A Case Study of an Optimal Detailed Analysis of a Standalone Photovoltaic/Battery System for Electricity Supply in Rural and Remote Areas

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This paper focused on a techno-economic study of a standalone PV/battery system for electrical energy supply. For a particular case study in Cameroon, the system is optimally designed thanks to a double-objective firefly optimization algorithm, based on a defined operational strategy. The two objective functions simulated simultaneously using FA are: the cost of energy (COE) function and the function defining the loss of power supply probability (LPSP). Different optimal configurations of the system have been obtained on the Pareto front with respect to their LPSP. For a total load demand of 20196.7 kWh, the lowest cost configuration with LPSP of 0% is composed by a number of 63 modules and a battery capacity of 370.295 kWh. The related COE is 0.2587 $/kWh, corresponding to a total net present cost of 87422 $. However with this configuration, the energy of batteries could not be able solely to respond to the energy demand for 3 continuous days. In that case, the increase of the PV power production (by increasing the number of PV modules) could allow to the batteries to fulfil this deficiency. But this solution increases the investment cost to up to 11.17%, considering a system with 80 PV modules. Another solution consists in reducing the size of the battery bank to avoid its unnecessary oversizing. In this case, the COE and the system investment cost reduce to up to 28.77% for 1 day batteries’ autonomy considered. The obtained results have demonstrated that the cost of a PV/battery system is mostly influenced by the batteries’ size, while the system reliability is mostly related to the PV size.

1. Introduction

The lack of electrical energy still remains a serious problem in remote and rural areas, although some efforts are made to solve this issue. The use of renewable energy systems such as off-grid photovoltaic systems is a proposed solution amongst others to overcome this energy shortage. However, PV systems can only operate during the day due to the partial availability of solar energy. Hybrid systems are thus proposed in order to make electrical energy available at any time of the day [1–19].

Costa and Villalva [1] studied a hybrid PV/diesel system for energy supply in a reserve of Brazil. The obtained results have shown that the proposed system is technically reliable and feasible for many applications in this reserve.
Falama et al. [2] compared different options of hybrid grid-connected systems for energy supply in Cameroon. The obtained results have proven that the diesel/grid-connected and the PV/battery/grid-connected systems are economically the best options, respectively, for short- and long-term investment.

Kumar and Channi [3] designed an optimal standalone hybrid PV/biomass system for rural electrification based on a techno-economic and environmental analysis. The study performed has demonstrated that the designed system and the proposed operational strategy could be applied for energy supply in any rural area of developing countries.

Nasser et al. [4] designed a hybrid PV/wind for hydrogen production in Egypt. It has been proven that the proposed system is suitable for the production and the storage of hydrogen.

El-Sattar et al. [7] optimally sized a standalone hybrid PV/biomass/battery system for energy supply in a village of Egypt. The performance of the designed system has been demonstrated using a modified quantum model of Runge-Kutta algorithm.

Deudjo et al. [8] analyzed the feasibility of a PV/wind/hydroelectricity/battery/DG system for energy supply in Sub-Saharan Africa. The obtained results have proven that the hybrid systems based on renewable energy are suitable solutions for the problem of lack of electrical energy in developing countries.

Allwyn et al. [9] analyzed the performance of a PV/battery system for street lighting in Oman using genetic algorithm. The obtained results have shown that the proposed study approach is economically profitable and could lead to the reduction of the CO₂ emissions.

A techno-economic analysis of a solar PV/battery system has been performed by Gul et al. [10] for a community energy supply. The outcome of their study has proven that the improvement of the system’s parameters such as reliability and flexibility requires to connect the proposed system to the grid.

The choice of a system should depend on the energy potential resource available in the site considered. In the present research work, the site of Maroua, a locality in the northern Cameroon, has been chosen as the study site. Because of the strong solar potential in this locality, this study is essentially based on a photovoltaic system including batteries for the energy storage.

