Optimal Decision-Making on Hybrid Off-Grid Energy Systems for Rural and Remote Areas Electrification in the Northern Cameroon

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1. Introduction

The electrification of rural and remote areas still remains a serious problem in some localities worldwide, especially in developing countries. Access to electricity improves the population’s living conditions and leads to sustainable development. Many rural and remote areas are not connected to the national electricity grid because of their isolation and economic reason, and because the main grid electricity cannot fulfill the energy demand in some cases. Solutions to rural electrification are envisaged by the use of off-grid energy production systems like standalone diesel generator (DG) systems [1], standalone PV/battery systems [2], or standalone Wind/battery systems [3]. However, it has been proven that the combination of several energy production sources could be more profitable than the use of only one source of energy economically, technically, and even environmentally. Several studies have
been conducted to demonstrate hybrid standalone systems’ performance and reliability [4–16]. Alshammari and Asu-
madu [4] performed an optimal hybrid renewable energy system sizing using a combined optimization algorithm. Different configurations of hybrid systems made up of wind, photovoltaic, biomass, and battery have been studied to minimize the cost and ensure the system’s reliability to meet the load’s demand. The best optimal reliable configuration obtained had a total system net present cost (NPC) of $581,218 and a cost of energy (COE) of 0.254 $/kWh. Akram et al. [5] proposed a hybrid energy system for energy supply in remote areas. The system was made up of photovoltaic, wind, diesel generator, and battery. The optimal design of the different scenarios considered has been performed using HOMER software. It has been demonstrated that hybrid renewable energy systems (HRESs) were very suitable for remote areas. A proper operational strategy definition could lead to cost reduction and an increase in the system’s performance. Costs reduction by hybrid energy systems has also been demonstrated by Cai et al. [6], who proposed a hybrid optimization algorithm to minimize the total life cycle cost of a hybrid photovoltaic/diesel generator system for energy supply in rural and remote areas. South Khorsasan has been considered as a real case study for this purpose. The performance of the used optimization approach based on the geographic information module has been demonstrated by comparison with other methods existing in the literature. It has been demonstrated that hybrid photovoltaic/diesel generators are more profitable than the use of the diesel-only system, leading to the reduction of greenhouse gas emissions by 59.6% and the energy cost by 22.2%. Kumar and Saini [7] analyzed the feasibility of an optimal off-grid hybrid renewable energy system to provide electricity and fresh water in some nonelectrified villages in India. The Salp Swarm Algorithm (SSA) has been used for the techno-economic analysis of the system. For a total of 266 households with an average of 4 living persons in a household, the optimal cost of energy determined was 0.21779 $/kWh for a loss of power supply probability of 0%. According to Ramesh and Saini [8], a significant Indian population lives in villages, and some live in remote areas which are disconnected from the grid connectivity. Since the connection to the grid is not feasible for these populations, the use of an off-grid hybrid renewable energy system appears to be viable. They have proposed a dispatch strategy based on performance analysis for energy supply in a remote rural area of Karnataka, a state of India. Two different configurations of hybrid systems have been considered for this study, including the photovoltaic/hydro/battery and the photovoltaic/wind/hydro/diesel generator/battery. The optimal configurations have been obtained by simulation in HOMER Pro (Hybrid Optimization Model for Electric Renewable). For a total of 297 households (with 4 persons per household), the feasible COE for the proposed hybrid systems has been found in the range of 0.1 $/kWh-0.162 $/kWh. A techno-economic analysis of off-grid solar PV/Fuel cell energy system has been realized by Ghenai et al. [9] for residential communities in desert regions. They have found that for an energy demand of 4500 kWh/day of a residential neighborhood (corresponding to 150 households), the corresponding cost of energy was 145 $/MWh with zero carbon dioxide emissions during electricity generation. A similar study has been performed by Vendoti et al. [10], who analyzed the techno-economic feasibility of off-grid solar/wind/biogas/biomass/fuel cell/battery system for villages’ electrification using HOMER software. Different configurations of the proposed system have been simulated. The obtained results showed that the combination of PV, wind, biomass, biogas, fuel cell with battery was the cheapest and most dependable solution with a COE of $0.214/kWh for a total load demand of 724.83 kWh/day.

However, some authors demonstrated that standalone hybrid systems were more expensive than grid energy. It is, for example, the case of Jahangir et al. [11], who studied the feasibility of hybrid on/off-grid photovoltaic/wind/wave energy converter for energy supply in coastal cities. A comparative analysis revealed that the grid-connected system with 0.093–0.139 $/kWh cost of energy was more cost-effective than the off-grid system with 0.136–0.182 $/kWh for large-scale demand. Moreover, the use of wave energy converter could reduce the need for batteries in hybrid energy systems, although it was more expensive for the areas with lower wave potential. Das et al. [12] have also performed a techno-economic and environmental study of a hybrid renewable energy system made up of photovoltaic, wind turbine, biogas generator, and battery. The system was used to supply electrical energy in Bangladesh’s remote island area, considered as a case study. It has been demonstrated that the proposed hybrid system configuration could only be competitive to the grid electricity supply at the loss of power supply probability of over 8% with significantly lower life cycle emissions. Duman and Güler [13] performed an economic comparison between an off-grid PV/wind/fuel cell hybrid systems and the grid-only system. For six different configurations of the hybrid system considered, the obtained results showed that the cost of electricity of off-grid renewable energy systems was found to be above the cost of grid electricity.

