Scientific Research Publishing

Smart Grid and Renewable Energy, 2025, 16(3), 57-73
https://www.scirp.org/journal/sgre
ISSN Online: 2151-4844
ISSN Print: 2151-481X

Energy Autonomy for Off-Grid Regions Using Hybrid Systems Based on Renewable Energy Generation

Nicodem Nisso[1,2*], Emilienne Bogwarbe[3], Kitmo[1*], Ngoussandou Bello-Pierre[1,3], Taissala Awe[2]

[1]Department of Renewable Energy, National Advanced School of Engineering of Maroua, University of Maroua, Maroua, Cameroon
[2]Department of Computer Science and Telecommunications, National Advanced School of Engineering of Maroua, University of Maroua, Maroua, Cameroon.
[3]Department of Renewable Energy, Faculty of Science, University of Garoua, Garoua, Cameroon
Email: *kitmobahn@gmail.com, *nissonicodem@gmail.com

How to cite this paper: Nisso, N., Bogwarbe, E., Kitmo, Bello-Pierre, N. and Awe, T. (2025) Energy Autonomy for Off-Grid Regions Using Hybrid Systems Based on Renewable Energy Generation. *Smart Grid and Renewable Energy*, **16**, 57-73.
https://doi.org/10.4236/sgre.2025.163004

Received: November 15, 2024
Accepted: March 28, 2025
Published: March 31, 2025

Abstract

Some localities in the three northern regions of Cameroon are still not connected to the electricity grids. However, most of these areas have significant potential for renewable energy sources such as wind, sunshine and water. These localities could take advantage of these resources for heating, electrification or telecommunications. Nevertheless, the implementation of such systems requires a detailed knowledge of the tools needed for analysis and technical and economic studies to ensure the feasibility of projects. In this article, a study is carried out in four localities with the aim of assessing the renewable energy potential with a view to proposing a multi-source power plant based on the renewable resources available at the chosen sites. The Bogor region was chosen as a location with a high potential for hydropower and photovoltaic energy. This compromise led to the configuration of a multi-source system consisting of a solar photovoltaic system and a hydraulic power plant. The test of the proposed system on the IEEE 33 bus standard shows that the power losses of the entire system are negligible and that the voltage profiles are acceptable. The technical and economic study of the project gives the values levelized cost of energy (LCOE) and the net present cost (NPC), which are respectively 0.025 USD/kWh and 163.547 USD/kWh. These performance indicators demonstrate the feasibility of delivering 178.854 MW of power from a system that is robust in terms of grid stability. The optimization of the multi-source power plant makes it possible to determine the size of the overall system using an objective function.

Keywords

Renewable Resources, PV Plant, Hydropower, Homer Pro, Electricity

Generation

1. Introduction

Cameroon is one of the African countries, particularly in Central Africa, with a significant renewable energy potential. Natural resources such as sunshine, wind, water and vegetable materials can be exploited to produce electricity locally. The use of renewable energy has now become a way to circumvent environmental pollution by greenhouse gases responsible for the destruction of the ozone layer [1]. This is why several countries have opted for the installation of solar power plants, hydraulic power plants, biomass power plants, wind power plants, and hydrogen power plants in order to have energy autonomy. Cameroon in particular and Africa in general have a significant amount of renewable energy. The most abundant renewable resources in Cameroon are: sunshine, wind, water and biomass [2]. However, some renewable natural resources cannot be exploited in such a way as to raise the level of power necessary to supply a large population in urban areas. In Cameroon, the use of photovoltaic solar energy is made by small localities isolated from electrical distribution lines. This is how, for example, we have a solar power plant in Banjo to supply this city. In Guider, a photovoltaic generator is injected into the northern interconnected networks with a view to strengthening it and supplying the city of Guider and its surroundings. But the problem that arises is that as the number of inhabitants increases, the need for energy also increases, which means that the existing installations are no longer sufficient to supply the locality concerned. This is why some thermal power plants are installed in regions such as Garoua, Maroua, Ngaoundere to be able to relay renewable energy sources or electrical distribution networks. However, it is true that the use of thermal power plants exposes the environment to carbon dioxide pollution responsible for the destruction of the ozone layer or the environment.

Although renewable resources exist in Cameroon and particularly in the northern part of Cameroon, knowledge of the stages of shaping electrical energy is important on the one hand and mastery of technology, design, installation or implementation is necessary in order to have operational safety or continuity of service. The advantage of using photovoltaic energy is that it is simple to implement, with fewer accessories [3]. Unlike wind energy, the impact of which is noted on birds and urban areas because wind farms are visual pollution and an obstacle for migratory birds. The use of hydraulic energy is also important, but rivers are not found everywhere in all localities in the Far North region. This is why it is important to identify areas where rivers or streams can easily be found at the same time as a significant deposit of photovoltaic solar energy. This will allow a fusion of two renewable energy sources, namely photovoltaic solar energy and hydraulic energy.

There are several techniques for setting up renewable energy plants. We have algorithms that allow the extraction of maximum power from generators. Several software such as MATLAB/Simulink, Homer Pro, PVsyst are used for the technical-economic study [4]. These softwares allow to evaluate the LCOE and the NPC which are necessary indicators in decision-making. These softwares also allow to have the pollution rate of the resources used. The same is true for the quality of the energy supplied when using certain standard tests such as the IEEE 33 bus, 69 bus, 118 bus standard, as well as other buses depending on the architecture or configuration of the network on which we are working [5]. This work uses the IEEE 33 bus standard test for the evaluation of the power losses of the proposed system as well as the voltage profile to see the behavior of the system on the one hand and the evaluation of the size of the entire system in order to meet the energy demand of the isolated localities of the Far North, Cameroon where there is a high population density living in the dark while the natural resources are available to be able to set up the renewable energy plants. This work consists of making an evaluation of education in some regions of the far north and the evaluation or identification of the different natural resources to be able to implement a multi-source plant made up of renewable energies. In order to have an organization of the work, the first part of this work is devoted to the evaluation of the available resources, the second part is devoted to the comparison of the results as well as the feasibility study in the Homer Pro software [6]. The last part is devoted to the analysis of the results and a conclusion followed by the perspectives concerning the implementation of this system in the locality of the far north.