It is important to carry out a techno-economic study of electrical power generation systems in order to allow to investors and users to choose the system configuration that best meets their expectations or priorities. Therefore, an optimal sizing of the system is requested based on the constraints defined by the user and according to his priorities. Many optimization techniques for energy systems are used in the literature [20–24]. The literature review has shown that Genetic algorithm and Particle swarm methods are the most used multiobjective evolutionary algorithms for energy systems optimization [24].

The aim of this work is to perform a techno-economic analysis based on a double-objective optimization technique using Firefly algorithm. This analysis will allow to determine the optimal configurations of the photovoltaic/battery system for the studied area, focusing on the COE and the performance of the system. An operational strategy of the proposed system is performed for this purpose. The identification of the most influential component on the cost and the reliability of a PV/battery system is also one of the main objectives of this research paper.

2. System Components and Site of Study

2.1. System Components and Location Site. The main components of the PV/battery system are: the PV generator, the charge regulator, the batteries, and the inverter. The PV generator produces the electrical energy for the load consumption. Batteries storage is used to store the excess electrical energy produced by the PV generator during the day. This energy is then consumed by the load during the night or when the generated energy by the solar panels is not enough (low sunlight) to respond to the load demand. The role of the charge controller is to ensure that the battery charging and discharging processes are carried out, so that they are always in the correct operating conditions. It also permits to maximize the power of the solar panels. The role of the inverter is to convert DC to AC current. Since photovoltaic solar panels generate direct electricity current, and most of the devices used in houses or in professional offices operate in DC current, this component is therefore for a particular importance in photovoltaic systems. Schematic representation of the studied system is given in Figure 1.

The locality of Maroua in Cameroon is facing the problem of lack of electricity. The great solar potential of Maroua is an asset to use photovoltaic solar energy in this area. Figure 2 presents the location of the study site on the geographical map.

The solar energy potential evaluation precedes any PV system implementation. The photovoltaic energy output is also influenced by the ambient temperature. For the different months of the year, the hourly solar energy potential of the study site is presented in Figure 3, whereas the hourly ambient temperature is presented in Figure 4. All these data have been collected experimentally from the facilities of the Energy Research Laboratory of the Institute of Geological and Mining Research of Cameroon.

2.2. Estimation of the Electrical Energy Demand. It is assumed in this study that the load demand is essentially for domestic use. A total of 50 households have been considered for simulation. The daily electrical demand varies with the period of the year since the use of some devices depends on the period of the year. For example, in the Northern Cameroon, from November to January and from June to August the use of a ceiling fan is not important. But from February to May and from September to October, the weather is hot and then requires the use of the ceiling fan. For each household, the load is composed by 5 LED lamps (9 W for each), 1 ceiling fan (45 W), 1 television (60 W), 1 radio, and 1 to 6 telephones (10 W). The estimated load
Figure 1: Standalone PV/battery system.

Figure 2: Location of Maroua on the geographical map [25].

Figure 3: Monthly hourly global irradiance over the year.

Figure 4: Monthly hourly ambient temperature over the year.
demand per day for one household corresponding to the different periods of the year is summarized in Table 1. The total yearly energy demand for the 50 households is 20196.7 kWh. The monthly hourly load profile for the different months of the year is presented in Figure 5.

### 3. Modeling and Optimization

3.1. Brief Description of the Firefly Algorithm. Firefly optimization algorithm (FA) is amongst the recent metaheuristic algorithms. This bioinspired algorithm has been developed by Yang [26, 27]. Many practical areas such as in electrical engineering use the Firefly algorithm to solve optimization problems.

According to Yang [28], FA could be considered in nonlinear system as the combination of the following methods: Differential Evolution, Particle Swarm optimization, Harmony Search, and Simulated Annealing. Thus, FA outperforms and is more efficient than these algorithms. Figure 6 presents the flowchart of a standard FA algorithm [11].