Hybrid standalone systems become more interesting when they are connected to the main grid. This is demonstrated by Samy et al. [14] who proposed a hybrid PV/wind/fuel cell system connected to the grid as a promising economic and environmental solution to the problem of power outages in distant districts. The obtained results demonstrated that the COE of the proposed system, which was 0.0628 $/kWh, was less than the purchase of the grid commercialized electricity in Egypt, which was 0.1 $/kWh. Thus, for localities that had access to the main grid electricity distribution, the hybrid renewable grid-connected systems could be economically more profitable.

Many localities in the northern part of Cameroon are not connected to the national electricity distribution network. Most of them are rural and remote areas. However, even the connected localities to the national grid are subjected to frequent network disturbances due to the insufficient grid power generated. Thus, both hybrid off- and on-grid-connected systems are necessary to be studied in this part of Cameroon. Furthermore, the northern part of Cameroon
has enormous wind and solar potential and is thus very adapted for the implementation of renewable energies. According to Mahmoudi et al. [15], the photovoltaic and wind systems to generate power are unreliable without a backup plan like diesel generators or storage devices like batteries.

Some research gaps related to rural electrification in developing countries need to be highlighted. Many configurations of standalone hybrid systems could fulfill the energy demand in the rural or remote locality considered. However, their optimal designs considering various comparative parameters are not always identified. Rural and remote areas in developing countries mostly use diesel generators for energy supply for economic reasons. However, the diesel generator is not always profitable even in the short-term investment. Thus, a depth understanding of different possible configurations and their interaction with the sensitive variables is requested.

The contribution of this research work is to optimally design different possible configurations of hybrid renewable energy systems for electrification in three localities of northern Cameroon, chosen as a case study. A comparative analysis allows identifying the optimal configuration for each selected comparative index. The classification of ten different configurations of energy systems according to the users’ priorities is realized for optimal decision-making related to the economic or environmental aspect. The advantages of associating diesel generator to renewable energy systems rather than considering the only diesel generator system for electrification in rural and remote areas are demonstrated in the present study.

2. Methods

Optimizing a renewable energy system requires identifying the potential energy resources of the site where the system could be implemented. Below are presented the areas of study and the modeling of the different components of the system.

2.1. Presentation of the Sites of Study. Cameroon is a country of Central Africa located between the 2nd and 13th degrees of north latitude and the 9th and 16th degrees of East longitude.

The natural environmental diversity of Cameroon includes the northern Sudano-Sahelian part, characterized by savannas and steppes.

The northern Cameroon is subdivided in three regions, namely, Garoua, Maroua, and Ngaoundéré. The geographical location of these tree localities chosen as case studies is presented in Figure 1 [17]. The irradiance, the wind speed, and the ambient temperature data of Garoua, Maroua, and Ngaoundéré are shown in Table 1 [18].

2.2. System Modeling. The main configuration of the studied systems is presented in Figure 2. From this main configuration which is the PV/DG/wind/battery system, nine other scenarios are analyzed and compared in the present study. These include PV/battery system, PV/wind/battery system, PV/wind/DG system, PV/DG system, wind/DG system, DG-only system, DG/battery system, wind/DG/battery system, and PV/DG/battery system. The modeling of the main components of all these configurations is presented in this section.

2.2.1. Estimation of the Load Demand. The systems are designed for household energy supply. A total of 12 households have been considered, with an average of 4 persons per household. From the daily profile of the energy demand corresponding to months, it can be observed that the energy demand is most important from February to May and from September to October (Figure 3). The energy demand decreases for the period of the year spanning from June to August and from November to January. The peak power of the load demand is 8.44 kW and the total annual energy demand is 46418 kWh with an average of 127.17 kWh/day.

2.2.2. PV Generator Modeling. The output power of the PV generator is calculated using

\[ P_{pv} = \frac{\beta_{pv} P_{pv,ref}}{G} \left[ 1 + \alpha(T_c - T_{c,NOCT}) \right], \]  

where

\[ T_c = T_a + \left( \frac{G}{G_{NOCT}} \right) \left( T_{c,NOCT} - T_{a,NOCT} \right) \left( 1 - \frac{\eta_{mp}}{0.9} \right). \]

\[ \beta_{pv} \] is the derating factor of the PV array; \( P_{pv,ref} \) is the PV array rated power; \( T_c \) is the PV cells’ temperature; \( T_{c,NOCT} \) is the PV cells’ temperature under standard test conditions; \( G \) is the solar radiation; \( G_{ref} \) is the solar radiation at reference conditions, \( G_{NOCT} \) is the solar radiation at the nominal operating cells temperature (NOCT); \( T_a \) is the ambient temperature; \( T_{c,NOCT} \) is the nominal operating cells temperature; \( T_{a,NOCT} \) is the ambient temperature at which NOCT is defined, \( \alpha \) is the power temperature coefficient; \( \eta_{mp} \) is the efficiency of the PV array at its maximum power point.

2.2.3. Diesel Generator Modeling. The fuel consumption of the diesel generator is defined by

\[ Fuel_{consumption} \left( \frac{l}{h} \right) = a \times P_{DG,N} + b \times P_{DG}. \]

\( P_{DG,N} \) is the rated power of the diesel generator, \( P_{DG} \) is the output power of the diesel generator, and \( a \) and \( b \) are, respectively, the fuel curve intercept (in l/kWh) and the fuel curve slope (in l/kWh).

