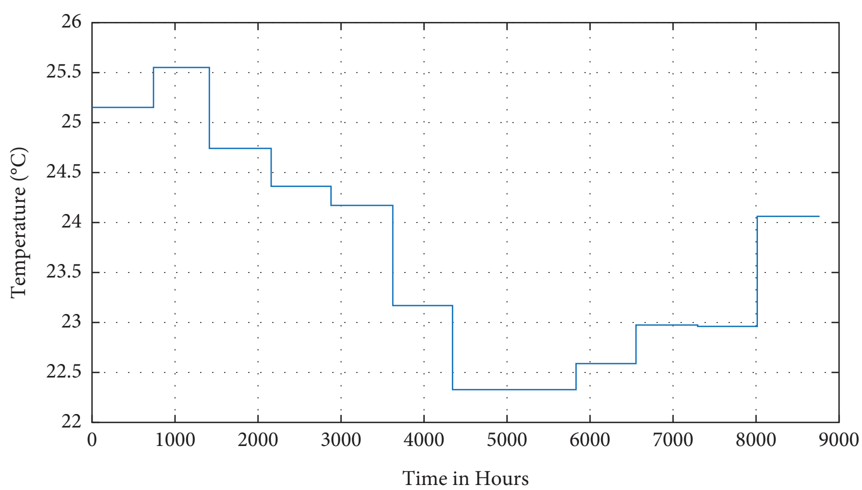

Figure 3: Monthly average temperature.

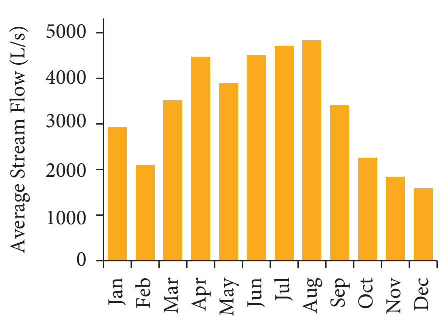

Figure 4: The monthly average flow rate of river Ye-Abuoh.

estimated considering the appliance rating and use patterns for households, potential commercial activities, and energy use in productive applications. Clearly, the demand estimation is a crucial element for the entire system design, and further improvement is possible by incorporating social

Table 3: Specifications of the hydro system.

Parameter	Value
Net head	3.2 m
Q_{min}	0.5 m^3/s
Q_{max}	1.5 m^3/s
Turbine efficiency	80%

information of the users as well as their preferences. The village under consideration has 100 households with an average of 5 persons per household, a community school (class 1 to class 6), a church, and a health post. To bring a little more improvement to the village, the researchers added more electric loads like flour milling machine and a community water pump. The loads like lighting, TV, radio, mobile phones, refrigerator, microphone (for the church), office equipment (printer, photocopy machine, and computer for the school) are taken to be primary loads, which should be supplied whenever required. Since most of the residents in the village are farmers and the primary loads are lighting loads, the peak load appears in the evening from 18:00–21:00. The sum total of the daily energy consumption of the community is approximately 431.32 kWh. Table 4 shows the loads considered in this study while Figure 5 shows the hourly load profile.

2.5. Modeling of the Hybrid Renewable Energy System. The HOMER Pro software was used in this study. HOMER Pro is the universal standard for optimizing microgrid design from village power and island utilities to grid-connected campuses and military bases [39]. Formerly conceived at the national renewable energy laboratory and improved and distributed by HOMER Energy, HOMER (hybrid optimization model for multiple energy resources) encompasses three powerful tools in one software product, so that engineering and economics work side by side. HOMER simulates the system for power generation over the time period of 25 years at 60 minutes of interval, presenting the results for a period of one year. The battery bank, the inverter and other important components that make up the hybrid system were also considered. The architecture system has an AC bus and a DC bus. The microhydro system generates AC power whereas the solar PV system generates DC power. A bidirectional converter is used to convey the excess energy in the system to charge the battery network. The battery network intervenes only when the system cannot meet the loads. The excess energy in the system after the battery is full, is sent to dump loads. The schematic shown in Figure 6 shows the proposed hybrid system.

2.6. Power Management Strategy of the System. The management of energy in hybrid off-grid systems is essential, as it ensures system reliability and security. It makes good use of energy with minimum wastage, optimum power generation, as well as the suitable operation of system components. A procedure was created in order to show the engineering process and offer a step-by-step way of predesigning the hybrid renewable energy solution. The emphasis was on choosing a cost-effective renewable energy system (hybrid solar-microhydro). The control strategy operates according to the following description:

(1) The dispatch of the subsystems of the hybrid RE has the following order of priority: hydro-solar-battery bank. The microhydro subsystem meets the base load. When the microhydro and solar PV outputs are equal to the load power, the battery bank does not extract energy. As soon as excess power becomes available from the two subsystems (microhydro and solar PV), the optimization program redirects the excess energy to charge the battery in case the state of charge (SOC) is not at the maximum level.

(2) If the total energy produced by the microhydro and solar PV is more than the load demand at any given time such that it can negatively affect the hybrid system, the energy surplus is discharged through dump loads.

(3) If the total power generated by the PV and hydro systems is less than the load demand, the energy deficit is covered by the battery, depending on the SOC.

Table 5 shows the economic parameters used in the model while Figure 7 shows the power management strategy of the hybrid system.

The control strategy of the hybrid PV microhydro off-grid system with storage operates according to the schematic in Figure 7. The main generators are the microhydro and the solar PV system. Once the program starts, the algorithm verifies whether the microhydro system can effectively meet the load without soliciting power from the solar PV and battery bank. If the load is more than the power generated by the microhydro system, the power generated by the solar PV system is added while the excess power is used to charge the battery bank, depending on whether the battery SOC is less than the minimum SOC. In case the battery bank is full while there is surplus power in the network, the surplus is directed to dumbed loads (power curtailment scenario). The flow of power in both the DC and AC buses is bidirectional with the help of a converter.

2.7. Genetic Algorithm (GA). GA is a computational meta-heuristic algorithm that is based on the natural evolution theory using chromosome structures and a recombining process during the iteration process [40]. GA has 3 fundamental operators, namely, crossover, selection and mutation. Weak species in the population are eliminated so that only strong species are retained and this is executed by the selection operator. The crossover operator searches better individuals in the population from the chromosomes of 2 parents in the population. The mutation operator helps in mutating individuals that generate better solutions in the search space. The mutation process retains the population variety with better solutions [41]. Table 6 shows the GA parameters.

The approach generates an initial population with individuals satisfying an LPSP less than 5% at a minimum LCOE. The Roulette wheel approach selects the operator that randomly transfers the genes to the next generation depending on their features. After the selection, the parent chromosomes undergo the process of crossover while checking if the LPSP is satisfied by the new generation of child individuals. If the program fails to meet the criterion, the parent chromosomes are not replaced by the new generation of child individuals, but in case the new generation of child individuals satisfies the criterion, then the parents are replaced. The individual genes change depending on the mutation rate and the LPSP criterion. The mutation process is successful if the criterion is met. Finally, the program termination criteria are verified and if they are met, the program stops. The steps in the algorithm are presented below;

Table 4: Appliances considered.

Load description	Number in use	Power rating (watts)	Power rating (kW)	Total rating (kW)	Rainy season (March–October)		Dry season (November–February)	
					Hours/day	kWh/day	Hours/day	kWh/day
Category A: residential load								
Lighting (CFL)	4	18	0.018	0.072	7	0.504	7	0.504
Television	1	80	0.08	0.08	5	0.4	5	0.4
DVD player	1	20	0.02	0.02	2	0.04	2	0.04
Radio	1	10	0.01	0.01	8	0.08	8	0.08
Ceiling fan	2	30	0.03	0.06	20	1.2	10	0.6
Total for 100 households				**24.2**		**222.4**		**162.4**
Category B: community loads								
Primary health center								
Lighting (CFL)	6	18	0.018	0.018	12	1.296	12	1.296
Refrigerator	1	480	0.48	0.48	14	6.72	12	5.76
Television	1	80	0.08	0.08	6	0.48	6	0.48
Ceiling fan	3	30	0.03	0.09	21	1.89	13	1.17
Total				**0.758**		**10.36**		**9.379**
Public primary/secondary school								
Lighting (CFL)	8	18	0.018	0.0144	0	0	0	0
Ceiling fan	3	30	0.03	0.09	5	0.45	2	0.18
Total				**0.234**		**0.45**		**0.18**
Community hall								
Lighting (CFL)	6	18	0.018	0.108	0	0	0	0
Television	1	80	0.08	0.08	8	0.64	8	0.64
Ceiling fan	4	30	0.03	0.12	9	1.08	6	0.72
Total				**0.308**		**1.72**		**1.36**

The bold values are the sum total of entries in the column where they appear. For example in category A, the bold value 24.2 represents the total kW of appliances in that category (i.e., category A).