The Firefly algorithm is able to find multiple optimal solutions simultaneously thanks to his multiswarm nature. Multiobjective Firefly Algorithm (MOFA) has been developed by Yang [29] to find the Pareto front optimal solutions of defined problems. The pseudo-code of the Multiobjective optimization FA is presented in Table 2 [29]. The performance of the proposed method has been proven by Yang, based on a comparative analysis of MOFA with other methods such as Multiobjective Differential Evolution, Vector Evaluated Genetic Algorithm, Multiobjective Differential Evolution optimization, Strength Pareto evolutionary algorithm, and Multiobjective bees algorithm. The comparative results revealed that the MOFA presented better results than the other considered methods. Another analysis performed by Yang [29] has also revealed that the multimodal optimization FA is much more efficient in finding the global optima with higher success rates than the Particle Swarm Optimization and the genetic algorithm.

Multiobjective optimization using firefly algorithm is performed in the case of the present study to find the optimal solutions of the defined problem. To this end, two different functions are simulated simultaneously. The first function evaluates the energy system’s cost, while the second function evaluates the system’s reliability.

3.2. PV Output Modeling. The PV power produced is defined by

\[ P_{pv} = N_{pv} \cdot P_{pv,ref} \cdot \left( \frac{G}{G_{ref}} \right) \cdot \left[ 1 - a\left( T_a + \frac{NOCT - 20}{800} \cdot G - Tc_{ref} \right) \right], \]

where \( P_{pv,ref} \) is the rated power.

3.3. Battery Storage Equation Model. The sizing of the storage capacity of the batteries is related to the daily load energy demand. More than one batteries arranged in series and/or parallel can be used in a PV/battery system operation. Equation (2) is used to determine the storage capacity of the batteries in a PV/battery energy system

\[ C_{batt,n} \text{(Wh)} = \frac{N_{ad} \times \text{Maximum daily load energy (Wh)}}{DOD \times \eta_{batt} \times \eta_{inverter} \times \eta_{regulator}}, \]

(2)

The number of batteries in series is given by

\[ N_s = \frac{U_n}{U_{n,unit}}. \]

(3)

The number of batteries in parallel is given by

\[ N_p = \frac{C_{batt}}{C_{batt,unit}}. \]

(4)

The total number of batteries is given by

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**Table 1: Estimation of the daily load demand for one household with respect to the months of the year.**

<table>
<thead>
<tr>
<th>Designation</th>
<th>Quantity</th>
<th>Power (W)</th>
<th>February-May</th>
<th>June-August</th>
<th>September-October</th>
<th>November-January</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lighting</td>
<td>5</td>
<td>9</td>
<td>7 Hr/d 315 Wh/d</td>
<td>7 Hr/d 315 Wh/d</td>
<td>7 Hr/d 315 Wh/d</td>
<td>7 Hr/d 315 Wh/d</td>
</tr>
<tr>
<td>Television</td>
<td>1</td>
<td>60</td>
<td>5 Hr/d 300 Wh/d</td>
<td>5 Hr/d 300 Wh/d</td>
<td>5 Hr/d 300 Wh/d</td>
<td>5 Hr/d 300 Wh/d</td>
</tr>
<tr>
<td>Radio, phone</td>
<td>1</td>
<td>10</td>
<td>9 Hr/d 90 Wh/d</td>
<td>9 Hr/d 90 Wh/d</td>
<td>9 Hr/d 90 Wh/d</td>
<td>9 Hr/d 90 Wh/d</td>
</tr>
<tr>
<td>Ceiling fan</td>
<td>1</td>
<td>45</td>
<td>18 Hr/d 810 Wh/d</td>
<td>0 Hr/d 0 Wh/d</td>
<td>18 Hr/d 810 Wh/d</td>
<td>0 Hr/d 0 Wh/d</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>1515 Hr/d 705 Wh/d</td>
<td>1515 Hr/d 705 Wh/d</td>
<td>1515 Hr/d 705 Wh/d</td>
<td>1515 Hr/d 705 Wh/d</td>
</tr>
</tbody>
</table>

**Figure 5: Profile of monthly hourly power demand.**

---
In the above equations, $N_{ad}$ is the autonomy days of batteries, $U_n$ is the input/output voltage of the batteries bank with the same characteristics, $U_{n, \text{unit}}$ is the input/output voltage of a single battery, $C_{\text{batt}}$ is the total storage capacity of the batteries bank, and $C_{\text{batt, unit}}$ is the storage capacity of a single battery.