2.2.4. Wind Turbine Modeling. The output power of the wind generator is determined by equation (4). The wind output power at the standard conditions of temperature and pressure \( P_{WTG,STP} \) is determined at the hub height wind
| Month | Clearness index | Daily radiation (kWh/m²/day) | Average wind speed (m/s) | Ambient temperature (°C) |
|-------|----------------|-------------------------------|--------------------------|--------------------------|
| **GAROUA** | | | | |
| Jan   | 0.611          | 5.384                         | 4.580                    | 26.600                   |
| Feb   | 0.613          | 5.826                         | 4.890                    | 29.060                   |
| Mar   | 0.593          | 6.052                         | 4.900                    | 31.520                   |
| Apr   | 0.572          | 6.017                         | 4.550                    | 31.510                   |
| May   | 0.539          | 5.634                         | 3.910                    | 29.450                   |
| Jun   | 0.519          | 5.357                         | 3.710                    | 27.760                   |
| Jul   | 0.448          | 4.638                         | 3.610                    | 25.910                   |
| Aug   | 0.436          | 4.550                         | 3.250                    | 25.230                   |
| Sep   | 0.497          | 5.101                         | 2.640                    | 25.840                   |
| Oct   | 0.584          | 5.647                         | 2.700                    | 26.720                   |
| Nov   | 0.667          | 5.956                         | 3.270                    | 26.720                   |
| Dec   | 0.657          | 5.619                         | 4.160                    | 26.170                   |
| **MAROUA** | | | | |
| Jan   | 0.645          | 5.679                         | 6.620                    | 24.440                   |
| Feb   | 0.635          | 6.034                         | 7.010                    | 26.910                   |
| Mar   | 0.617          | 6.298                         | 6.510                    | 30.290                   |
| Apr   | 0.617          | 6.492                         | 5.020                    | 32.260                   |
| May   | 0.579          | 6.057                         | 4.690                    | 31.410                   |
| Jun   | 0.551          | 5.692                         | 4.770                    | 29.330                   |
| Jul   | 0.487          | 5.038                         | 4.310                    | 26.720                   |
| Aug   | 0.473          | 4.938                         | 3.620                    | 25.400                   |
| Sep   | 0.525          | 5.383                         | 3.470                    | 25.920                   |
| Oct   | 0.622          | 6.017                         | 3.760                    | 27.290                   |
| Nov   | 0.677          | 6.049                         | 4.930                    | 26.680                   |
| Dec   | 0.661          | 5.651                         | 6.310                    | 24.770                   |
| **NGAOUNDÉRÉ** | | | | |
| Jan   | 0.631          | 5.817                         | 5.080                    | 20.890                   |
| Feb   | 0.609          | 5.974                         | 5.080                    | 22.810                   |
| Mar   | 0.580          | 5.989                         | 4.200                    | 24.960                   |
| Apr   | 0.537          | 5.624                         | 3.410                    | 24.630                   |
| May   | 0.492          | 5.041                         | 3.300                    | 23.300                   |
| Jun   | 0.481          | 4.827                         | 3.130                    | 22.240                   |
| Jul   | 0.412          | 4.157                         | 2.990                    | 21.010                   |
| Aug   | 0.432          | 4.452                         | 3.050                    | 20.740                   |
| Sep   | 0.453          | 4.671                         | 3.100                    | 21.210                   |
| Oct   | 0.523          | 5.189                         | 3.580                    | 21.610                   |
| Nov   | 0.613          | 5.715                         | 4.100                    | 21.610                   |
| Dec   | 0.636          | 5.718                         | 4.810                    | 20.700                   |
speed using the wind generator power curve. The hub height wind speed is given by equation (5).

$$P_W = \left( \frac{\rho}{\rho_o} \right) P_{W,TG,STP}.$$  \hspace{1cm} (4)

$$V = V_o \left( \frac{H_o}{H} \right)^\gamma.$$  \hspace{1cm} (5)

$V$ is the wind speed at the hub height of the wind turbine (m/s), $V_o$ is the anemometer speed (m/s), $H$ is the hub height of the wind turbine (m), $H_o$ is the anemometer height (m), $\gamma$ is the power law exponent, $\rho$ is the actual air density, and $\rho_o$ is the air density under standard temperature and pressure (1.225 kg/m$^3$).

2.2.5. Battery Storage Modeling. The maximum capacity of the battery storage is determined using equation (6). $P_{batt,Cmax,kbm}$, $P_{batt,Cmax,mcr}$, and $P_{batt,Cmax,mcc}$ are, respectively, given by

$$P_{batt,Cmax} = \min \left( P_{batt,Cmax,kbm}, P_{batt,Cmax,mcr}, P_{batt,mcc} \right) \left( \frac{1}{\eta_{batt}} \right).$$  \hspace{1cm} (6)

$$P_{batt,Cmax,kbm} = \frac{kQ_1 e^{-k\Delta t} - Qk c_1 (1 - e^{-k\Delta t})}{\eta_{batt}}.$$  \hspace{1cm} (7)

$$P_{batt,Cmax,mcr} = \left( 1 - e^{-\alpha_c \Delta t} \right) \frac{(Q_{max} - Q)}{\Delta t}.$$  \hspace{1cm} (8)
In the above equations, \( P_{\text{batt, max, mcc}} \) is the maximum storage charge power related to the kinetic battery model, \( P_{\text{batt, max, mcr}} \) is the maximum storage charge power related to the maximum charge rate, \( \eta_{\text{batt}} \) is the efficiency of the charge storage, \( \Delta t \) is the time step duration (h), \( k \) is the storage rate constant \((\text{h}^{-1})\), \( Q_1 \) is the available energy in the battery in the starting time step (kWh), \( Q \) is the energy available in the battery in the first time step (kWh), \( c \) is the battery’s capacity ratio, \( \alpha_c \) is the maximum charge rate of the battery \((A/\text{Ah})\), \( Q_{\text{max}} \) is the total capacity of storage (kWh), \( N_{\text{batt}} \) is the number of batteries, \( I_{\text{max}} \) is the battery’s maximum charge current (A), and \( V_n \) is the battery’s nominal voltage.