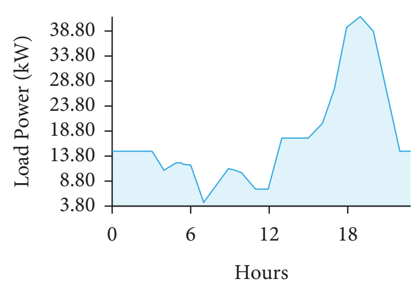

Figure 5: Hourly load profiles within the study.

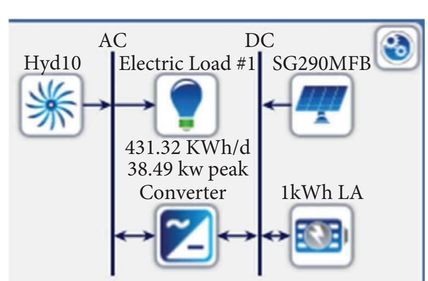

Figure 6: The schematic of the hybrid system.

2.8. Sizing of Charge Controller. The solar charge controller is rated based on the voltage and the ampacity which depend on the PV array configuration and the output current of the module supplied to the controller. A 30% tolerance is given to the charge controller ratings to cover the surge current and is given by the following equation [37]:

$$I_R = I_{SC} \times N_p \times 1.3, \quad (11)$$

where I_R is the controller current ratings, I_{SC} is the short-circuit current of a single solar panel, and N_p is the number of solar panels connected in parallel.

Table 5: Cost specifications for the design.

Component	PV	Battery bank	Converters	Hydro
Capital cost ($/kW)	2000	1500 ($/kWh)	345	2500
O & M cost ($/kW/year)	86.4	20	10	100
Life time (year)	25	10	15	25
Efficiency (%)	15 (STC)	95	90	80
Interest rate (i)	5%	—	—	—
Cost of replacement ($/kW)	1200	1000	245	2200

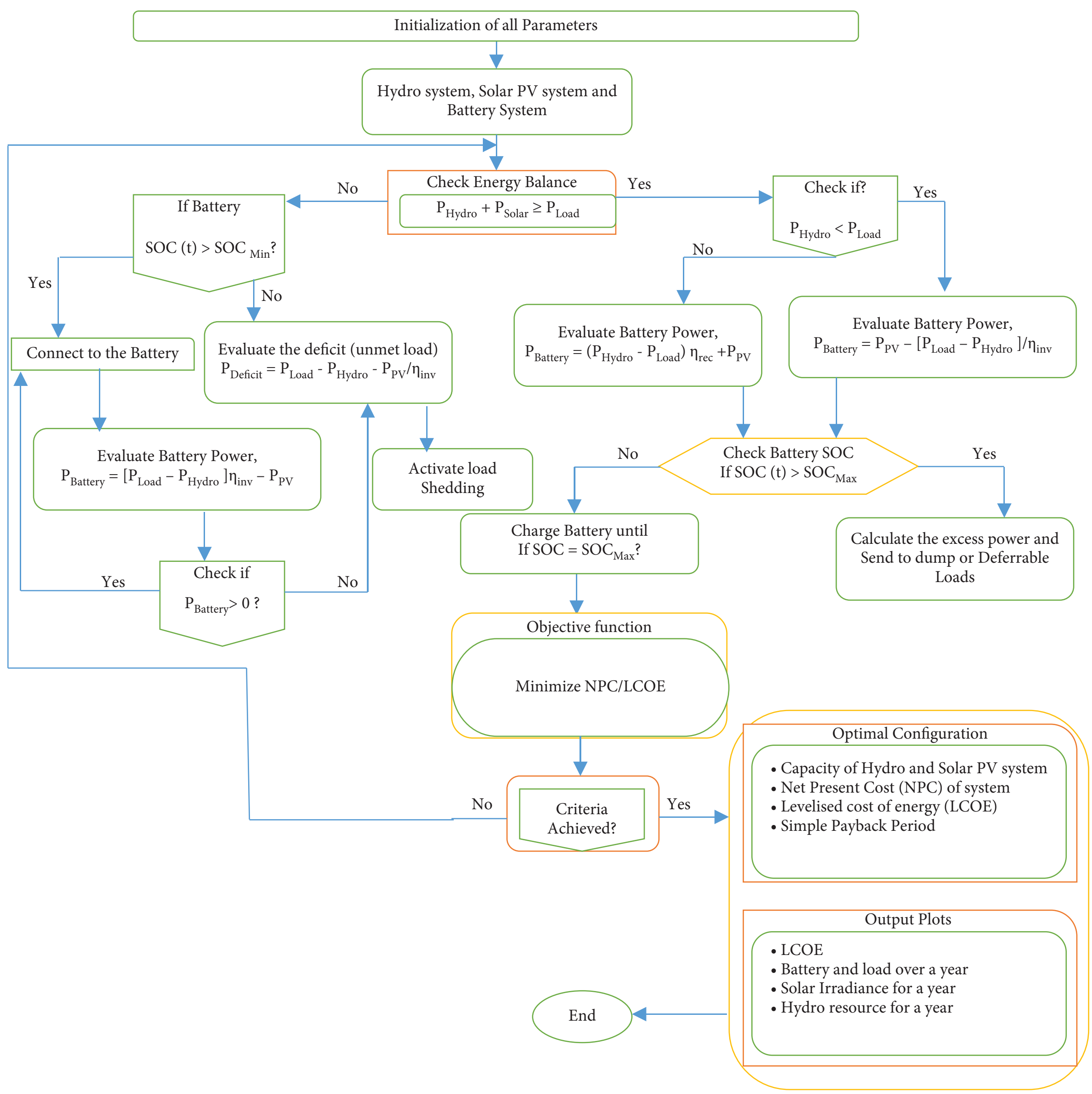

Figure 7: Power management of the hybrid system.

2.9. Sizing of the Converter. From the simulation, the maximum power discharged by the battery network during peak load was 6.43 kW, and the power from the hybrid system converted for battery charging was 11.64 kW. Nonetheless, the bidirectional converter considers the maximum power converted, implying that the power contributions at the DC bus are 11.64 kW from the battery bank and 4 kW from PV, making a total of 16.64 kW. Considering the possibilities of load growth for a period of 5 years, the inverter oversize factor was assumed to be 1.3 [37]. The converter power ratings are determined by equation (12) [37]:

Table 6: GA parameters.

Parameter	Value
Population size	50
No of Iterations	100
Mutation rate	0.1
Selection	Roulette wheel
Crossover rate	0.8

$$\begin{aligned} P_{R\_\text{Con}} &= P_{\text{Trans}} \times 1.3, \\ P_{R\_\text{Con}} &= 16.64 \times 1.3 = 21.63\,\text{kW}, \end{aligned} \tag{12}$$

where $P_{\text{R\_Con}}$ is the converter power ratings and P_{Trans} is the maximum transferred power.

3. Evaluation of the Cost of the Hybrid System Components Using HOMER Pro

From the inputs, the various costs of the hybrid system components are shown in Figure 8, as simulated in HOMER Pro. It is observed that the NPC of the optimum system combination was $90,469.16. The energy generated by all resources and the power flow from December 7 to December 13 are depicted in Figure 9. Figure 9 shows that hydropower production is highly fluctuating, as this is the dry season in Cameroon with much reduced river flow. It is also observed that the solar PV and battery provide relatively less energy in meeting the loads. Interestingly, high solar radiation is observed during this period such that the solar PV complements the deficiency in the microhydro system.