### 3.4. System Optimization

#### 3.4.1. The Objective Functions

A double-objective optimization is used in the present work to evaluate the optimal key parameters of the system. This optimization consists to minimize the system’s cost while satisfying the load demand. Such studies [9, 20, 24] have been conducted by several authors using genetic algorithms. Based on the performance of the FA, this study is focused on a double-objective optimization firefly algorithm. The first objective function to optimize is the COE defined by equation (6). This function is determined from the cost of the system’s components and the total annual energy demand.

$$COE = \frac{\text{Cost}_{\text{PV}} + \text{Cost}_{\text{batteries}} + \text{Cost}_{\text{inverter}} + \text{Cost}_{\text{regulator}}}{E_{\text{demand}}} \cdot \text{CRF}$$

where

$$\text{CRF} = \frac{\chi (1 + \chi)^{c}}{(1 + \chi)^{c} - 1}$$

and

$$N_{\text{batt}} = N_s \times N_{p}$$

(5)
In the above equations, CRF is the capital recovery factor, $\chi$ is the annual interest rate, $\omega$ is the interest rate, and $\gamma$ is the system lifetime (years).

The second objective function to optimize given by equation (9) is related to the reliability of the system by evaluating the LPSP index. 

$$\text{LPSP} = \frac{\sum^{8760}_{t=1} \text{hours} \left[ P_{\text{supply}} (\Delta \xi) < P_{\text{demand}} (\Delta \xi) \right]}{8760} \quad (9)$$

The details concerning the key components of the studied system such as their cost and their lifetime are presented in Table 3. The operation and the maintenance costs of the components have been neglected.

### Table 3: Cost of the key components.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Unit</th>
<th>Cost ($)</th>
<th>Lifetime (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV array</td>
<td>W</td>
<td>1.5</td>
<td>25</td>
</tr>
<tr>
<td>Batteries</td>
<td>Ah</td>
<td>1.63</td>
<td>8</td>
</tr>
<tr>
<td>Inverter</td>
<td>kW</td>
<td>750</td>
<td>15</td>
</tr>
<tr>
<td>Charge regulator</td>
<td>kW</td>
<td>450</td>
<td>15</td>
</tr>
</tbody>
</table>

The second objective function to optimize given by equation (9) is related to the reliability of the system by evaluating the LPSP index.

$$\chi = \frac{\chi'}{1 + \omega} \quad (8)$$

In the above equations, CRF is the capital recovery factor, $\chi$ is the annual interest rate, $\chi'$ is the nominal interest rate, $\omega$ is the interest rate, and $\gamma$ is the system lifetime (years).

The second objective function to optimize given by equation (9) is related to the reliability of the system by evaluating the LPSP index. 

$$\text{LPSP} = \frac{\sum^{8760}_{t=1} \text{hours} \left[ P_{\text{supply}} (\Delta \xi) < P_{\text{demand}} (\Delta \xi) \right]}{8760} \quad (9)$$

The details concerning the key components of the studied system such as their cost and their lifetime are presented in Table 3. The operation and the maintenance costs of the components have been neglected.

### 3.4.2. Optimization Constraints and Operational Strategy

The meteorological data (irradiance and ambient temperature), constituting an important input parameters of the PV generator, were collected experimentally. The energy demand is also a key input parameter for the simulation of the system. The variables to be determined through the simulation process based on the operational strategy of the studied system are: the number of PV modules ($N_{pv}$) and the number of autonomy days of the batteries ($N_{ad}$).

In the defined operational strategy, at each time interval, the power production is evaluated. The detailed description of the operational strategy of the studied system associated to the optimization process is given in Figure 7. In this description, the following points are taken into account:

The PV output power produced is evaluated at $\Delta \xi = 1$ h ($\Delta \xi$ is the time interval).