2. Methodology

The configuration of the proposed system is given in **Figure 1** and consists of a photovoltaic generator source and the hydropower plant. An energy storage tank

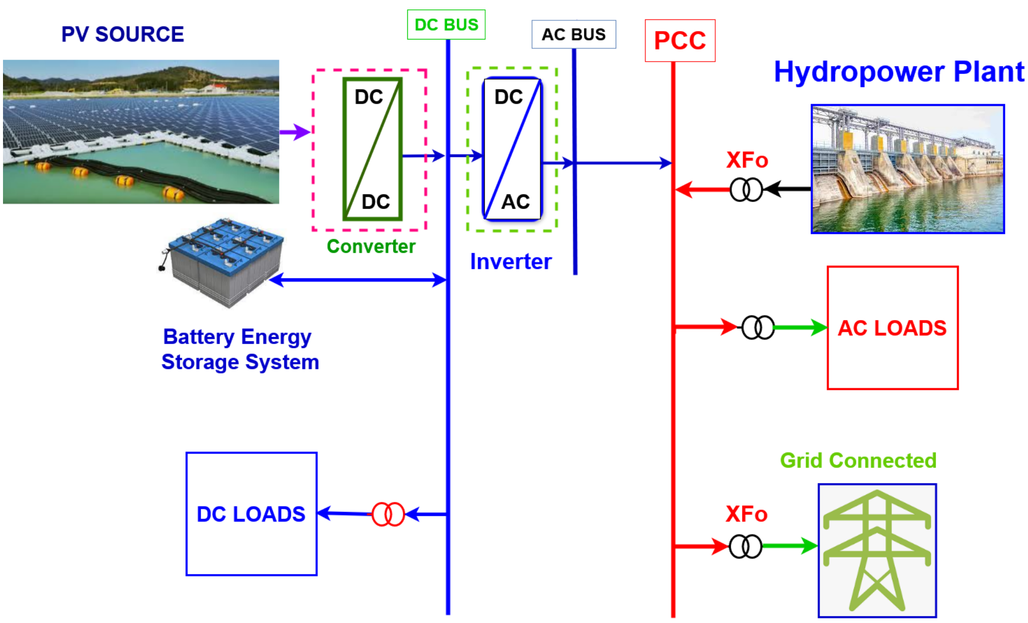

Figure 1. Overall system configuration.

is installed to boost the power level of the DC bus. DC loads can be connected to this DC bus. A DC/AC converter is used to process signals in order to supply AC loads to an AC bus. At this common coupling point, the electrical grids can be connected, as well as the AC loads. At this connection point, the hydraulic power plant is connected to raise the power level at the common point of coupling. The configuration of such a system makes it possible to have the scenario that offers an affordable NPC and LCOE when evaluating the technical-economic study in the Homer Pro software.

3. Data Collection and Selected Sites Profiles

The configuration of the proposed system is depicted in **Figure 2**, using the Homer Pro software interface for the techno-economic study to obtain the values of performance indicators such as the LCOE and the NPC. These parameters give us an idea of the feasibility of the system on the one hand, and the evaluation of the size of the system in general, as well as the performance related to the stability and robustness of the system on the other [7]. The Homer Pro software can be used to study and evaluate renewable energy systems using meteorological data from NASA data collections, which provide sunshine, temperature and wind speed values at 10 m height [8]. Unfortunately, in this study, carried out using the Homer software, the focus is only on assessing photovoltaic solar potential and hydraulic potential.

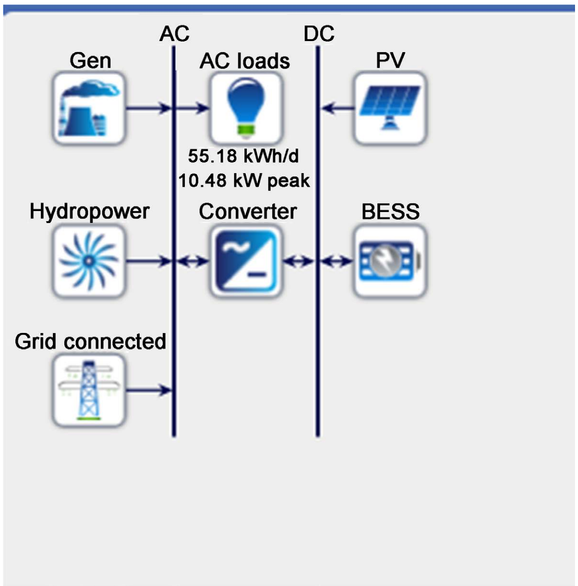

Figure 2. System configuration using meteorological data resources.

4. Problem Formulation

4.1. Objective Function

Power losses are minimized using the objective function that defines the constraints in Equation (4) and the inequalities given in Equations (6)-(9). This formula also considers the value of the power factor for analyzing the behavior and stability of the radial system under consideration [9]. The constraints on the active and reactive powers are given in Equations (4) and (5) respectively [10].

$$\Sigma P_{LT} = \sum_{\alpha=1}^{\xi} P_{L_\alpha} = \sum_{\alpha=1}^{\xi} \sum_{\chi \in \delta} \left[g_\chi \left\{ V_{x\alpha}^2 + V_{y\alpha}^2 - 2V_{x\alpha} V_{y\alpha} \cos\left(\theta_{x\alpha} - \theta_{y\alpha}\right) \right\} \right] \tag{1}$$

4.2. Constraints

The distributed generations are always used with constraints on equality and inequality.