3.1. Solar PV Power Generation from the HOMER Pro Simulation. The annual solar energy production has a rated capacity of 3.5 kW, with a maximum yield of 3.1 kW (Table 7 and Figure 10). It is seen in Figure 11 that the PV system produces electricity from 6 am to 6 pm with maximum power production occurring at noon. There is an average of 4 sunny hours (10 am to 2 pm) where power generation fluctuates within the range of 2.8 to 3.5 kW. Generally, it is observed that there is high solar irradiation during the months of January, February, and December. Hence, the power generated from the solar system is higher. Solar radiation, as well as the generated electricity, during the other months is marginally lower.

3.1.1. Solar PV Sizing. The 260 W Peimar SG290MFB solar panel, with an efficiency of 17.8%, was selected while considering a 2000 $/kWp capital cost. An equipment lifetime of 25 years and a replacement cost of 1200 $/kWp were considered. The system voltage (V_{sys}) considered in this study is 48 V, and it is used to calculate the number of panels in a parallel connection. The derating factor used in the analysis was 80%.

Step 1. Calculating the installed power

The peak sun hours (hours at $1\,\text{kW/m}^2 = \text{kW/m}^2/\text{day}$) are determined considering the worst month of the year. A peak sun hour of 4 h/day is chosen in this study.

To determine the installed power [4]:

$$\begin{aligned} &\text{Energy consumed by laod } (E_{\text{Load}}) = \text{Power} \times \text{time}, \\ &E_{\text{Load}} = 3\,\text{kW} \times 4h = 12\,\text{kWh}, \\ &E_{\text{Solar}} = \frac{\text{load energy}}{\text{inverter efficiency}} \\ &\quad = \frac{12}{0.8} = \frac{15\,\text{kWh}}{\text{day}}, \\ &P_{\text{Peak}} = \frac{15\,\text{kWh/day}}{4\,\text{hour/day}} = 3.75\,\text{kW}_p. \end{aligned} \tag{13}$$

Computing the number of solar modules in a string using a module voltage of 26.3 V [4]

$$N_s = \frac{V_{\text{sys}}}{V_m} = \frac{48}{26.3} = 1.82 \cong 2 \text{ solar modules}, \tag{14}$$

where N_s is the number of solar panels connected in series, V_m is the nominal voltage of a single solar panel, and V_{sys} is the system voltage.

Computing the number of parallel connections using 260 Wp PV module [4]

$$N_p = \frac{P_{\text{Peak}}}{P_{\text{PV\_rated}} N_s} = \frac{3.75\,\text{kW}}{260 \times 2} = 7.2 \approx 7 \text{ parallel strings}, \tag{15}$$

where N_p is the number of solar panels connected in parallel, $P_{\text{PV\_rated}}$ is the power ratings in W of a single solar panel, and P_{peak} is the PV peak power of the system.

The total number of solar modules becomes [37]

$$N_{T\_\text{PV}} = N_s P_{\text{PV\_rated}} = 7 \times 2 = 14 \text{ solar panels}, \tag{16}$$

where $N_{\text{T\_PV}}$ is the total number of solar panels.

The solar module considered in the study has an area of $1.627\,\text{m}^2$. Therefore, the overall area needed to install the solar PV array will be [37]

$$\text{Area} = N_{T\_\text{PV}} \times A_{\text{PV}} = 14 \times 1.627 = 22.778\,\text{m}^2, \tag{17}$$

where the A_{PV} is the area of a single solar panel.

3.2. Microhydro Power Generation from the HOMER Pro Simulation. Table 8 and Figure 12 show the output features of the microhydro system. Power production drops during the months of November, December, January, and February due to the reduction in the river flow rate, as seen in Figure 12. December is the month which is most affected by the dry season, causing the least hydropower production. This power drop is supported by the battery bank and solar PV to meet the power demand.

Figure 13 shows the heat map of the annual microhydropower production where three colours are used to categorize the variation of output power throughout the year. The red colour running from day 1 to day 280 represents the output power from the microhydro at 31.5 kW

Start
Step 1: initialization of the mutation and crossover functions
Step 2: Initialization of the population of chromosomes of size N and dimension dXi, j $\forall$ $i \in \{1, 2, \ldots, N\}$ and $\forall$ $j \in \{1, 2, \ldots, d\}$
Step 3: Evaluate the fitness value of each chromosome Fi $= f$ (Xi, j) and determine the best solution
Step 4: set the iteration number $y = 1$
Step 5: Determine the chromosomes' reproduction percentage
  For $l = 1:1:N$
    $i = \text{randi}\ (N) \epsilon \{1, 2, \ldots, N\}$
    $x_{l,j} = X_{i,j}^{y}$
  End
Step 6: Generate percentage crossover of parent chromosomes ($x_{l,j,b}$ is $x_{i,j}$ in binary form) and offspring mutation
  For $l = 1:2:\text{CF} \times N$
    $g = \text{randi}$ (bits of chromosome) $\epsilon \{1, 2, \ldots,$ (bits of chromosome)$\}$
    $$X_{l,j,b}^{y+1} = \begin{cases} x_{l,j,b} & \forall\, j \leq g \\ x_{l+1,j,b} & \forall\, j > g \end{cases}$$
    $$X_{l+1,j,b}^{y+1} = \begin{cases} x_{l+1,j,b} & \forall\, j \leq g \\ x_{l,j,b} & \forall\, j > g \end{cases}$$
  End
Step 7: Generate percentage mutation of chromosomes $X_{l,j,b}^{y+1}$
  For $l = 1:1:N$,
    if rand () $<$ MF
    $i = \text{randi}$ (bits of chromosome)
    $$X_{l,j,b}^{y+1} = \begin{cases} 0 & \text{if } x_{l,j,b} = 1 \\ 1 & \text{if } x_{l,j,b} = 0 \end{cases}$$
    End
  End
Step 8: Calculate fitness $F_i^{y+1} = f\,(X_{l,j}^{y+1})$ and determine the best fit chromosome b ($X_{l,j}^{y+1}$ is the decimal representation of $X_{l,j,b}^{y+1}$)
Step 9: If $F_b^{y+1} = F_{b1}^{y}$ then $b = \text{b}1$
Step 10: If $y <$ max_iteration, then $y = y + 1$; and go to step 5 and continue henceforth
Step 11: Return $X_{j,b}^{y+1}$ which is the optimum solution.

Algorithm: Genetic algorithm.

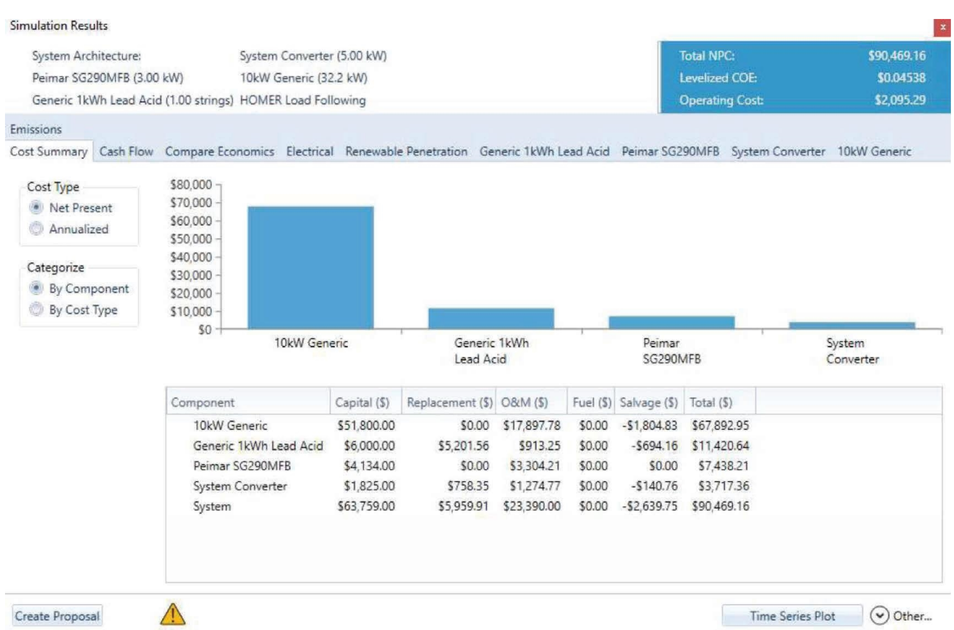

Figure 8: Summary of system cost.

whereas the green colour represents the 24.61 kW (reduction in power generation). As for the blue colour, it represents the power output of the least power generation from the microhydropower (worst period of the year). After running the system to understand the output power for each component for one year, December 13 was found to be the worst day with the lowest microhydro output and maximum battery charging and discharging.