If the instantaneous PV power is greater than the power demand ($P_{\text{pv}} (\Delta \xi) > P_{\text{demand}} (\Delta \xi)/\eta_{\text{inverter}} \times \eta_{\text{converter}}$), then the batteries are charged by the excess PV power produced. However, if the state of charge (SOC) of the batteries is greater than or equal to 1 (100%), then the excess PV power produced is lost, because the batteries are fully charged. The updated storage capacity of the batteries for each time interval is given by

$$C_{\text{batt}} (\Delta \xi) = C_{\text{batt}} (\Delta \xi - 1) + \left( P_{\text{pv}} (\Delta \xi) - \frac{P_{\text{demand}} (\Delta \xi)}{\eta_{\text{inverter}} \times \eta_{\text{regulator}}} \right) \cdot \eta_{\text{batt},r} \quad (10)$$

The corresponding state of charge of the batteries at $\Delta \xi$ is

$$\text{SOC} (\Delta \xi) = \frac{C_{\text{batt}} (\Delta \xi)}{C_{\text{batt},n}} \quad (11)$$

$C_{\text{batt},n}$ is the nominal capacity of the batteries.

If the PV output power is unable to satisfy the load demand ($P_{\text{pv}} (\Delta \xi) < P_{\text{demand}} (\Delta \xi)/\eta_{\text{inverter}} \times \eta_{\text{converter}}$), then the unmet load demand is supplied by the batteries, the discharging process of the batteries is thus launched. If the batteries capacity is at its minimum level (less or equal to 20%), then the discharging process ends, even if the load demand is not met. The updating equation of the storage capacity of batteries at $\Delta \xi$ is given in this case by

$$C_{\text{batt}} (\Delta \xi) = C_{\text{batt}} (\Delta \xi - 1) - \frac{P_{\text{demand}} (\Delta \xi)}{\eta_{\text{inverter}} \times \eta_{\text{regulator}}} \cdot \frac{1}{\eta_{\text{batt},d}} \quad (12)$$

The optimal combination of $N_{pv}$ and $N_{ad}$ is determined by computing the objectives functions and the operational strategy using FA algorithm. This optimal combination is obtained for a desired LPSP and his corresponding lowest COE. The optimization constraints are given as follows:

$$P_{\text{pv}} (\Delta \xi) + P_{\text{batt},d} (\Delta \xi) \geq P_{\text{demand}} (\Delta \xi)$$

$$N_{\text{pv,min}} \leq N_{\text{pv}} \leq N_{\text{pv,max}}$$

$$N_{\text{ad,min}} \leq N_{\text{ad}} \leq N_{\text{ad,max}}$$

$N_{\text{pv,min}}$ and $N_{\text{pv,max}}$ are, respectively, the minimum and maximum values of the PV modules number. $N_{\text{ad,min}}$ and $N_{\text{ad,max}}$ are, respectively, the minimum and maximum values of the number of days of batteries’ autonomy.

The used parameters for simulation are given in Table 4.

### 4. Results and Discussion

Since the peak load demand is 8 kW, the inverter power considered for simulation is 9 kW. The sizing of the charge regulator is a function of the PV generator. The purpose of the simulation is to determine the optimal configurations of the electrical energy supply system studied based on their cost and their reliability. Pareto front computation is used to this end, based on the Firefly optimization algorithm. All the combinations of solutions obtained in the Pareto front are optimal solutions. Figure 8 presents the combinations of the optimal solutions (Pareto front) of the studied system. In this figure, the variation of the COE with respect to LPSP is given. It comes out from Figure 8 that the cost of energy increases (and thus the investment cost) when the LPSP decreases. Thus, when the reliability of the system increases, the cost of energy increases too. For the optimal configuration obtained, corresponding to 0% LPSP ($N_{pv} = 63$, $N_{ad} = 3$ days), the COE is 0.2587 $/kWh. The total investment cost for this configuration (including installation, replacement, operation, and maintenance) is 87422 $.
size variation of the PV modules and the variation of the autonomy days of batteries on the Pareto front are presented, respectively, in Figures 9 and 10. Each marked point (data) given in Figure 8 corresponds to another point given in Figures 9 and 10. The combinations of these points form the different configurations of the system with their related cost and reliability. Some configurations of the system according to their LPSP are given in Table 5. The results of Table 5 show clearly the decreasing variation of the system cost with the decreasing variation of its reliability. According to Table 5, since the difference between the batteries capacity of the different configurations is not too much in comparison with the difference between the number of PV modules, the variation of the system's

![Flowchart of the combined optimization and operational strategy.](image-url)
reliability is mostly dominated by the variation of the PV array size (the number of PV modules). The number of batteries for each combination of optimal solution could be determined using equations (3)–(5) for a specific choice of the type of the battery.