4.3. Equality Constraints

The equality constraints are defined using the following Equations [11]:

$$P_{G_T x\alpha} - P_{Lx\alpha} + V_{x\alpha} \sum_{y=1}^{\kappa} V_{y\alpha} Y_{xy} \cos\left(\phi_{xy\alpha} + \theta_{y\alpha} - \theta_{x\alpha}\right) = 0, x \in \varpi bus, \alpha \in \xi \tag{2}$$

$$Q_{G_T x\alpha} - Q_{Lx\alpha} + V_{x\alpha} \sum_{y=1}^{\kappa} V_{y\alpha} Y_{xy} \sin\left(\phi_{xy\alpha} + \theta_{y\alpha} - \theta_{x\alpha}\right) = 0, x \in \varpi bus, \alpha \in \xi \tag{3}$$

4.4. Inequality Constraints

The minimum and the maximum limits of distributed generations are defined when considering testing on classical standard like IEEE test system: there are limits in voltages, powers and phases as specified respectively in Equations (5) and (6) [12].

$$\sum_{x=1}^{\kappa} P_{G_T x\alpha} = \sum_{x=1}^{\kappa} P_{LTx\alpha} + P_{L\alpha}, \alpha \in \xi \tag{4}$$

$$V^{\min} \le V_{x\alpha} \le V^{\max}, x \in \varpi bus, \alpha \in \xi \tag{5}$$

$$\theta^{\min} \le \theta_{x\alpha} \le \theta^{\max}, x \in \varpi bus, \alpha \in \xi \tag{6}$$

The power factor is supposed to be suitable for the reliability and stability of the considered system. The minimum and the maximum limits must be respected as defined below [13]:

$$SPF_{Hybrid\_x}^{\min} \le SPF_{Hybrid\_x\alpha} \le SPF_{Hybrid\_x}^{\max}, \alpha \in \xi \tag{7}$$

Any distributed generations lines must respect the constraints that [14]:

$$S_{x\alpha} \le S_x^{\max}, x \in \chi, \alpha \in \xi \tag{8}$$

It is possible to compensate the reactive power using the condition that [15]:

$$Q_c^{\min} \le Q_{c_{x\alpha}} \le Q_c^{\max}, x \in \varpi bus, \alpha \in \xi \tag{9}$$

5. Photovoltaic Energy Generation

The energy generated by a photovoltaic generator is produced by the total number of modules in parallel and in series, where the modules are made up of a certain number of solar cells [16]. The photo-generated current is a function of the amount of sunshine and the ambient temperature under standard conditions. This energy is defined in Equation (10) [17].

$$P_{SP} = P_{SP_v}\varsigma \times \left[1+\varsigma_v \times \left(T_v - T_{STC}\right)\right] \times \frac{G_v}{1000}, \varsigma \in N_{SP}, \alpha \in \xi \quad (10)$$

6. Use of Hydropower Plant

Hydraulic power stations obey a law of conservation of energy according to the capacity of the power station [18]. This condition is formulated in Equation (13) [19]:

$$Pz_{\varsigma\alpha} = C_{1\varsigma}Vz_{\varsigma\alpha}^2 + C_{2\varsigma}Qz_{\varsigma\alpha}^2 + C_{3\varsigma}Vz_{\varsigma\alpha}Qz_{\varsigma\alpha} + C_{4\varsigma}Vz_{\varsigma\alpha} + C_{5\varsigma}Qz_{\varsigma\alpha} + C_{6\varsigma}, \varsigma \in \varpi_z, \alpha \in \xi \quad (11)$$

The constraints on the correct operation of hydroelectric power stations are ensured by the conditions defined such that the water level in the tanks is within the admissible margin for fear of creating a malfunction [20]. These constraints define the range of minimum and maximum voltages and powers [21].

$$Vz_{\varsigma}^{\min} \le Vz_{\varsigma\alpha} \le Vz_{\varsigma}^{\max}, \varsigma \in \varpi_z, \alpha \in \xi \quad (12)$$

$$Qz_{\varsigma}^{\min} \le Qz_{\varsigma\alpha} \le Qz_{\varsigma}^{\max}, \varsigma \in \varpi_z, \alpha \in \xi \quad (13)$$

The reliability of service on the conservation of water in a tank in a hydropower plant is ensured by the equation defined by [22]:

$$Vz_{\varsigma(\alpha+1)} = Vz_{\varsigma\alpha} + Iz_{\varsigma\alpha} - Qz_{\varsigma\alpha} - Sz_{\varsigma\alpha}, \varsigma \in \varpi_z, \alpha \in \xi \quad (14)$$

7. Topology of the Multi-Source Based on IEEE Test Standard

The IEEE 33 bus standard test is used in **Figure 3**. This method makes it possible to highlight power profiles, voltage profiles and active and reactive power losses. In this topology of the system configuration, bus 1 represents the main source and bus 31 represents the secondary source, made up of the photovoltaic generator and the hydro plant respectively. The alternative loads are connected to bus 7 to ensure the continuity of the energy in the photovoltaic source. The configuration is divided into four scenarios. Scenario 1, which represents the photovoltaic source, scenario 2, which represents the hydroelectric plant, scenario 3, which represents the photovoltaic plant with battery, and scenario 4, which represents the entire hybrid photovoltaic generator-hydroelectric plant system and the battery storage bank. This configuration defined in **Figure 3** can be modified automatically by reconfiguration, due to the definition of constraints derived from the objective function and the distribution of branches and buses using the Newton Raphson method [23]. This method enables the entire system to be implemented on the basis of the IEEE standard, using advanced algorithms such as heuristics and meta-heuristics [24].

8. Feasibility Study of the Proposed System

The optimization and evaluation of the size of the whole system takes into account the NPC which is given by Equation (16) and the LCOE defined by Equation (18).