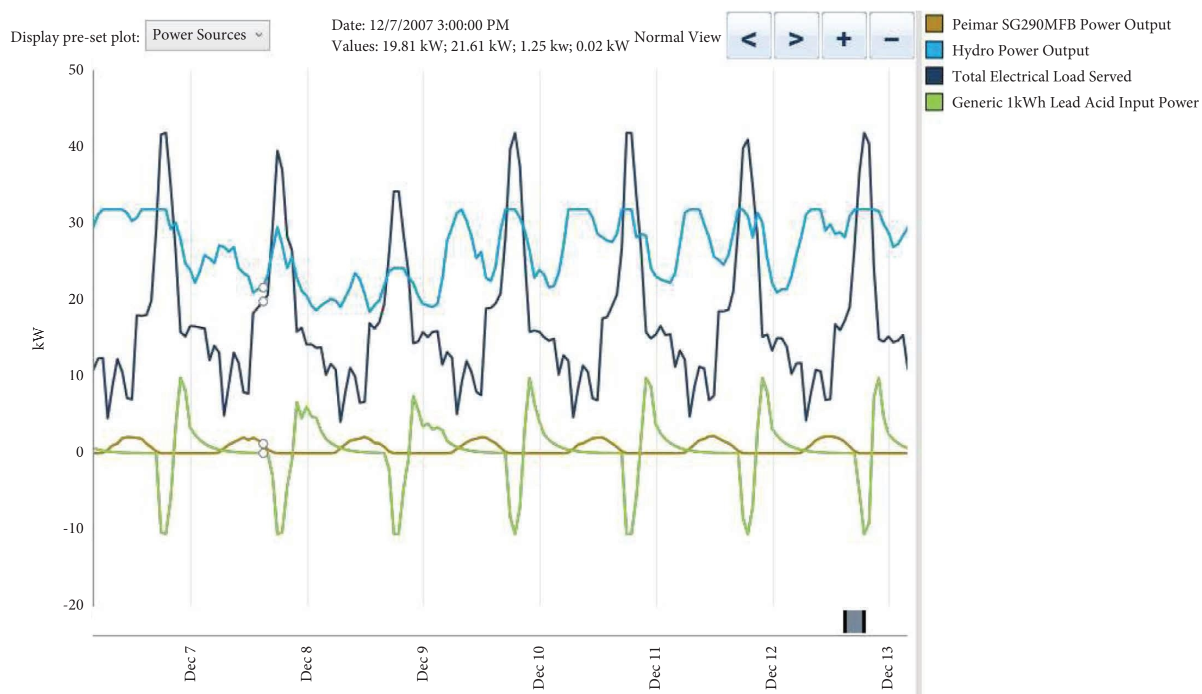

Figure 9: Annual energy flow of the hybrid system.

Table 7: Data for solar PV production.

Item	Value
PV penetration	3.41%
Minimum output	0 kW
Maximum output	3.10 kW
Rated capacity	4 kW
Capacity factor	15.3%
Hours of operation	4380 hrs/year
LCOE	0.145 $/kWh
Total annual energy yield	5363 kWh/year

3.3. Battery Charging and Discharging from the HOMER Pro Simulation. From the simulation, the annual energy supplied to the loads by the battery bank was 287 kWh/yr while the annual charging energy of the battery system was 326 kWh/yr. It is noticed that the annual battery charging energy is greater than the energy supplied to the load because the battery system charges slowly but discharges rapidly to quickly respond to the peak demand. It is recommended to charge batteries slowly, especially lead batteries, in order to extend their lifetime through a reduction in the current flowing through their terminals.

Figure 14 shows that the input power from the hybrid system used for battery charging and the battery state of charge during the months of February. February 19 to February 15 is the period with the worst battery discharge scenario where maximum battery discharge went down to 38.06% of the state of charge. It is observed that the system input power used to charge the battery reduces exponentially while the battery state of charge increases. Also, it is observed that as the battery SOC increases, less and less input power from the hybrid system is needed to charge the battery.

3.3.1. Battery Sizing. After running the simulation, the battery bank's maximum power delivered in a year is 6.43 kW per hour, and hence, the load energy provided by the battery is 6.43 kWh.

Thus, the net capacity storage of the battery (B_{charge}) in Ah/day is [4]

$$B_{\text{charge}} = \frac{E_t}{V_{T\_\text{bat}} \times \text{DOD}} = \frac{6430\ \text{Wh/day}}{48\ V_{\text{DC}} \times 0.4} = \frac{334.89\ \text{Ah}}{\text{day}}, \tag{18}$$

where DOD is the battery depth of discharge and assumed to be 40%, E_t is the total load energy met by the battery bank, and $V_{\text{T\_bat}}$ is the battery bank terminal voltage.

The battery autonomy is 1.9 hours because there is a high flow rate from the run-of-river hydro, and the optimization program supports more hydropower generation because it is cost-competitive. Therefore,

$$B_{\text{charge}} = \frac{334.89\text{Ah}}{\text{day}}. \tag{19}$$

The total Ah needed in the system is determined by calculating the number of batteries connected in series and in parallel. The selected battery is 260 Ah.

$$N_{\text{bat\_}P} = \frac{B_{\text{charge}}}{B_{\text{Single\_bat}}} = \frac{334.89\text{Ah}}{260} = 1.28 \cong 1\text{battery}, \tag{20}$$

where $N_{\text{bat\_P}}$ is the number of batteries in parallel and $B_{\text{Single\_bat}}$ is the charge in ampere hour (Ah) of a single battery.

Computing the number of series connected batteries [4]

$$N_{\text{bat\_Series}} = \frac{V_{\text{sys}}}{V_{\text{bat}}} = \frac{48}{24} = 2\ \text{batteries in series}, \tag{21}$$

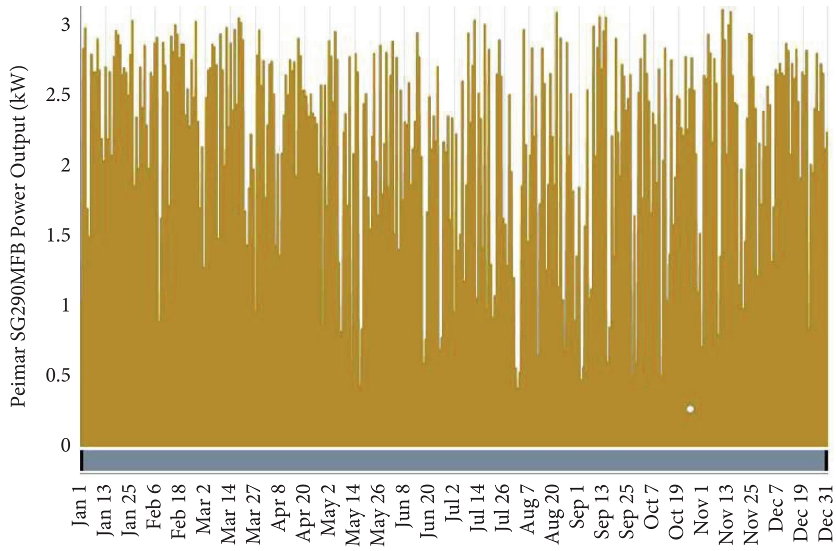

Figure 10: Peimar SG290MFB solar power output.