2.2.6. The Inverter Modeling. The size of the inverter is related to the load size. Since the peak power of the load in the case of this study is 8.436 kW, then the inverter power considered is 9.5 kW.

2.2.7. Economic Modeling. The feasibility of a project is determined from the net present cost (NPC) of the system and the total annual energy demand. The NPC is determined from the costs of the system components including the capital cost, the replacement cost, and the operation and maintenance costs.

\[
\text{COE} \left( \frac{\$}{\text{kWh}} \right) = \frac{\text{NPC} \times \text{CRF}}{\text{Annual energy demand}}
\]

(10)

The capital recovery factor CRF is given by

\[
\text{CRF} = \frac{i(1+i)^\delta}{(1+i)^\delta-1},
\]

where

\[
i = \frac{i' - f}{1 + f}
\]

(11)

(12)

In equations (11) and (12), \( i \) represents the discount rate, \( i' \) is the nominal discount rate, \( f \) is the annual inflation rate, and \( \delta \) is the project lifetime (years).

2.2.8. Power Balance Modeling. The total renewable power generated by the system at each time step duration \( \Delta t \) is given by

\[
P_{\text{RE}} (\Delta t) = P_{\text{PV}} (\Delta t) + P_{\text{W}} (\Delta t).
\]

(13)

In the proposed studied approach, renewable power systems are the main energy sources of the load. The system operation description can be summarized as follows:

(1) When the renewable power generated is greater than the load power demand \( P_D \),

(ii) Otherwise, the excess energy is lost

(2) When the renewable power generated is not enough to cover the load demand at each time interval \( \Delta t \) \((P_{\text{RE}} (\Delta t) < P_D (\Delta t))\)

(i) If the state of charge of batteries (SOC) is less than the maximum permissible state of charge \((\text{SOC}_{\text{max}})\), then the excess energy generated is used to charge the batteries

(ii) Otherwise, the excess energy is lost

\[
P_S (\Delta t) = P_{\text{RE}} (\Delta t) + P_{\text{batt}} (\Delta t) + P_{\text{DG}} (\Delta t),
\]

(14)

\[
P_{\text{DG}} (\Delta t) = P_D (\Delta t) - P_{\text{RE}} (\Delta t) - P_{\text{batt}} (\Delta t).
\]

(15)

\[
P_{\text{batt}} \] is the discharge power of the batteries.

(ii) If not, then the total power supply is given by equation (16). In that case, the diesel generator power supply is given by equation (17).

\[
P_S (\Delta t) = P_{\text{RE}} (\Delta t) + P_{\text{DG}} (\Delta t),
\]

(16)

\[
P_{\text{DG}} (\Delta t) = P_D (\Delta t) - P_{\text{RE}} (\Delta t).
\]

(17)

2.3. Optimization with HOMER Pro

2.3.1. Brief Description of the Working Principle. HOMER Pro (Hybrid Optimization of Multiple Electric Renewables) is an optimization software dedicated to microgrid design in all sectors. This software is used to perform simulation and optimization in the present study. Energy systems simulated in HOMER are optimized by cost. The energy balance of each system considered is calculated for a given period of the year. To ensure system reliability, the energy demand and the energy supply are compared for each time interval of the year. The charge and the discharge of the batteries are checked for each time interval. The energy balance of each system configuration determines the feasibility of a system or not. The sensitivity analysis is also performed in HOMER.

Two optimization algorithms are considered in HOMER Pro: (1) the original grid search algorithm that simulates all of the feasible system configurations defined by the Search Space and (2) the new HOMER Optimizer®, which is based on a proprietary derivative-free algorithm to search for the least-costly system. In this latter approach, the simulations consider the lower and the upper limits of the variables to optimize. The optimal size of the variables is determined automatically. Both the two optimization algorithms are considered in the present study. Constraints are also defined for simulation in HOMER Pro. They are conditions that the systems must satisfy; otherwise, they are not considered feasible solutions. In
the present study, the maximum renewable fraction ranges from 0 to 100%, the maximum unmeet energy is 0%, and the maximum annual capacity shortage is 0%. A simplified flowchart of the HOMER Pro optimization algorithm is presented in Figure 4.

2.3.2. Dispatch Strategy. HOMER Pro software uses a set of rules that controls the operation of the generators and the storage devices called a dispatch strategy. Dispatch strategies include the load following strategy (LF), the cycle charging strategy (CC), and the combined dispatch strategy (CD). In the load following strategy approach, the diesel generator produces only the necessary power to meet the primary load requirement. The charge of the storage bank and the energy supply to deferrable load are provided by renewable power resources. In the cycle charging strategy approach, the diesel generator operates full power. After serving the primary load, the energy surplus is used to serve the deferrable load and charge the storage tank. According to Ramesh and Saini [8], the most optimal operational costs of a hybrid renewable energy system are obtained under the combined dispatch strategy. Thus, the CD strategy approach is used in the present study. The working principle of the CD strategy is presented in Figure 5. The parameters used for simulation are presented in Table 2.

3. Results and Discussion

HOMER Pro has simulated ten different scenarios of feasible hybrid standalone systems for rural and remote areas electrification. The choice of these different scenarios is related to the available energy resources in the study sites. A comparative analysis between these different scenarios leads to choosing the optimal system configuration based on reliability, economic, and environmental criteria. Table 3 presents the optimal size of the various systems configurations considered and their economic evaluation. In contrast, Table 4 shows the energy balance and the carbon dioxide emissions of the different systems configurations considered. It can be observed from Table 4 that for each system configuration in the different sites considered, the total energy production is greater than the energy demand. This result shows that all the designed systems’ configurations are reliable and able to fulfill the load demand at 100%. Table 3 revealed that the most cost-effective system among the ten systems configurations considered is the PV/DG/battery system for all three sites of study.