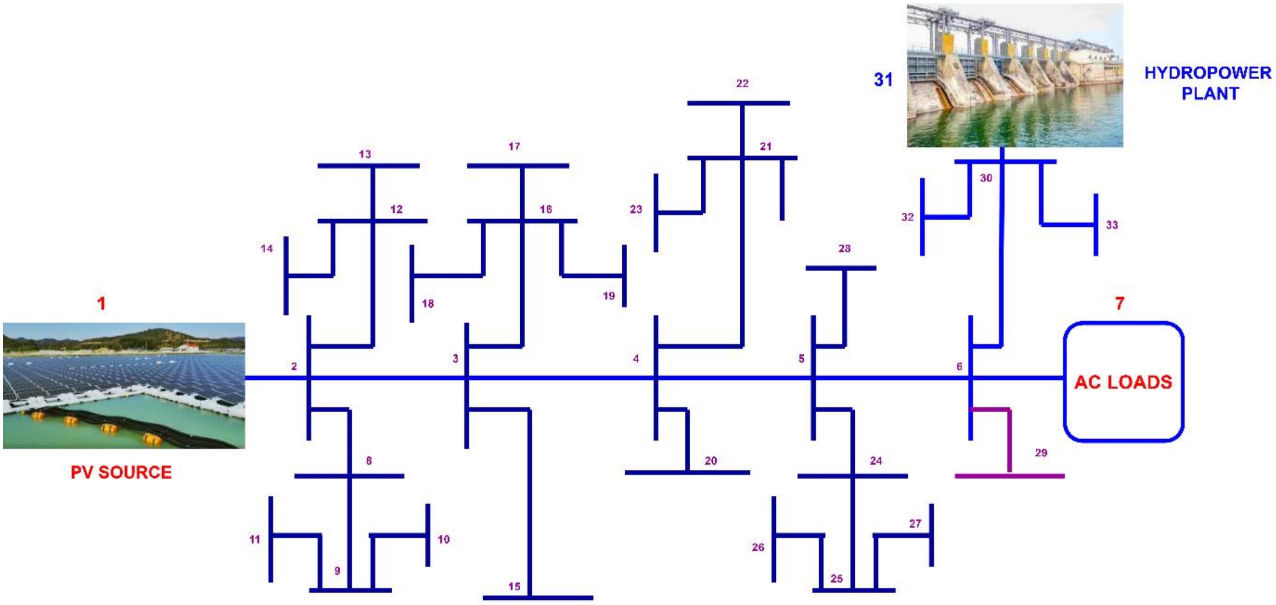

Figure 3. Configuration of the multi-source system using IEEE 33 bus.

These performance indicators give an idea of the feasibility study and the cost of producing and installing the system [25]. These are the parameters to be taken into account when carrying out a technical and economic study of a renewable energy system.

$$C_{Total} = CRF\left(\varepsilon, \eta_{Hybrid}\right) * C_{NPC(Total)} \tag{15}$$

In these mathematical relationships [26], the $C_{NPC(Total)}$ is valid for the entire time or overall duration of the project and the LCOE represents the discount rate and η_{Hybrid} represents the capital payback time in relation to a given annuity. This equation is used to determine the present value of an annuity and the current cost of an installation compared with a previous cost [27].

$$NPC = \frac{C_{Total}}{CRF\left(\varepsilon, \lambda\right)} \tag{16}$$

From its technical aspects, the *CRF* is equivalent to the recovery capital, whereas the *NPC* is equivalent to the recovery interest of a facility whose maintenance, recovery and operating costs are known in advance [28].

$$CRF\left(\varepsilon, \lambda\right) = \frac{\varepsilon\left(1+\varepsilon\right)^{\lambda}}{\left(1+\varepsilon\right)^{\lambda} - 1} \tag{17}$$

$$COE = \frac{C_{Total}}{AC_{load} + DC_{load}} \tag{18}$$

The analysis carried out using the *COE* allows an estimate to be made of the overall discounted cost of an electrical energy production system that has to supply a certain number of households.

9. Results and Discussion

Based on the evaluation of the solar photovoltaic potential in the different areas selected in **Figure 4**, it is possible to identify the most suitable location for the implementation of the hybrid system to meet demand in the Far North. The Far North is supplied by a single hydroelectric plant located in the town of Lagdo, and part of the Northern Interconnected Grid has been strengthened by the photovoltaic plant located in the town of Guider since 2022 [29].

9.1. Potentials of Selected Sites

The sunshine profile shows that the locality of Bogor has sunshine levels approaching 1000 W/m^2. From 6 am, this locality is already receiving radiation, which dissipates around 6.15 pm. Yagoua, on the other hand, is not an appropriate location for a photovoltaic plant to supply a large population. Bogor is followed by Maga. Maga, unlike Lokoro, receives regular irradiation of up to 1000 W/m^2, but unfortunately this illumination only covers a shorter period of time than Bogor. Sunshine in Lokoro is seen between 7 am and 6 pm. According to data provided by the NASA website [30], Bogor has significant photovoltaic energy resources. In addition to these renewable natural resources, Bogor has a large, constant river that could be used to power a hydroelectric plant.

9.2. Analysis of the Results for the Selected Sites

It is necessary to consider exploiting this hydroelectric resource with a view to combining it with the photovoltaic resource to supply the isolated areas of the Far North region as well as the various neighboring localities. In Bogor, there is not only an abundance of water, but also plenty of sunshine. The data provided and analyzed show that even the wind speed is interesting, varying around an average of 6 m/s. **Figure 4** depicts the configuration, profile and calibration of the various natural sources.

10. Evaluation of the Power's Profiles

The data collected (**Figure 4**) provided the power profiles depicted in **Figure 5**. These results give an idea of the size and level of energy needed to supply the Far North zone and to strengthen the Northern Interconnected Network (NIN) [31]. The power profile produced by the hybrid plant highlights that an average of 170 MW of power is generated, with a surplus of 25 MW. On the other hand, energy demand is around 15 MW. This configuration corresponds to scenario 4. This demonstrates that the PV/Hydro/BESS configuration can meet the energy demand on the one hand, and on the other provides a surplus of energy that can be stored or injected into the North Interconnected Network (NIN).