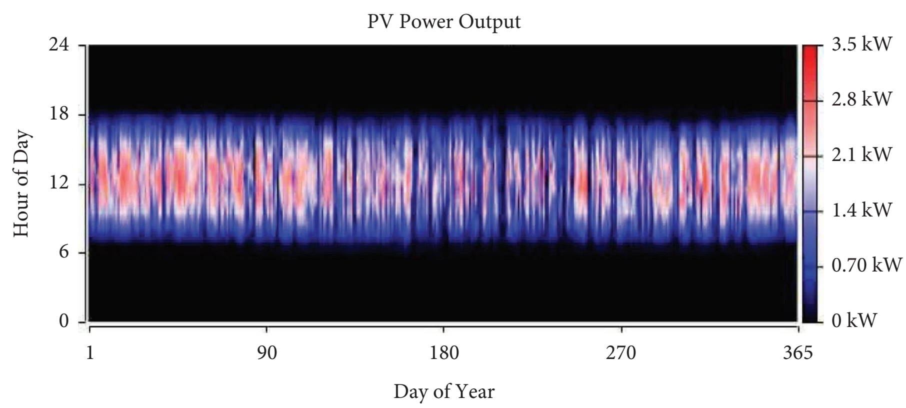

Figure 11: Power output of the solar PV system.

where N_{bat_series} is the number of series connected batteries, V_{bat} is the voltage of a single battery.

The total number of batteries needed in the system is [4]

$$N_{bat\_Total} = N_{bat\_P} \times N_{bat\_Series} = 2 \times 1 = 2\,\text{batteries}, \quad (22)$$

where N_{bat_Total} is the total number of battery units.

3.4. Grid Extension Analysis in HOMER Pro. The impact of the system's LCOE is compared with the actual average cost of electricity in Cameroon without subsidy. The amount used for the unsubsidized cost of electricity in Cameroon is 0.12 \$/kWh for residential users. The electricity tariff in Cameroon is currently subsidized by the government, and it is 0.07 \$/kWh for residential customers. Comparing the unsubsidized electricity tariff helps in the identification of the cost-optimal solution of the mini-grid with respect to grid extension. The extension of the medium voltage (MV) line in Cameroon is 10,000 \$/km [42], with an O & M cost of 200 \$/year/km. It was observed that the system's break-even grid extension distance was 2.21 km. This implies that the hybrid off-grid system with an LCOE of 0.0453 \$/kWh is competitive for locations further than 2.21 km from the nearest grid-connected community. However, the community is about 23 km away from Esu village which is the nearest grid-connected community; therefore, the off-grid option is economical. Figure 15 shows the system's break-even grid extension distance.

Table 8: Output of the microhydro system.

Item	Value
Hydro penetration	175%
Nominal capacity	32.5 kW
Average output	31.5 kW
Total hydro production	275584 kWh/year
Operating hours	8760 hrs/year
LCOE	0.063 \$/kWh
Capacity factor	134%
Maximum output	31.8 kW
Minimum output	18.4 kW

3.5. Sensitivity Analysis of the Hybrid Microhydro-Solar Battery System. A sensitivity assessment is required to examine how system variables are affected by major changes in

Figure 12: Microhydro system output power.

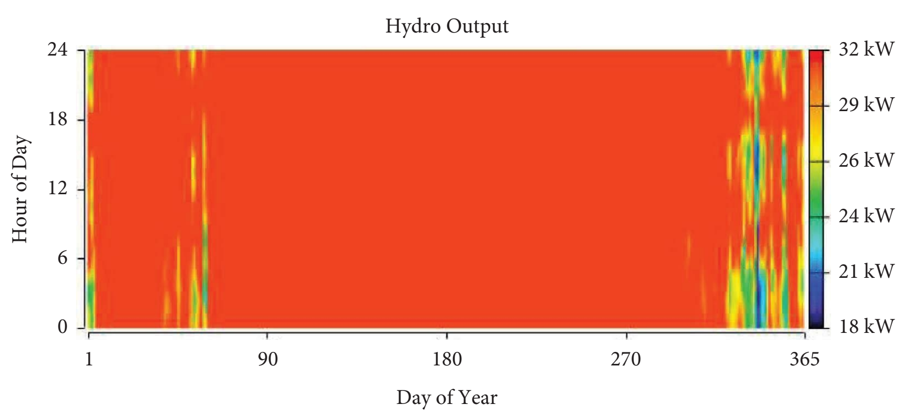

Figure 13: Heat map of the annual microhydropower production.

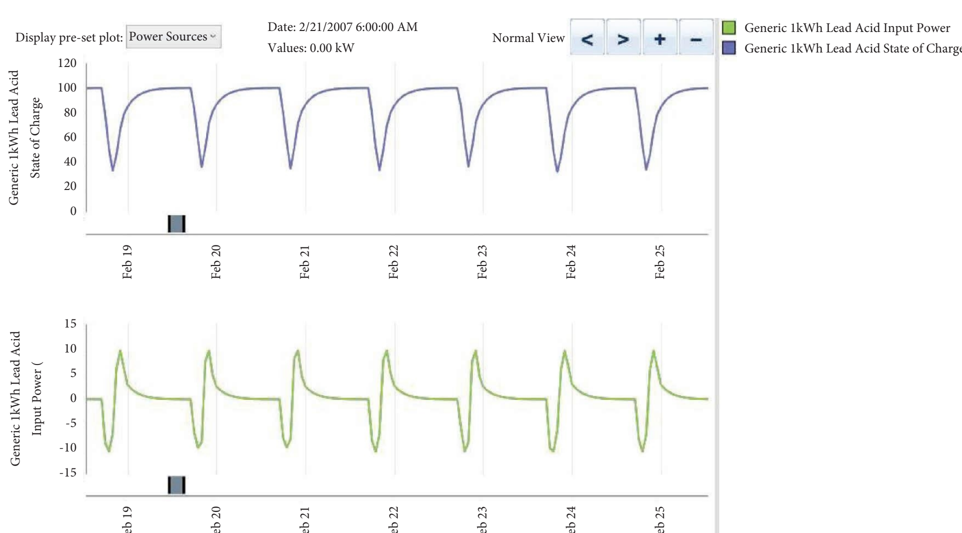

Figure 14: Hybrid system input power supplied to charge the battery and battery state of charge.

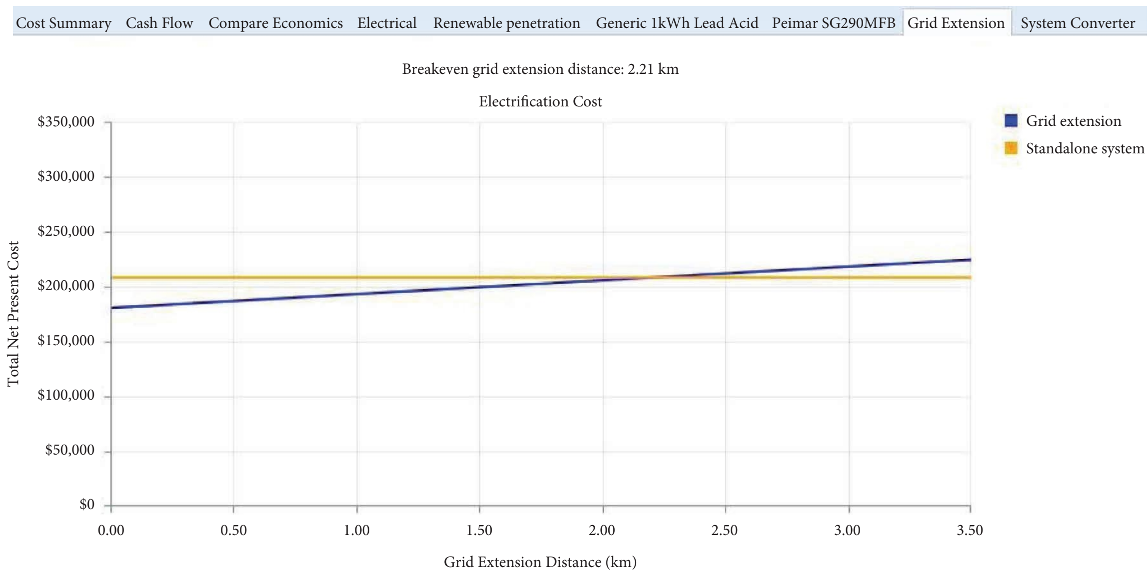

Figure 15: The assessment of the hybrid system and the existing grid.

the network. In optimizing off-grid system with a battery bank, the HOMER tool usually supports the configuration of having a battery bank because it uses the lifetime of the battery bank which is far from what happens in practical applications. This is the reason why results obtained from a simulation tool, with often ideal considerations, need to be properly interpreted from a practical perspective. This weakness of the choice of system suggested by HOMER is reflected in the variation of microhydropower output and the LCOE, as shown in Figure 16. It shows how the LCOE steadily drops as the hydropower input increases, an indication that the microhydropower is capable of providing power at one of the lowest costs for off-grid applications in Cameroon.