Moreover, the COE of the PV/DG/battery system is less expensive in Maroua (COE is 0.359 $/kWh) than in Garoua (COE is 0.378 $/kWh) and Ngaoundéré (COE is 0.394 $/kWh). Since the diesel fuel price is the same in these three zones, the COE difference is due to the difference in the solar energy potential. This means that the solar energy potential is more important in Maroua than in Garoua and Ngaoundéré. However, the solar energy potential is more important in Garoua than in Ngaoundéré. These conclusions are also confirmed by the percentage of the renewable energy penetration given in Table 4. Indeed, the renewable energy penetration of the PV/DG/battery system is 96.3% in Maroua, 95.5% in Garoua, and 95.1% in Ngaoundéré.

Table 5 presents a classification of the different systems’ configurations in the various sites of study. Two different types of classification are provided. The first classification is based on economic measures whereas the second classification is based on environmental considerations. When considering the economic criteria, the PV/DG/battery standalone system appears to be the best solution for rural and remote areas electrification in Maroua, Garoua, and Ngaoundéré. The PV/DG/wind/battery standalone system appears as the second best option in Maroua (COE is 0.360 $/kWh), Garoua (COE is 0.392 $/kWh), and Ngaoundéré (COE is 0.403 $/kWh). The costly hybrid standalone system for rural and remote areas’ electrification in Garoua is the Wind/DG system (COE is 1.18 $/kWh). This is followed by the DG (COE is 1.17 $/kWh), the DG/battery (COE is 1.01 $/kWh), the wind/DG/battery (COE is 0.922 $/kWh), the PV/wind/DG (COE is 0.855 $/kWh), the PV/DG (COE is 0.849 $/kWh), the PV/battery (COE is 0.459 $/kWh), and the PV/wind/battery (COE is 0.449 $/kWh). In Maroua, the costly hybrid standalone system for rural and remote areas’ electrification is the DG (COE is 1.17 $/kWh). It is followed by the DG (COE is 1.04 $/kWh), the wind/DG system (COE is 0.973 $/kWh), the PV/DG (COE is 0.866 $/kWh), the PV/wind/DG (COE is 0.837 $/kWh), the wind/DG/battery (COE is 0.726 $/kWh), the PV/wind/battery (COE is 0.469 $/kWh), and the PV/battery (COE is 0.447 $/kWh). In Ngaoundéré, the costly hybrid standalone system...
Work under Combined Dispatch strategy

Start

Inputs data

Compute \( P_{\text{PV}} \) and \( P_{\text{W}} \) for each time interval \( \Delta t \)

\[ P_{\text{RE}}(\Delta t) = P_{\text{PV}}(t) + P_{\text{W}}(\Delta t) \]

\[ P_{\text{RE}}(\Delta t) > P_{\text{D}}(\Delta t) \]

\[ P_{\text{S}}(\Delta t) = P_{\text{RE}}(\Delta t) + P_{\text{balt}}(\Delta t) \]

\[ P_{\text{T}}(\Delta t) = P_{\text{RE}}(\Delta t) \]

\[ P_{\text{T}}(\Delta t) = P_{\text{D}}(\Delta t) \]

\[ P_{\text{S}}(\Delta t) \geq P_{\text{D}}(\Delta t) \]

\[ P_{\text{T}}(\Delta t) \geq P_{\text{S}}(\Delta t) \]

\[ P_{\text{D}}(\Delta t) = P_{\text{D}}(\Delta t) - P_{\text{balt}}(\Delta t) \]

\[ P_{\text{T}}(\Delta t) = P_{\text{S}}(\Delta t) + P_{\text{D}}(\Delta t) \]

\[ P_{\text{RE}}(\Delta t) < P_{\text{D}}(\Delta t) \]

\[ P_{\text{RE}}(\Delta t) > P_{\text{D}}(\Delta t) \]

If

If

SOC < SOC_{\text{max}}

SOC >= SOC_{\text{max}}

If

SOC < SOC_{\text{max}}

SOC >= SOC_{\text{max}}

Update the state of charge of battery

Battery charging

Dump load

Load demand

DG is on

Working under Combined Dispatch strategy

Figure 5: The combined dispatch strategy.

Table 2: Input parameters for simulation.

| Designation                                      | Value |
|-------------------------------------------------|-------|
| PV capital cost ($/W)                           | 2     |
| PV replacement cost ($/W)                       | 2     |
| PV lifetime (year)                              | 25    |
| PV derating factor (%)                          | 88    |
| Battery capital cost ($/kWh)                    | 1000  |
| Battery replacement cost ($/kWh)                | 800   |
| Battery O&M cost ($/year)                       | 50    |
| Battery lifetime (year)                         | 8     |
| Battery initial state of charge (%)             | 100   |
| Battery minimum state of charge (%)             | 20    |
| Bidirectional inverter capital cost ($/kW)      | 800   |
| Bidirectional inverter replacement cost ($/kW)  | 750   |
| Bidirectional inverter O&M cost ($/year)        | 100   |
| Bidirectional inverter efficiency (%)           | 95    |
| Bidirectional inverter lifetime (year)          | 15    |
| Wind turbine BWC XL.1 capital cost ($)          | 3900  |
| Wind turbine BWC XL.1 replacement cost ($)      | 3900  |
| Wind turbine BWC XL.1 O&M cost ($/year)         | 100   |
| Wind turbine BWC XL.1 hub height (m)            | 10    |
Table 2: Continued.