11. Evaluation and Feasibility of the Project

After assessing the size of the overall system using three scenarios, the proposed system, based on the hydropower plant, the photovoltaic generator and the energy

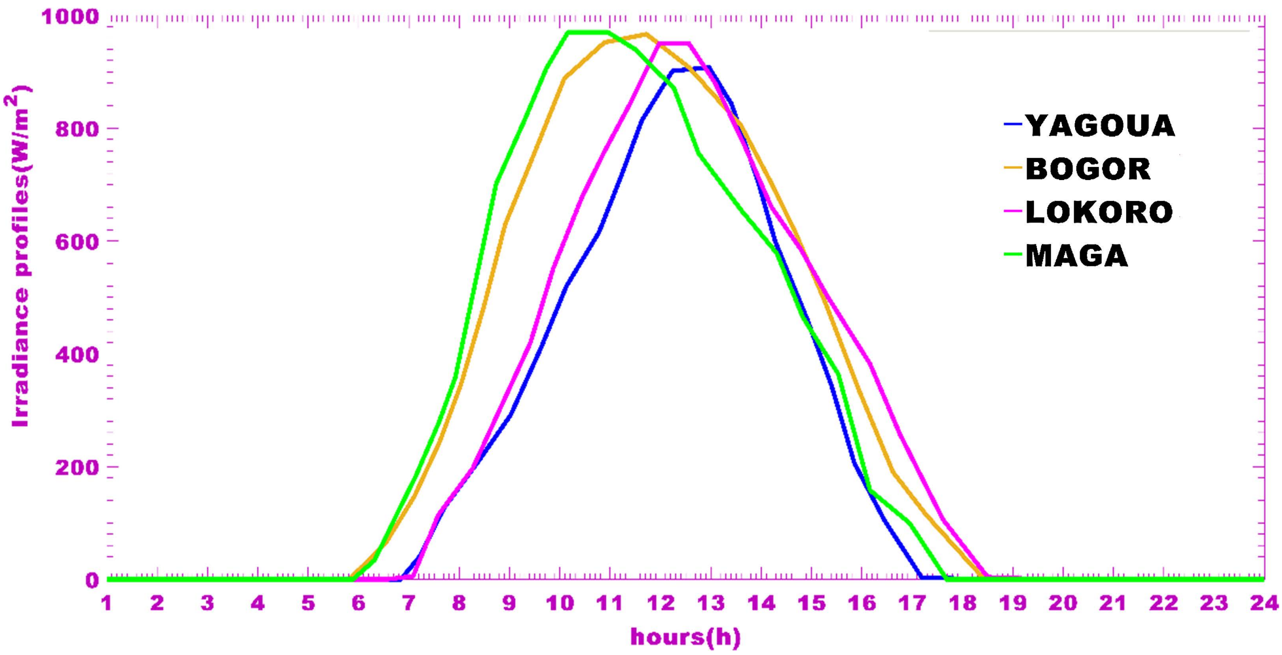

Figure 4. Photovoltaic resources of four selected zone.

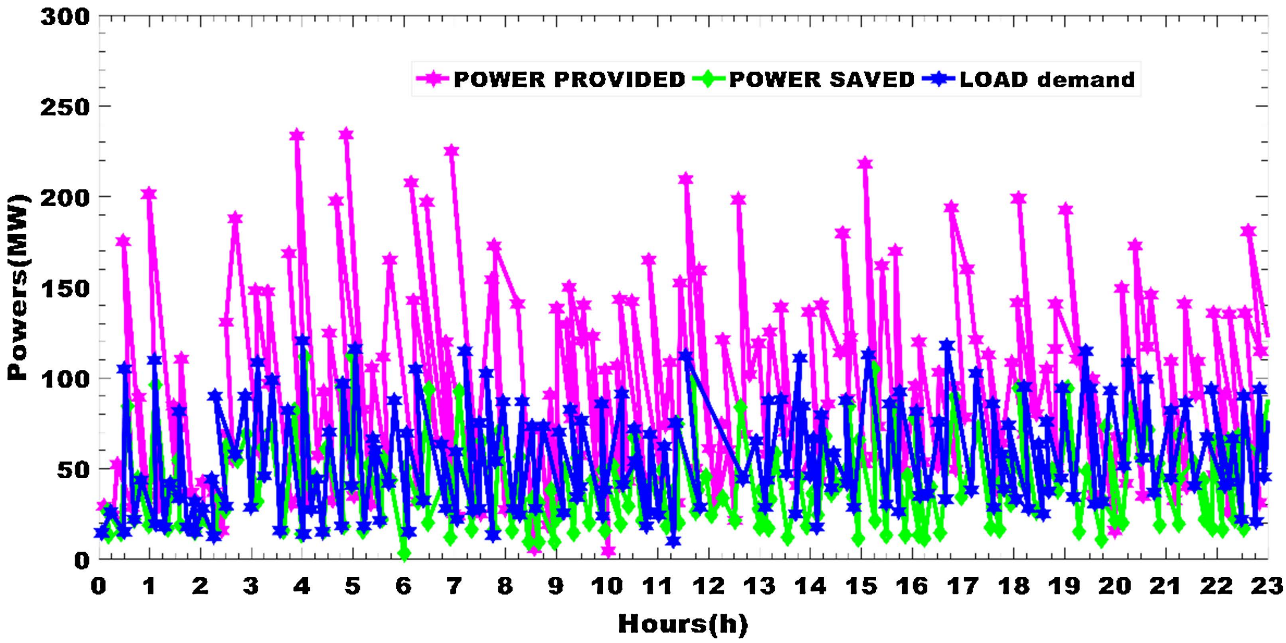

Figure 5. Produced power profiles considering AC loads demand.

storage system, achieves an active power level of 215 kW. The importance of the hydraulic source and sunshine for a temperature that varies in the best conditions allows the implementation of such a multi-source system in the Homer Pro software and the IEEE 33 standard test gives an idea of the feasibility of the system. The locality of Bongo offers the best climatic data, which favors the implementation of a multi-source system made up of photovoltaic solar energy and hydropower. Figure 6 depicts the configuration of the different scenarios that led to the choice of the proposed system.