The battery capacity required in the system was monitored while the hydropower output was increasing, and it was observed that the battery size dropped considerably with rising hydropower generation, as seen in Figure 17. The figure shows a drastic drop in the battery capacity as the hydropower output is increased. It implies that the battery bank can be completely eliminated with the addition of more hydropower capacity. The battery plates undergo considerable stress that helps reduce their expected lifetime. The addition of more batteries in the system leads to high O & M costs and having to replace the battery over two times before the end of the project. These challenges make the use of this configuration unfavorable for rural electrification.

The optimal combination of the hybrid system is the 32.2 kW microhydro and the 3 kW solar PV, without a battery bank. The HOMER Pro simulation intuitively supports the option based on the battery autonomy of less than 2 hours (1.96 hours) obtained after the system optimization. A huge investment in adding a battery system with an autonomy of less than two hours is a reckless economic decision especially for an off-grid system targeting rural areas. Besides, eliminating the battery bank helps to avoid the deep and extended battery discharges which significantly reduce the lifespan of the battery. The selection of this configuration considers the practical and operational resilience of hydro systems which deliver fairly stable power supply to the base load at a relatively lower LCOE and less failure rates. Small-scale hydroelectric plants can also provide flexibility to support solar PV systems [43]. The optimization saw a steady solar PV capacity with rising hydropower output, as seen in Figure 18.

The sensitivity analysis shows a stable solar PV output, a decreasing size of the battery bank and LCOE while the hydropower is increasing. With the abundance of microhydropower resources in Cameroon, this option will help to provide cheap electricity to low-income earners in rural communities. However, the system's reliability depends on a broad study of the river flow rate of the facility in order to determine the seasonal variation and flow rates. Therefore, it is advisable to add hydropower generation to storage capacity. Though the use of energy storage will help to stabilize the intermittent solar PV in providing energy on demand, the cost of frequent battery replacement has been a major obstacle over the years. The optimum system combination depends on the load profile, and hence, studying the power demand profile is vital in matching demand and supply of electricity. It should be noted that the LCOE (0.0453 $/kWh) for the optimum system proposed by the HOMER simulation is far less than the grid parity in Cameroon for residential customers (60 XAF/kWh ≈ 0.07 $/kWh). This is so because the electricity tariff has been subsidized by the government and any economic assessment that fails to consider this aspect will yield a deceptive economic decision. However, a further increase in hydropower capacity is capable of further reducing the LCOE as well as the battery capacity.

Meanwhile, hydropower will greatly contribute to carbon reductions for future decades [44]. While wind and solar installations have equally grown recently, the most-used RE resource for power generation globally is currently hydropower. Hydroelectricity will continue to play a unique role in

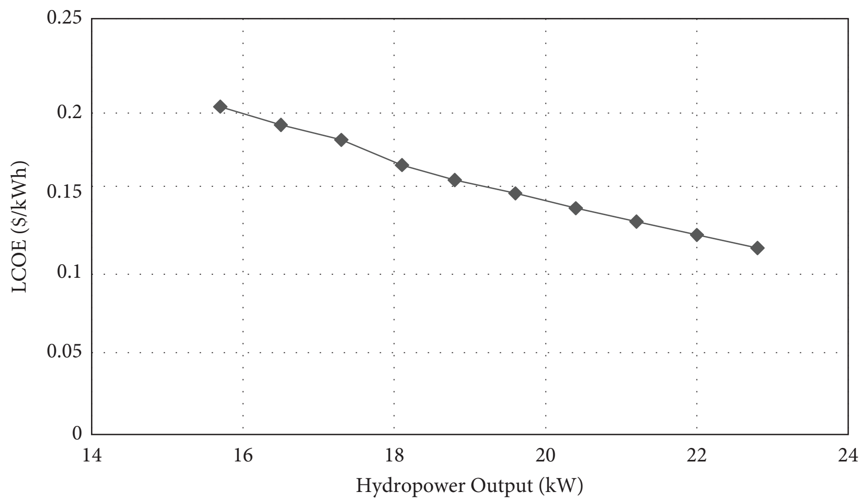

Figure 16: Variation of LCOE against hydropower output.

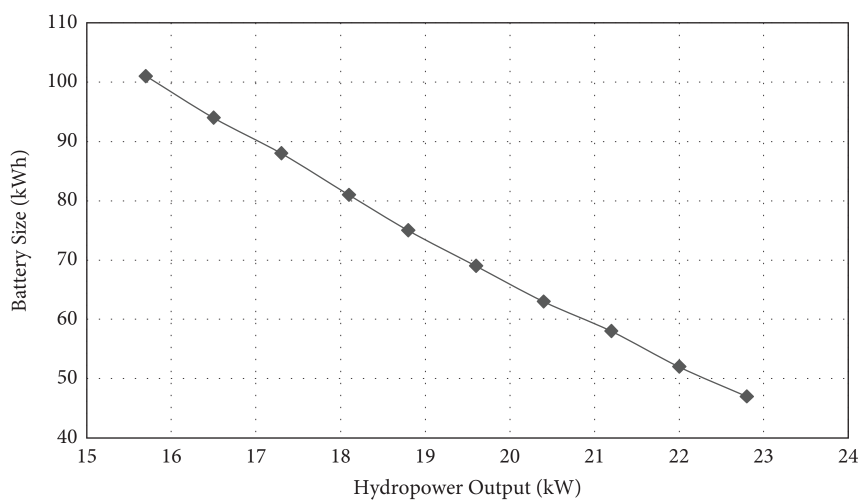

Figure 17: Variation of battery size versus hydropower output.

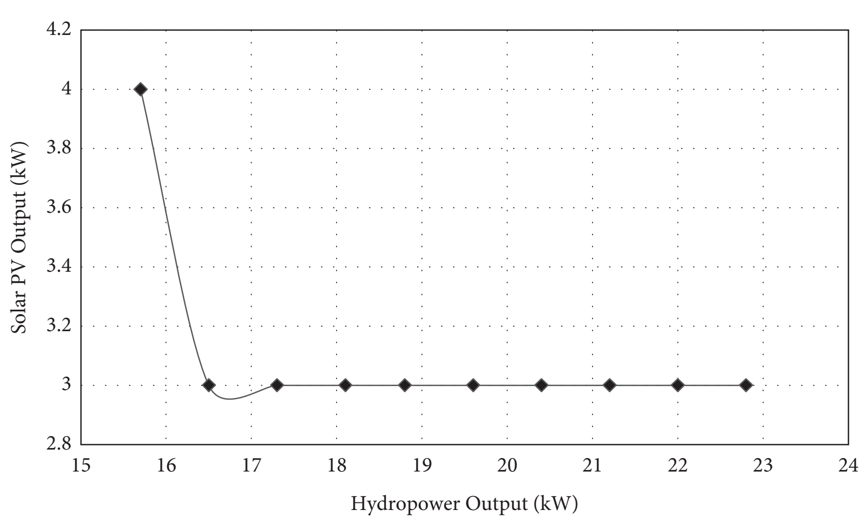

Figure 18: Variation of solar PV output versus hydropower output.

modern power grids due to its economic viability [45]. The deployment of small-scale hydroelectric technologies for rural electrification is cost-effective and has low environmental impacts. Another important driving force in hydroelectric development is their role in pumped storage where they facilitate the integration of intermittent wind and solar PV systems [6]. Therefore, it is recommended that the government promotes, the use of the huge hydropower potentials, ensuring the production of base power in off-grid communities from hydro, which will help provide the needed flexibility for the subsequent integration of wind and solar in the network.