| Designation                                      | Value  |
|--------------------------------------------------|--------|
| Wind turbine BWC XL.1 lifetime (year)            | 20     |
| Charge regulator lifetime (year)                 | 15     |
| Diesel generator capital cost ($/kW)             | 200    |
| Diesel generator replacement cost ($/kW)         | 200    |
| Diesel generator O&M cost ($/op.hr)              | 0.5    |
| Diesel generator emissions (g/l)                 | 16.5   |
| Diesel generator load ratio (%)                  | 30     |
| Diesel generator lifetime (hours)                | 15000  |
| Diesel fuel price ($/l)                          | 1.07   |
| Nominal discount rate (%)                        | 8      |
| Inflation rate (%)                               | 2      |
| Project lifetime (years)                         | 25     |

Table 3: Optimal sizes of the different systems configurations considered and their economic evaluations.

| Site      | Scenario      | PV rated capacity (kW) | Wind rated capacity (kW) | DG rated capacity (kW) | Nominal capacity of batteries (kWh) | Converter rated power (kW) | NPC ($) | COE ($/kWh) |
|-----------|---------------|-------------------------|--------------------------|------------------------|-------------------------------------|----------------------------|---------|-------------|
| GAROUA    | PV/battery    | 55.4                    | —                        | —                      | 442                                 | 9.5                        | 275098  | 0.459       |
|           | PV/wind/battery | 63.4                   | 1                        | —                      | 366                                 | 9.5                        | 269191  | 0.449       |
|           | PV/wind/DG    | 29.2                    | 1                        | 8.5                    | —                                   | 9.5                        | 512906  | 0.855       |
|           | PV/DG         | 29.2                    | —                        | 8.5                    | —                                   | 9.5                        | 509296  | 0.849       |
|           | Wind/DG       | 1                       | —                        | 8.5                    | —                                   | 706953                     | 1.180   |             |
|           | DG            | —                       | —                        | 8.5                    | —                                   | 704244                     | 1.170   |             |
|           | DG/battery    | —                       | —                        | 8.5                    | 138                                 | 9.5                        | 603962  | 1.010       |
|           | PV/DG/wind/battery | 41.2                   | 1                        | 8.5                    | 228                                 | 9.5                        | 210567  | 0.392       |
|           | Wind/DG/battery | —                      | 24                       | 8.5                    | 131                                 | 9.5                        | 553479  | 0.922       |
|           | PV/DG/battery | 42                      | —                        | 8.5                    | 235                                 | 9.5                        | 227016  | 0.378       |

MAROUA

| Site      | Scenario      | PV rated capacity (kW) | Wind rated capacity (kW) | DG rated capacity (kW) | Nominal capacity of batteries (kWh) | Converter rated power (kW) | NPC ($) | COE ($/kWh) |
|-----------|---------------|-------------------------|--------------------------|------------------------|-------------------------------------|----------------------------|---------|-------------|
|           | PV/battery    | 50                      | —                        | —                      | 401                                 | 9.5                        | 267833  | 0.447       |
|           | PV/wind/battery | 69                     | 1                        | —                      | 318                                 | 9.5                        | 281553  | 0.469       |
|           | PV/wind/DG    | 20.8                    | 14                       | 8.5                    | —                                   | 9.5                        | 502394  | 0.837       |
|           | PV/DG         | 27.1                    | —                        | 8.5                    | —                                   | 9.5                        | 519587  | 0.866       |
|           | Wind/DG       | —                       | 25                       | 8.5                    | —                                   | 9.5                        | 583764  | 0.973       |
|           | DG            | —                       | —                        | 8.5                    | —                                   | 704244                     | 1.170   |             |
|           | DG/battery    | —                       | —                        | 8.5                    | 138                                 | 9.5                        | 622514  | 1.040       |
|           | PV/DG/wind/battery | 38.2                   | 1                        | 8.5                    | 228                                 | 9.5                        | 215845  | 0.360       |
|           | Wind/DG/battery | —                      | 27                       | 8.5                    | 173                                 | 9.5                        | 435825  | 0.726       |
|           | PV/DG/battery | 38.5                    | —                        | 8.5                    | 235                                 | 9.5                        | 215160  | 0.359       |
Table 3: Continued.

| Site         | Scenario                  | PV rated capacity (kW) | Wind rated capacity (kW) | DG rated capacity (kW) | Nominal capacity of batteries (kWh) | Converter rated power (kW) | NPC ($) | COE ($/kWh) |
|--------------|---------------------------|------------------------|--------------------------|------------------------|-------------------------------------|--------------------------|---------|-------------|
| NGAOUNDÉRÉ  | PV/battery                | 88.2                   | —                        | —                      | 318                                 | 9.5                      | 314142  | 0.524       |
|              | PV/wind/battery           | 87.7                   | 1                        | —                      | 318                                 | 9.5                      | 318805  | 0.532       |
|              | PV/wind/DG                | 31.2                   | 1                        | 8.5                    | —                                   | 9.5                      | 536820  | 0.895       |
|              | PV/DG                     | 31.3                   | —                        | 8.5                    | —                                   | 9.5                      | 533079  | 0.888       |
|              | Wind/DG                   | —                      | 1                        | 8.5                    | —                                   | —                       | 707029  | 1.180       |
|              | DG battery                | —                      | —                        | 8.5                    | —                                   | —                       | 704244  | 1.170       |
|              | DG/battery                | —                      | —                        | 8.5                    | 96.7                                | 9.5                      | 618097  | 1.030       |
|              | PV/DG/battery             | 46.5                   | 1                        | 8.5                    | 242                                 | 9.5                      | 241669  | 0.403       |
|              | DG/battery                | —                      | 19                       | 8.5                    | 138                                 | 9.5                      | 574704  | 0.958       |
|              | PV/DG/battery             | 45.8                   | —                        | 8.5                    | 228                                 | 9.5                      | 236590  | 0.394       |