12. Automatic Reconfiguration of the Proposed System Based on Power Loss Minimization

Using the IEEE 33 bus standard as shown in Figure 7 to carry out an analysis of the system in general, automatic reconfiguration of the various nodes in the

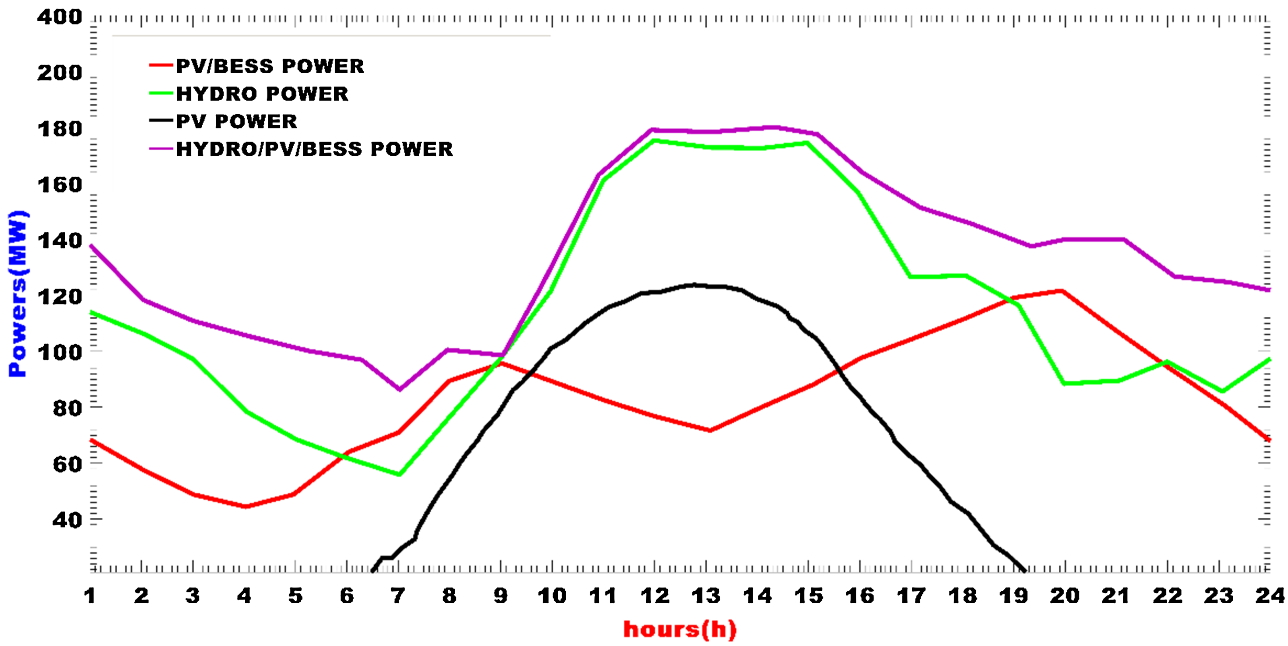

Figure 6. Power profiles of four selected zone based on proposed scenarios.

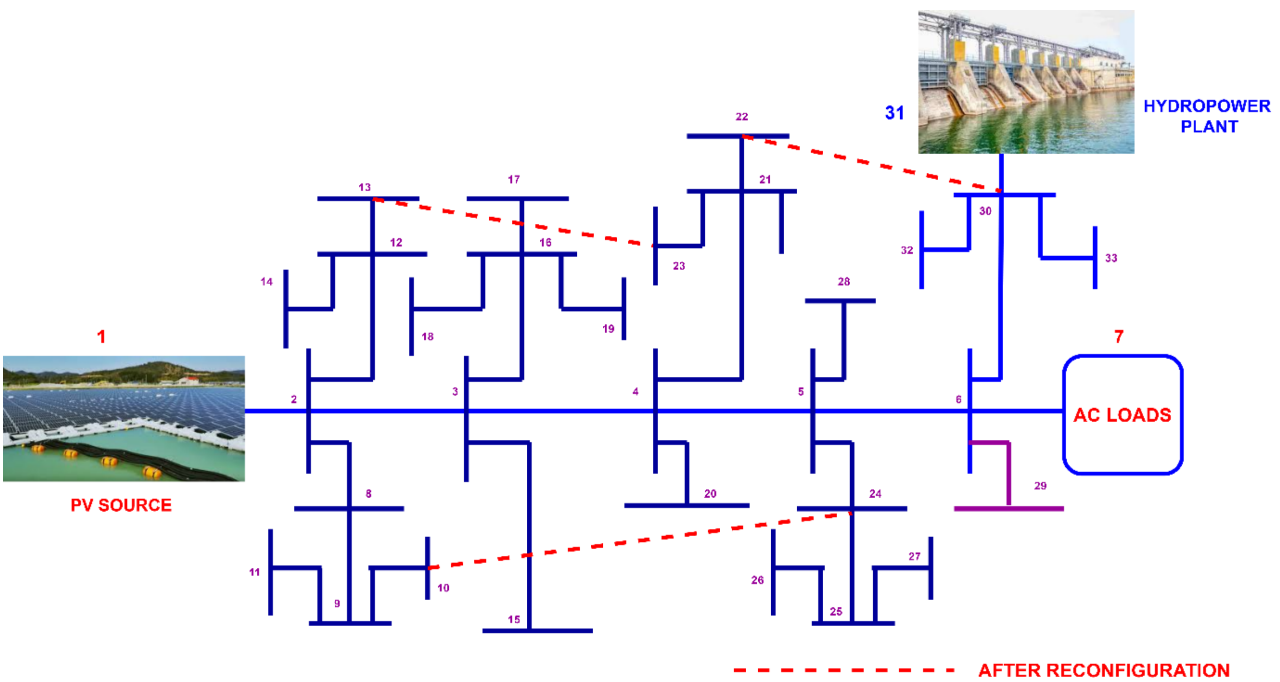

Figure 7. Automatic reconfiguration of the proposed system using IEEE 33 bus.

appropriate set of branches can be carried out. These nodes and branches correspond to the best locations for raising the power level and improving the voltage profile. In the event of a disturbance or blackout, or even load shedding, the system is automatically reconfigured. Different nodes, such as node 10 with node 24, node 13 with node 23 and node 22 with node 30, are connected. This automatic process increases the power generated and reduces power losses throughout the system. The automatic reconfiguration of the system also improves the voltage profile on the 33-bus standard test, due to the operating constraints related to the power loss minimization of the fitness function [32].