Figure 11 presents the time variation of the PV power production, whereas Figure 12 presents the time variation of the charge and the discharge power of batteries for 0% LPSP \((N_{pv} = 63, N_{ad} = 3 \text{ days})\). It is observed from these figures that the charge of the batteries occurs when the PV power produced is over the peak load demand (8 kW), while the discharge of the batteries occurs when the PV power produced is under the peak load demand.

Figure 13 presents the power supply (which is the sum of the PV power and the discharge power of batteries) and the power demand. It is demonstrated in this figure that at any time, the power supply is greater or equal than/to the load power. This result proves the good reliability of the designed system for which the load requirement is fully met.

Figure 14 presents the contribution of each component of the system on the total investment cost for the LPSP of 0% \((N_{pv} = 63, N_{ad} = 3 \text{ days})\). The most costly components are the batteries bank subsystem which represents 43% of the total investment cost, followed by the PV array subsystem representing 25% of the system NPC. The remaining total investment cost is divided between the charge controller cost which represents 16% of the NPC and the inverter cost representing 15% of the NPC.

Figure 15 presents the frequency distribution of the state of charge (SOC) of the batteries bank for 0% LPSP \((N_{pv} = 63, N_{ad} = 3 \text{ days})\). It is observed from this figure that the SOC of the batteries range from 20% to 45% of his maximum capacity. Most of the time, the SOC of the batteries is between 35% and 40% (with 28.13% of relative frequency distribution) and between 25% and 30% (with 27.43% of relative frequency distribution). This result shows that the storage capacity of the batteries is not fully used for the designed configuration corresponding to 0% LPSP \((N_{pv} = 63, N_{ad} = 3 \text{ days})\), thus the batteries will not be able solely to fulfil the energy demand for 3 continuous days. In that case, it becomes important to increase the number of PV modules in order to increase the charge power of the batteries. However, this solution will lead to the increase of the system cost.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of PV modules</td>
<td>BP 3 series 235 W</td>
</tr>
<tr>
<td>Batteries charge efficiency</td>
<td>85%</td>
</tr>
<tr>
<td>Batteries discharge efficiency</td>
<td>85%</td>
</tr>
<tr>
<td>Allowable depth of discharge of batteries</td>
<td>80%</td>
</tr>
<tr>
<td>Efficiency of inverter</td>
<td>95%</td>
</tr>
<tr>
<td>Efficiency of charge controller</td>
<td>95%</td>
</tr>
<tr>
<td>Batteries bank voltage</td>
<td>48 V</td>
</tr>
<tr>
<td>Interest rate</td>
<td>8%</td>
</tr>
<tr>
<td>Annual inflation rate</td>
<td>4%</td>
</tr>
</tbody>
</table>

Figure 8: Pareto front solutions based on a double-objective optimization.

Figure 9: Variation of the number of PV modules on Pareto front.

### Table 4: Parameters used for simulation.

<table>
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</tr>
<tr>
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<td>4%</td>
</tr>
</tbody>
</table>

Figure 10: Variation of batteries autonomy days’ number on Pareto front.