Table 4: Energy balance and carbon dioxide emissions of the different systems’ configurations considered.

| Site         | Scenario                  | PV production (kWh/y) | Wind production (kWh/y) | DG production (kWh/y) | Total energy production (kWh/y) | Load demand (kWh/y) | Renewable penetration (%) | CO2 emissions (kg/y) |
|--------------|---------------------------|-----------------------|-------------------------|------------------------|-------------------------------|---------------------|----------------------------|----------------------|
| GAROUA       | PV/battery                | 82841                 | —                       | —                      | 82841                         | 46418               | 100                        | 0                    |
|              | PV/wind/battery           | 104249                | 886                     | —                      | 105135                        | 46418               | 100                        | 0                    |
|              | PV/wind/DG                | 47990                 | 886                     | 27944                  | 76820                         | 46418               | 39.8                       | 24230                |
|              | PV/DG                     | 47990                 | —                       | 28363                  | 76353                         | 46418               | 38.9                       | 24504                |
|              | Wind/DG                   | —                     | 927                     | 45491                  | 46418                         | 46418               | 0                          | 39566                |
|              | DG battery                | —                     | —                       | 46418                  | 46418                         | 46818               | 0                          | 39296                |
|              | PV/DG/battery             | 67773                 | 927                     | 2108                   | 70808                         | 46418               | 95.5                       | 1869                 |
|              | Wind/DG/battery           | 21259                 | 32968                   | 54227                  | 46418                         | 46418               | 29                         | 25407                |
|              | PV/DG/battery             | 69112                 | —                       | 2041                   | 71153                         | 46418               | 95.6                       | 1809                 |
Table 4: Continued.

| Site     | Scenario                  | PV production (kWh/y) | Wind production (kWh/y) | DG production (kWh/y) | Total energy production (kWh/y) | Load demand (kWh/y) | Renewable penetration (%) | CO₂ emissions (kg/y) |
|----------|---------------------------|-----------------------|-------------------------|-----------------------|--------------------------------|---------------------|---------------------------|---------------------|
| MAROUA   | PV/battery                | 87103                 | —                       | —                     | 87103                          | 46418               | 100                       | 0                   |
|          | PV/wind/battery          | 120278                | 1972                    | —                     | 122250                         | 46418               | 100                       | 0                   |
|          | PV/wind/DG               | 36293                 | 27611                   | —                     | 19529                          | 83433               | 57.9                      | 17858               |
|          | PV/DG                    | 47181                 | —                       | 28132                 | 75313                          | 46418               | 39.4                      | 24295               |
|          | Wind/DG/DG               | —                     | 49306                   | 23924                 | 73230                          | 46418               | 48.5                      | 21914               |
|          | DG/battery               | —                     | —                       | 51430                 | 51430                          | 46418               | 0                         | 39296               |
|          | DG/battery/wind          | 66463                 | 1972                    | 1591                  | 70026                          | 46418               | 96.6                      | 1426                |
|          | DG/battery/wind/DG       | —                     | —                       | 51430                 | 51430                          | 46418               | 0                         | 39234               |
|          | DG/battery/wind/DG/battery | 75233             | 905                     | 1871                  | 78009                          | 46418               | 96                        | 1663                |
|          | Wind/battery/DG/battery  | —                     | 17189                   | 35966                 | 53155                          | 46418               | 22.5                      | 27646               |
|          | PV/DG/battery/wind/battery | 74136            | —                       | 2292                  | 76428                          | 46418               | 95.1                      | 2025                |

Table 5: Classification of the different scenarios in the different zones for optimal decision-making.

| Site      | Economic criteria evaluation basis | Environmental criteria evaluation basis |
|-----------|-----------------------------------|----------------------------------------|
|           | Scenario                          | COE ($/kWh)   | Classification | Scenario | CO₂ emissions (kg/y) | Classification |
| GAROUA    | PV/DG/battery                      | 0.378        | 1st            | PV/battery | 0               | 1st            |
|          | PV/DG/wind/battery                | 0.392        | 2nd            | PV/wind/battery | 0       | 2nd            |
|          | PV/wind/battery                   | 0.449        | 3rd            | PV/DG/battery | 1809  | 3rd            |
|          | PV/battery                        | 0.459        | 4th            | PV/DG/wind/battery | 1869 | 4th            |
|          | PV/DG                             | 0.849        | 5th            | PV/wind/DG  | 24230 | 5th            |
|          | PV/wind/DG                        | 0.855        | 6th            | PV/DG      | 24804 | 6th            |
|          | Wind/DG/battery                   | 0.922        | 7th            | Wind/DG/battery | 25407 | 7th            |
|          | DG/battery                        | 1.01         | 8th            | Wind/DG    | 38994 | 8th            |
|          | DG                                | 1.17         | 9th            | DG/battery  | 39226 | 9th            |
|          | Wind/DG                           | 1.18         | 10th           | DG         | 39566 | 10th           |
system for rural and remote areas electrification is the wind/DG system (COE is 1.18 $/kWh). This is followed by the DG (COE is 1.17 $/kWh), the DG/battery (COE is 1.03 $/kWh), the wind/DG/battery (COE is 0.958 $/kWh), the PV/wind/DG (COE is 0.895 $/kWh), the PV/DG (COE is 0.888 $/kWh), the PV/wind/battery (COE is 0.532 $/kWh), and the PV/battery (COE is 0.524 $/kWh).