Cameroon has an estimated large hydropower potential of 23 GW and a potential for small hydro of about 970 MW [46] distributed across the country. This represents an indisputable asset for electrifying remote areas in Cameroon. There is also a useable potential of about 34 GWh for pumped hydropower in Cameroon which has less environmental impact [47]. Nonetheless, it remains under-exploited with large hydro having an exploitation rate of less than 5%, 0% for pumped-hydro and <0.1% for small-hydro. Hybridizing these small hydro-based renewables with other sources can contribute in stabilizing the transmission network in Cameroon. There are promising prospects for small hydro in Cameroon especially with the backing of the HYPOSO (hydropower solutions) framework [48], whose aim is to increase the renewable energy share and rural electricity access through sustainable hydropower solutions within five countries including Cameroon. Pumped-hydro storage plants, because of their mode of operation, would significantly contribute to Cameroon's energy policy in that they would facilitate the integration of variable energy sources and improve on the required flexibility to regulate possible grid congestion. The government established the Vision 2035 as the nation's expansion blueprint. The objective of the vision is to transform Cameroon into an industrialized, middle-income country with a guaranteed high living standards for Cameroonians by 2035, and clean energy supply has been identified as a pillar in meeting this goal. In line with this strategic vision, Cameroon has equally adopted the UN SE4ALL (Sustainable Energy for All) program.

This study shows how small-hydroelectric installations can cost-effectively electrify rural communities and opines that the government should facilitate an institutional framework that does not emphasize only on large-scale hydroelectric generation but also on small-scale facilities which are known for their less environmental and social impacts. The pumped-storage hydro can be used to replace the battery storage and hence evade the high cost imposed by a battery. This will help to intervene during peak-load periods and store power during periods of excess generation. Interestingly, the technical potential in Cameroon is sufficient to adequately shape the institutional framework.

3.6. System Validation with GA. To validate the results obtained from HOMER Pro, the optimization was done using GA following the procedure mentioned in Section 2.7 above. System optimization of LCOE, LPSP, and NPC was executed using GA developed in the MATLAB environment with an HP ProBook workstation equipped with two 2.50 GHz Intel Core CPUs and 4 GB of RAM.

The GA approach converged into an optimal solution at the 10^{th} iteration, as seen in Figure 19. GA is stronger at exploring the global search space than HOMER Pro, giving it the ability to perform better at locating the global optimum. It implies that the fitness landscape of this optimization problem can be better solved using GA, as it can quickly locate an optimal solution.

The optimum system size of GA showed the least LCOE with the proposed capacities of 3 kW solar PV, 34.56 kW hydropower, and no battery storage. The NPC, LPSP, and LCOE obtained by GA were, respectively, \$86,990.94, 0.99%, and 0.0344 \$/kWh. The LPSP of 0.99% obtained in the GA showed that the proposed hybrid RE system respected the LPSP condition (LPSP < 5%), implying that the system is reliable.

Comparing the results from GA and HOMER Pro, GA gave a lesser LCOE of 0.0344 \$/kWh than HOMER Pro (0.0453 \$/kWh). However, the LCOE obtained from the two approaches is acceptably satisfactory especially for rural electrification where the beneficiaries are often low-income earners. Similarly, the NPC obtained from the GA method (\$86,990.94) was less than that obtained using the HOMER Pro (\$90,469.16) approach. The lower LCOE and NPC values of GA can be explained by its sensitivity to minimize or completely ignore components of the system that increase system cost, as seen in the optimal configuration that has no battery storage. This supports the fact that stochastic methods are more realistic, economically viable, and accurately predict system operation than deterministic methods.

A summary of the results from the GA and HOMER Pro are presented in Table 9. The results show that the GA approach is more cost-effective compared to HOMER Pro. The LCOE of GA was 0.0344 \$/kWh while that of the HOMER Pro simulation was 0.0453 \$/kWh. Also, the GA simulation had more hydropower capacity than the HOMER Pro simulation. The GA's more orientation towards hydropower generation is due to the cost-competitive nature of hydroelectric plants over solar PV and battery storage. From Table 9, it is observed that GA gave zero battery capacity, and it is explained by the high cost of purchasing and replacing batteries within the project life.

3.7. Discussion of Results. The plot in Figure 16 is a curve response on the sensitivity of the system's LCOE to the variation in hydropower capacity of the optimum configuration system. According to the figure, the LCOE of the optimal system seems to respond directly to variation in the hydropower capacity, as seen in the steepness of the curve. This implies that sufficient resources should be allocated for the accurate mapping of microhydroelectric sites in Cameroon.

Considering the results obtained from this study and comparing them with similar studies in Cameroon and beyond, we benchmark our findings with the results

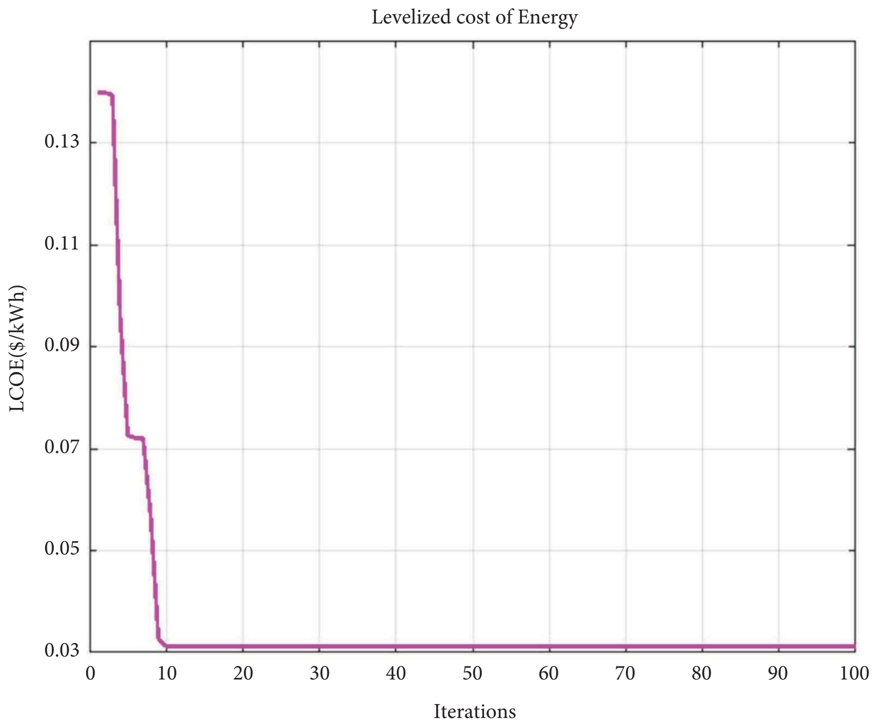

Figure 19: Convergence curve of the GA simulation.

Table 9: Comparative analysis of HOMER Pro and GA simulation.

Optimization approach	HOMER Pro	GA
Total NPC ($)	90,469.16	86,990.94
LCOE ($/kWh)	0.0453	0.0344
Hydropower capacity (kW)	32.2	34.56
Solar PV capacity (kW)	3	3
Battery capacity (Ah)	334.89	0

presented by [16] where they used the particle swarm optimization (PSO) to design a hybrid off-grid power system in Cameroon. Their study found the battery-PV-diesel generator (DG) as the optimum configuration at an LCOE of 0.132 $/kWh which is far more than the amount obtained in our study. This puts the affordability of this system into question and casts doubt on whether this system can be sustainably managed by the beneficiaries who are mostly low-income earners. Still in Cameroon, the findings of [18] on the optimum microhydro/DG/PV/battery architecture using the HOMER software did not tally with those obtained from our study, as the LCOE for their study was 0.443 $/kWh. It is evident that the addition of a DG as part of the optimal system not only increases the operation cost but equally damages the environment, and this justifies the difference between the LCOE obtained in their studies and that gotten from this study. The findings from our research agree with those of [17] where the hydro-PV was designed for a rural community in Cameroon. The scholars found an optimum LCOE of 0.06192 $/kWh which is closer to the value obtained in our study.

Comparing with the findings by [49], we equally observed that the biogas-PV-biomass-wind-fuel cell-battery system did not agree with the results of our study. Their LCOE of 0.214 $/kWh was, however, higher when gauged with the outcome of our study. Judging the results of our studies with that of [50] where GA was used on a rural power system in India, the optimum solar-biogas-biomass-wind-fuel cell-battery system disagreed with the findings of our studies. Unlike our study with a low LCOE, their study produced electricity at an LCOE of 0.163 $/kWh. Similar studies in Nigeria by [51] using the same method presented an optimal solar-wind-battery-DG system with an LCOE of 0.25 $/kWh which is high when compared to the LCOE of the optimal system in our study. Judging our studies with findings from [52] using HOMER where the PV-micro-hydro-battery combination was selected as the optimal system to power an off-grid community in Ethiopia, their results were in harmony with those obtained from our study. The LCOE obtained in their study was 0.044 $/kWh as the system was mainly powered by hydroelectricity.