Figure 8 International Transactions on Electrical Energy Systems
Therefore, the users could decide to reduce the autonomy duration of the batteries in order to avoid useless over sizing, resulting in the reduction of the system cost. Table 6 shows that the increase of the PV generator size results in the increase of the system cost from 4.6% (for $N_{pv} = 70$) to up to 11.17% (for $N_{pv} = 80$). Table 7 shows that the reduction of the batteries size results in the reduction of the system cost from 7.19% (for $N_{ad} = 2.5$) to up to 28.77% (for $N_{ad} = 1$). This analysis reveals that the effect of the variation of the batteries size on the system cost is higher than the effect of the variation of the PV size.
5. Conclusion

In this paper, a detailed techno-economic study of an off-grid PV/battery system for energy supply has been realized for a locality in Cameroon. A double-objective optimization has been used to optimally design the system’s configuration. The optimal configuration of the system has been identified for 0% LPSP (PV modules number: 63, batteries autonomy: 3 days, batteries nominal storage capacity: 370.2949 kWh). The corresponding cost of energy to this configuration is 0.2587 $/kWh. With this optimal configuration, the load demand is fully satisfied at all the times of the year. However, the analysis revealed that, with this configuration, at least half of the storage capacity of batteries is not used and thus reduces the ability of the system to respond for a long time to the power demand, when the PV power production is not able to satisfy the load. The sensitivity of the system has been studied for this purpose by increasing the number of PV modules (to increase the power production and thus to increase the energy to store in batteries) resulting in the increase of the system investment cost and thus the increase of the COE. Rather to have a system with 3 days autonomy of batteries at high cost, the users have also the possibility to reduce the storage capacity of the system (reduction of the batteries bank size) by reducing the autonomy of the batteries, resulting in the reduction of the COE and the system investment cost to up to 28.77% (for 1 day autonomy of batteries).

Based on the difficulties for remote and rural areas to access to electricity, the PV/battery system could be very advantageous financially and even technically. This research paper has proven the effectiveness of the proposed modeling and optimization for the optimal design of PV/battery systems (used for energy supply). It has been shown that the optimal analysis of energy systems based on a double-objective Firefly optimization algorithm is a powerful tool for decision making.
Nomenclature

PV: Photovoltaic
$N_{pv}$: Number of photovoltaic modules
$P_{pv}$: Photovoltaic power (W)
$P_{pv,ref}$: Photovoltaic power at reference condition (25°C or 298°K)
NOCT: Nominal operating cells temperature (°C)
$T_{a}$: Ambient temperature (°C)
G: Irradiance (W/m²)
$G_{ref}$: Irradiance at reference condition (W/m²)
$\alpha$: Temperature coefficient of short-circuit current (A/K)
$T_{c}$: Cell temperature (°C or K)
$T_{c,ref}$: Cell temperature at reference condition (25°C or 298°K)
$C_{batt}$: Storage capacity of batteries (kWh or kAh)
$C_{batt,n}$: Nominal storage capacity of batteries (kWh or kAh)
$C_{batt,unit}$: Nominal storage capacity of single battery (kWh or kAh)
$U_{n}$: Nominal voltage of batteries bank (V)
$U_{n,unit}$: Nominal voltage of single battery (V)
$P_{c,regulator}$: Charge power of batteries (W)
$P_{dis,regulator}$: Discharge power of batteries (W)
$N_{batt}$: Total number of batteries
$N_{p,batt}$: Number of batteries string
$N_{c,batt}$: Number of batteries in series per string
$N_{aut}$: Number of autonomy days of batteries
$\eta_{inverter}$: Efficiency of inverter (%)
$\eta_{regulator}$: Efficiency of charge regulator (%)
$\eta_{batt,c}$: Efficiency of charge of batteries (%)
$\eta_{batt,d}$: Efficiency of discharge of batteries (%)
$DOD$: Depth of discharge of batteries (%)
$P_{demand}$: Power demand (W)
$E_{demand}$: Total annual energy demand (kWh)
LED: Light emitting diode
$N_{pv,ref}$: Number of photovoltaic modules
SOC: State of charge of batteries (%)
LPSP: Loss of power supply probability
COE: Cost of energy
FA: Firefly algorithm
Cost$_{pv}$: Cost of photovoltaic modules
Cost$_{batteries}$: Cost of batteries
Cost$_{regulator}$: Cost of charge regulator
Cost$_{inverter}$: Cost of inverter
$: American dollar
DG: Diesel generator
DC: Direct current
AC: Alternating current.

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.

References