When considering the environmental criteria, the PV/battery and the PV/wind/battery systems appear to be the best options for rural and remote areas electrification in the three sites of study considered with 0 kg CO₂ emissions. For Garoua, the most polluting system is the DG, followed, respectively, by the DG/battery, the wind/DG, the wind/DG/battery, the PV/DG/battery, the PV/DG/battery, and the PV/DG/battery. For Maroua, the most polluting system is the DG, followed, respectively, by the DG/battery, the wind/DG, the PV/wind/DG, the PV/DG/wind/battery, the PV/DG/battery, and the PV/DG/battery. For Ngaoundéré, the most polluting system is the DG, followed, respectively, by the DG/battery, the wind/DG, the wind/DG/battery, the PV/DG/battery, the PV/DG/battery, and the PV/DG/wind/battery. The obtained results in Table 5 show that the hybrid renewable energy systems proposed in the present study are economically better than the DG-only system, except the case in Garoua and Ngaoundéré where the DG-only system is economically better than the wind/DG energy system. The studied hybrid renewable energy systems are environmentally better than the DG-only system for the cases considered.

The sensitivity of the systems is analyzed by the variation of three parameters, including the project lifetime, the
Table 7: Effect of the discount rate variation on the COE.

| Optimal system | Discount rate (%) | COE_garoua ($/kWh) | COE_maroua ($/kWh) | COE_ngaoundere ($/kWh) |
|----------------|-------------------|--------------------|--------------------|------------------------|
| PV/DG/Battery  | 1                 | 0.253              | 0.240              | 0.264                  |
|                | 2                 | 0.269              | 0.255              | 0.281                  |
|                | 4                 | 0.304              | 0.288              | 0.316                  |
|                | 6                 | 0.341              | 0.323              | 0.354                  |
|                | 8                 | 0.378              | 0.359              | 0.394                  |
|                | 10                | 0.418              | 0.396              | 0.436                  |
|                | 12                | 0.460              | 0.436              | 0.480                  |
|                | 14                | 0.504              | 0.477              | 0.525                  |
|                | 15                | 0.526              | 0.498              | 0.547                  |

Table 8: Effect of the diesel fuel price variation on the COE.

| Optimal system | Fuel price ($/l) | COE_garoua ($/kWh) | COE_maroua ($/kWh) | COE_ngaoundere ($/kWh) |
|----------------|-----------------|--------------------|--------------------|------------------------|
| PV/DG/Battery  | 0.01            | 0.359              | 0.342              | 0.371                  |
|                | 0.02            | 0.359              | 0.342              | 0.372                  |
|                | 0.04            | 0.359              | 0.342              | 0.372                  |
|                | 0.08            | 0.360              | 0.343              | 0.373                  |
|                | 1.07            | 0.387              | 0.359              | 0.394                  

discount rate, and the diesel fuel price. These parameters’ effects on the COE are studied by considering the best economic system configuration obtained for the three sites of study considered. It has been shown in Table 5 that the PV/DG/Battery standalone system is the best economical option for rural and remote areas electrification in Garoua, Maroua, and Ngaoundéré. Table 6 presents the effect of the variation of the project lifetime on the COE of the PV/DG/battery system in the three sites studied. It can be observed from Table 6 that the COE increases when reducing the project lifetime to values less than the base value considered (marked row represents the base case in Table 6). The COE decreases when increasing the project lifetime to values greater than the base value. It comes out that the effect of the variation of the project lifetime is more important for the values less than the base value considered. The reverse situation is observed for the variation of the discount rate and the variation of the diesel fuel price, for which the COE decreases when decreasing the parameters to values less than the reference values (marked rows in color represent the base case in Tables 7 and 8) and increases when increasing the parameters to values greater than the base values. In summary, the sensitivity analysis reveals that the studied energy systems are more competitive for higher project lifetime, lower discount rate, and lower diesel fuel price.

4. Conclusion
Within the framework of this paper, different configurations of hybrid standalone systems for rural and remote areas electrification have been compared for optimal decision-making.

The choice of the proposed systems is based on the energy resources available in the studied sites. Garoua, Maroua, and Ngaoundéré in Cameroon have been considered for the case study. The comparative indexes considered are system reliability, COE, and CO₂ emissions. The simulation performed in HOMER optimization software leads to the optimal sizing of the different components considered. The investment costs of all the systems considered have been evaluated for up to 25 years. Considering the economic parameter as the comparative index, the PV/DG/battery system is the best option in the three studied sites, followed by the PV/DG/wind/battery system. However, when considering the environmental aspect, for all the studied sites considered, the PV/battery and the PV/wind/battery systems are the best options with 0 kg CO₂/year emissions and a renewable energy penetration of 100%. The PV/DG/battery system is environmentally the 3rd option in Garoua (renewable energy penetration of 95.6%) and the 4th option to consider in Maroua (renewable energy penetration of 96.3%) and Ngaoundéré (renewable energy penetration of 95.1%). With these high renewable energy penetration values, considering both the economic and environmental criteria, the PV/DG/battery system could be the best option for rural and remote areas electrification in Garoua, Maroua, and Ngaoundéré. It has been proven in this study that the more important is the solar energy potential, the lower is the COE. The results have shown that hybrid renewable energy systems are better than the only DG system; however, an
exception could be made when considering a hybrid wind integration system.

The proposed optimization approach in the present study can be applied to other cases study (other sites). The results could be generalized to the same meteorological conditions (such as Sodano-Sahelian zones) and the same diesel fuel price.

**Data Availability**

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

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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