A glaring observation, which is significant to note, is that while the DG forms part of the major component in the optimal systems of the research works [16, 18, 20, 51], it is absent in the optimal configuration of our study. This has considerably affected the LCOEs of these systems, as fuel prices and operation cost are likely to affect the economic viability of the systems. The possible justifications for these noteworthy differences are as follows:

(i) Variation in resource availability influences the output.

(ii) Nearness to component manufacturers cuts the replacement and capital costs of components which in-turn reduces the LCOE and NPC.

(iii) Changes in diesel prices cause variation in LCOE.

(iv) Addition of more hydropower capacity to the electricity generation mix can potentially reduce the LCOE of the project.

There are a few hydro-based hybrid systems available in the literature. The year 2009 witnessed the construction of the world's first 10 MW hydro-solar power plant in Yushu, China [53]. Six years later, a larger hydro-solar PV power plant was constructed in Qinghai, China, with an overall solar capacity of 850 MW [54]. Although hydroelectricity significantly contributed to meeting the peak load in our study, the overall outlook seems to suggest that solar PV technology is ideal, as we observe a stable 3 kW solar capacity in Figure 18. This implies that just like microhydro water flow rate data, substantial investment is equally needed to establish an effective solar radiation data center in Cameroon. The system's viability can also be improved by providing tax cushions on RE components. This will significantly reduce the initial capital cost and hence, minimize the LCOE and NPC.

4. Conclusion

This paper presents the results of the optimization of a hybrid solar PV-micro hydro energy system for the electrification of a remote community in Cameroon. The proposed system was simulated using GA and HOMER Pro with inputs such as the stream flow rate, the solar radiation, and the cost of system components. The analysis was compared with the grid extension option to determine whether the hybrid off-grid option was competitive, and the break-even grid distance was determined. The system's life-cycle cost was conducted for over 25 years. First, HOMER was used to optimize the system, and the results of the HOMER simulation revealed that the solar/hydro/battery system can meet the village loads with an optimal size of 32.2 kW microhydro, 3 kW solar PV, 2 units of generic 260 Ah lead battery, and 21.63 kW converter. This option represents an LCOE of \$0.0453/kWh and an NPC of \$90,469.16. Furthermore, the GA was simulated with MATLAB coding, and it gave an NPC, LCOE, and LPSP of respectively \$86,990.94, 0.0344 \$/kWh, and 0.99%. The optimal system configuration obtained during the GA approach was 34.56 kW hydropower capacity, 3 kW solar PV, and zero battery storage. When the GA and the HOMER simulations were compared, the GA method was more cost-effective than the HOMER method with the least LCOE and NPC. All the sources used in the system were renewable, and hence, the proposed system was environmentally friendly. With the increasing global advocacy for sustainable development goal (SDG) 7, this study is in line with the tenet of affordable and clean energy. Again, there is no general optimal solution for hybrid renewable energy systems due to multiple constraints. Some in-depth technical details need to be carried out by the modeler to make final design decisions, and the best hybrid system depends on the customer's consumption profile. A limitation of this study is that the load profile was based on estimates which are likely to deviate from reality if the system is to be deployed in real life. Hence, there is a need to conduct a thorough load demand assessment in the community before the implementation of the hybrid system. The optimum operational reliability of a hybrid system including hydro in the mix is dependent on extensive analysis of river flow rates to ascertain the season of possible flow variations. The flow data used in this study were scaled from data obtained from a neighboring river, and the deployment of this system in the community will require analysis of the river flow in the community. Also, demand response is essential in microgrid design due to uncertainties in supply and to maintain operational reliability when energy production is less than demand. If reserved power is needed to meet short-term power shortages, an extra expenditure needs to be considered for the suitable reserve with a pondage that will provide auxiliary power supply to complement supply during seasons of low inflows or low solar radiation and minimize excess energy production.

This study demonstrates the use of a hybrid renewable energy system to meet the electricity needs of the Munkep community at a cost that is far below the unsubsidized utility tariff of 80 CFAF/kWh (\$0.12/kWh) in Cameroon. The study proposes a solution to meet the electricity needs of the village. The viable solution recommended by this study is the installation of a 32.2 kW hydropower capacity of 3.2 m height at an average flow of 1.5 m^3/s and a 3 kW solar PV system without a battery network. These findings will help stimulate policy on renewable energy utilization, especially incentives on the acquisition of PV and hydropower systems by communities. However, future studies can explore the use of cascaded hydropower turbines within the same river corridor to improve overall system efficiency as well as possibly integrate another energy resource to improve energy production in the village.

Nomenclature

A_{PV}:	Area of a single solar panel
B_{charge}:	Net capacity storage of the battery
CF:	Cross-over factor
C_{Cap}:	Capital cost of the system
$C_{\mathrm{O\&M}}$:	System's operation and maintenance cost
C_R:	System's replacement cost
$\mathrm{dX}_{i,j}$:	Chromosome dimension
$E_{\mathrm{Batt(t)}}$:	Energy stored in the battery at a time t
$E_{\mathrm{Batt\_min}}$:	Minimum energy that can be stored in the battery
E_{Load}:	Energy consumed by load
E_t:	Total load energy met by the battery bank
Fi:	Fitness value of each chromosome
g:	Acceleration due to gravity
G:	Solar radiation
G_{ref}:	Solar radiation at reference conditions
H_n:	Net head
i:	Interest rate
I_R:	Controller current ratings
I_{SC}:	Short-circuit current of a single panel

K_T: Panel temperature coefficient
MF: Mutation factor
n: Project life time
N: Total number of iterations
$N_{\text{Bat\_max}}$: Maximum number of batteries
$N_{\text{bat\_P}}$: Number of batteries in parallel
$N_{\text{bat\_Total}}$: Total number of battery units
N_p: Number of solar panels connected in parallel
N_s: Number of solar panels connected in series
$N_{\text{solar\_Max}}$: Maximum number of solar modules
$N_{\text{T\_PV}}$: Total number of solar panels
P_H: Power produced by the hydro system
P_{Hydro}: Total generated hydroelectric power
$P_{\text{Hydro\_Max}}$: Hydro turbine's maximum power
P_{load}: Total system load
P_{Peak}: Peak solar power capacity
P_{PV}: Total generated PV power
$P_{\text{out\_pv}}$: Output power of the PV system
$P_{\text{PV\_rated}}$: Solar panel rated power
$P_{\text{R\_Con}}$: Converter power ratings
P_{Trans}: Maximum transferred power
Q: Flow rate
Q_{min}: Minimum flow rate
Q_{max}: Maximum flow rate
T_{amb}: Ambient temperature
T_c: Cell temperature
T_{ref}: Cell temperature at reference conditions
V_{bat}: Voltage of a single battery
V_m: Nominal voltage of a single solar panel
V_{sys}: System voltage
$X_{l,j,b}^{y+1}$: Bits of chromosome
ρ: Water density
η_{TG}: Turbine and generator efficiency
$: United States dollar
ASC: Annualized system cost
BO: Bonobo optimizer
CPU: Central processing unit
CRF: Capital recovery factor
DE: Differential evolution
DG: Diesel generator
DOD: Depth of discharge
ENEO: Energy of Cameroon
GA: Genetic algorithm
GHG: Greenhouse gas
HOMER: Hybrid optimization model for multiple energy resources
HYPOSO: Hydro power solutions
LCOE: Levelised cost of energy
LPG: Liquefied petroleum gas
LPSP: Loss of power supply probability
NASA: National aeronautic and space administration
NGOs: Nongovernmental organizations
NPC: Net present cost
MV: Medium voltage
O & M: Operation and maintenance
PSO: Particle swarm optimization
PV: Photovoltaic
RAM: Random access memory
RE: Renewable energy
SE4ALL: Sustainable energy for all
SHSs: Solar home systems
SOC: State of charge
STC: Standard test conditions
TAC: Total annual cost
XAF: Central African franc

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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