13. Power Losses Profiles and Configurations on IEEE 33 Bus

Performance indicators such as voltage and power stability lead work on renewable energies to use the IEEE 14 bus 69, IEEE 33 bus, IEEE 118 bus standard test, as well as other buses depending on the configuration and architecture of the networks that can supply the loads [33]. These performance indicators make it possible to assess power losses, the size of the system as a whole, and the stability of the system during steady state operation [34]. In this work, four configurations are presented in the form of scenarios (**Figure 8**):

- **Scenario 1:** system consisting of the photovoltaic power plant;
- **Scenario 2:** system consisting of a hydroelectric power plant;
- **Scenario 3:** system consisting of the photovoltaic power plant and the storage system;
- **Scenario 4:** system comprising the photovoltaic power plant, the hydroelectric power plant storage system.

After evaluation of the performance indicators using the IEEE 33 bus, the system comprising the photovoltaic power plant, the hydroelectric power plant storage system showed the best performance. Power losses were around an average

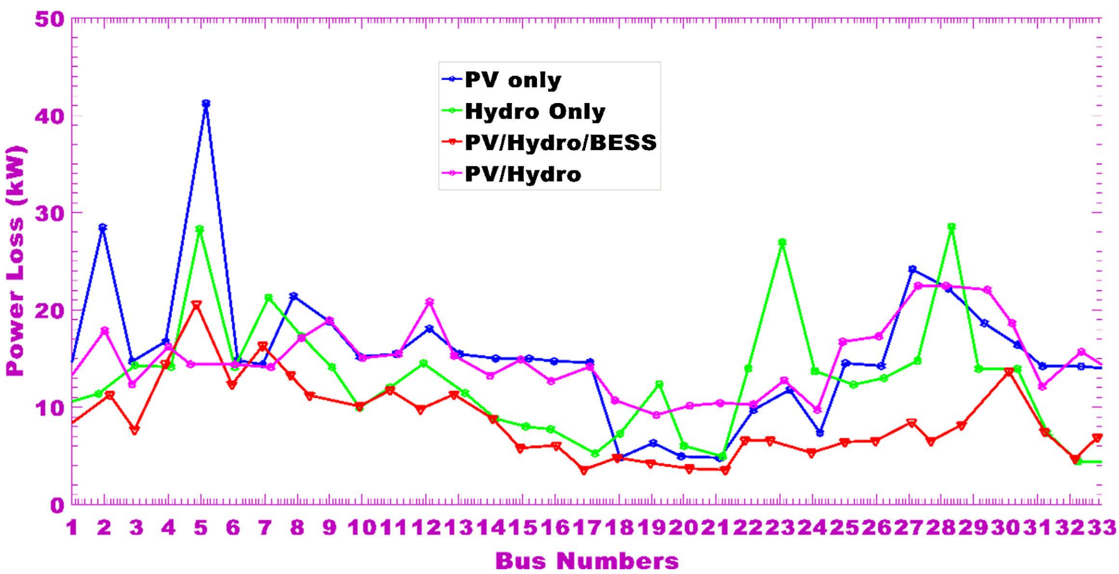

Figure 8. Power losses profiles based on the scenarios using IEEE 33 bus.

of 20 kW and voltage fluctuations were within the voltage fluctuations are within the affordable range in terms of stability index [35]. The objective function is defined around the constraints linked to the harmonic disturbance and the uncertain nature of AC or DC loads.

14. Voltage Profiles Using Test on IEEE 33 Bus Standard

The configurations of the overall hybrid system for the different scenarios are depicted in Figure 9. The voltage profiles for the different configurations are illustrated on the IEEE 33 bus standard. Instability is observed for scenario 1, corresponding to the photovoltaic generator, where there is a significant voltage drop at nodes 9, 11, 29 and 31. Configuration 4, on the other hand, improves the voltage profile, offering stability and the possibility of injection or connection to a common point of coupling. The configuration gradually improves with the combination of two or more renewable sources. It can be seen that as we move from the configuration of scenario 1 to scenario 4, the voltage profile improves. It is therefore clear from Figure 9 that the voltage profile is approaching unity per unit [36]. This scenario corresponds to the hybrid PV/Hydro/BESS system.

15. Evaluation of the LCOE Using Fitness Function

According to the evaluation of the size of the whole system based on the IEEE 33 bus standard test [37]. Figure 10, on the other hand, presents the value of the LCOE, which decreases to 0.025 USD/kWh. We also observe a good convergence speed, which matches a constant value over a long period of time.

16. Conclusion

The aim of this article is to evaluate the solar photovoltaic and hydraulic potentials with a view to implementing a hybrid photovoltaic-hydraulic system with energy

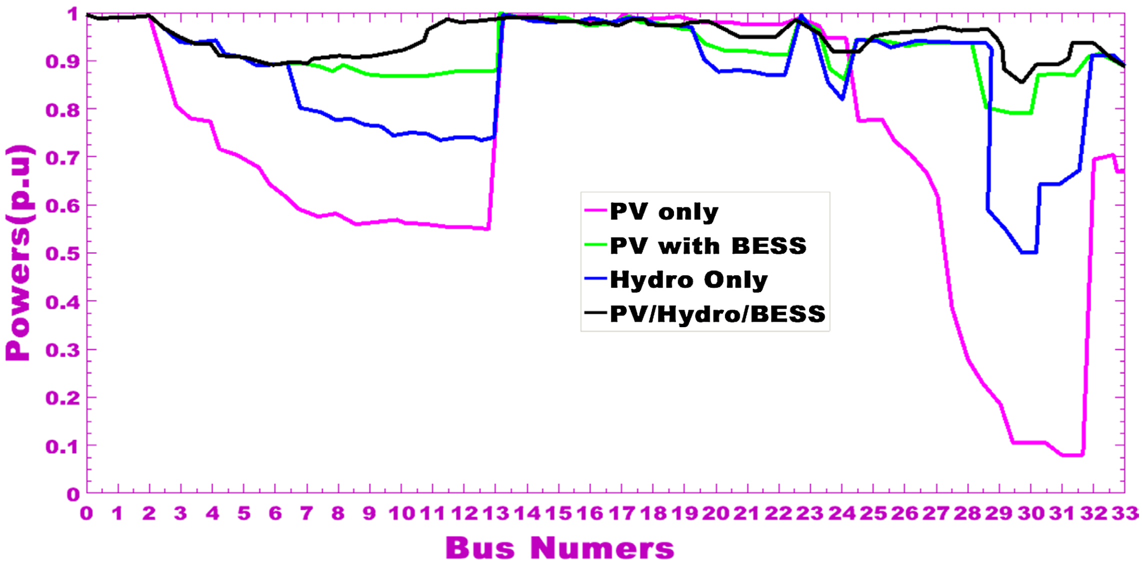

Figure 9. Voltage profiles based on the scenarios using IEEE 33 bus.

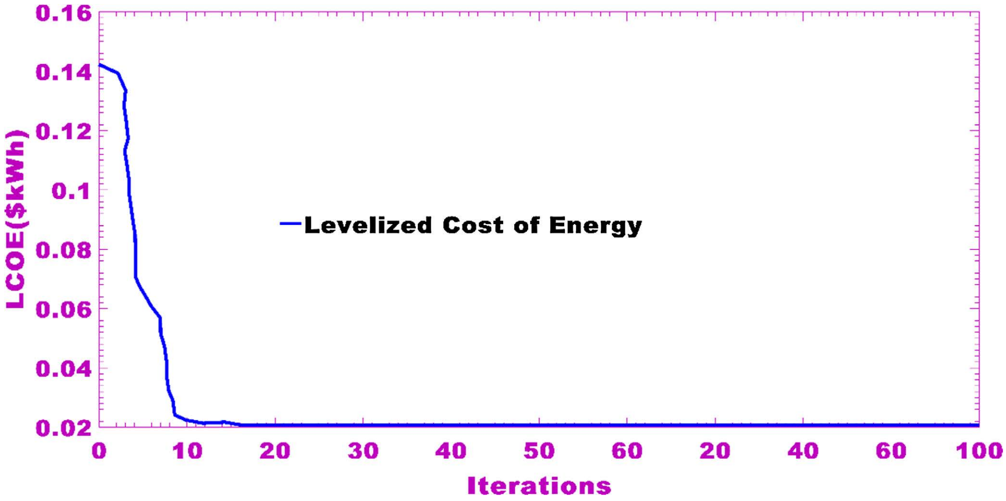

Figure 10. Evaluation of the LCOE using fitness function.

storage, with a view to integrating the thermal power plant. The evaluation of the NPC and LCOE shows the feasibility of such a system, whose production and installation costs remain affordable. Following analysis of the results, the power losses over the entire system are negligible and the voltage profiles show good forms of stability on the IEEE 33 bus standard test. A configuration of the proposed system makes it possible to assess the size of the overall system, which is flexible in terms of robustness and accuracy when the speed of convergence of the objective function is observed. The evaluation of the solar hydraulic potential in four regions of the far north shows that the Bogor locality was chosen on the basis of three other localities, namely the Maga locality, the Lokoro locality and the Yagoua locality, where power estimates were made with a view to meeting the energy demand of localities that are isolated in the northern part of Cameroon, on the one hand, and at the same time meeting and reinforcing the electrical system of the interconnected northern network, on the other. Although the far north of Cameroon is supplied by the Northern Interconnected Network (NIN), electricity is not distributed to all localities at all times. Unfortunately, in localities where there are significant deposits of solar and hydraulic energy, the electricity networks do not cover these localities on a permanent basis. However, these areas are rich in resources that could be used as renewable energy power stations; these areas can be supplied with green energy without any risk of environmental pollution and at a reasonable cost. The feasibility study of the system proposed in this article shows that the configuration of the proposed system can meet the demand of localities in the far north on the one hand, and on the other, this energy can reinforce the only source of electrical energy production at the Lagdo hydropower plant, which supplies three regions in northern Cameroon. The aim is to assess energy demand in all the isolated areas of Cameroon, from the north to the south, and from the east to the west, so that renewable energy plants can be set up and green cities created, to give households access to electricity and a minimum of comfort.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature

P_{PV}	PV array power output
Y_{PV}	Rated capacity of PV array in kW
f_{PV}	Solar PV derating factor in percentage
G	Incident solar radiation in kW/m^2
G_r	Incident solar radiation at STC in kW/m^2
α_p	Temperature coefficient of power in ˚C
T_c	Solar PV cell temperature in ˚C
T_{cr}	Solar PV cell temperature under STC in ˚C
τ	Solar transmittance of PV array in percentage
α	Solar absorptance of PV array in percentage
η	Conversion efficiency of solar PV in percentage
U	Coefficient of heat transfer to the surroundings in kW/m^2/˚C
T_a	Ambient temperature
$T_{c,NOCT}$	Solar PV nominal operating cell temperature in ˚C
$T_{a,NOCT}$	Ambient temperature under NOCT in ˚C
G_{NOCT}	Incident solar radiation under nominal operating cell temperature in kW/m^2
E_{AC}	AC output of solar PV in kWh
E_{DC}	DC output of solar PV array in kWh
μ	Efficiency of the converter
Y_{array}	Array yield expressed in h/d
$R_{Project}$	Project life time in yr
E_{Served}	Total Electrical load served in a year in kWh/yr
P_R	Renewable energy power in kWh
P_T	Total power generated from whole system in kWh
CRF	Capital recovery factor