Chapter

Methodology for Sizing Hybrid Battery-Backed Power Generation Systems in Off-Grid Areas

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Abstract

In developing countries, rural electrification in areas with limited or no access to grid connection is one of the most challenging issues for governments. These areas are partially integrated with the electrical grid. This poor electricity distribution is mainly due to geographical inaccessibility, rugged terrains, lack of electrical infrastructure, and high required economic investment for installing large grid-connected power lines over long distances to provide electricity for regions with a low population. On the other hand, rapid depletion of fossil fuel resources on a global scale and progressive increase of energy demand and fuel price are other motives to reduce the reliance on fossil fuels. Hybrid renewable energy system (HRES) can be a suitable option for such remote areas. The objective of this chapter is to develop a methodology for sizing hybrid power generation systems (solar-diesel), battery-backed in non-interconnected zones, which minimizes the total cost and maximizes the reliability of supply using particle swarm optimization (PSO). The proposed methodology assists the sizing and designing process of an HRES for an off-grid area minimizing the cost of energy (COE) and maximizing the reliability of the system. Economic incentives offered by the Colombian government are considered in the model.

Keywords: hybrid renewable energy system (HRES), stand-alone systems, off-grid areas, particle swarm optimization (PSO), photovoltaic energy, power dispatch strategy

1. Introduction

Due to the technological and industrial worldwide progress and the growing industry and society need of power generation for the development and increment of life quality, it is of unquestionable importance to increase sustainable access to electrical energy. In developing countries, there are still many locations without power supply.

Power generation through fossil generators offers a continuous and reliable source of energy making it a very popular option for electrification in off-grid areas. This alternative presents an initial investment cost relatively low compared to other sources of power generation. However, fossil power generators are sized to meet peak demand and have a low performance when the load is quite below to its rated capacity. Additionally, operating and maintenance costs are high; the cost of energy (COE) is subject to changes according the national and international fuel markets. In addition, logistical challenges associated with fuel supply in remote areas can cause a significant increase in generation costs [1]. A solution for these disadvantages is the implementation of HRES which includes fossil and other energy sources. For warm and high-average daily radiation levels, photovoltaic solar energy with battery backup represents an attractive complementary source to diesel generation systems. This solution allows the reduction of generation costs and increased system reliability [2, 3].

Hybrid systems have shown lower generation costs and greater reliability than dependent systems of a single source of energy [1, 2–6]. Each element of the system has to be properly sized to achieve a techno-economic profitability. Therefore, the penetration of renewable energy sources in the energy market depends mainly on the applied sizing methodology to optimize its design [7].

The optimization of these systems could be complex, since many variables are naturally stochastic and linked to the selected location. Examples of these variables are temperature, solar resource, and load profile of the location [8]. Moreover, the optimization technique depends on the selected objective function, which can be oriented in seeking financial gain, increasing system reliability, and reducing the environmental impact [9].

Then, it is necessary to develop a methodology for optimizing the design of HRES that allows the integration of photovoltaic and diesel generation systems, with or without energy storage, allowing to reduce energy costs and maintaining a high reliability in energy supply in off-grid areas. The methodology requires a set of input information linked to the project site, as meteorological and load profile data, and also technical and economic information of the main equipment of the HRES. Then, an optimization process is necessary to determine the best combination of diesel power, PV power, and battery bank capacity. Economic and reliability parameters that support the solution obtained is expected to be presented with the solution.

In the last decade, several optimization techniques have been used to obtain an optimal solution of the sizing of HRES [7, 10–13]. The results among different approaches may vary depending on the characteristics of the model which permits to simulate the behavior of different elements of the system and also the economic and reliability model used as base on the optimization process.

The main objective of this work is to develop an optimization methodology for sizing HRES in off-grid areas of developing countries. In contrast to other works, each step of the methodology is described in detail. Also, special condition will be considered on the development of the economic and reliable model to adjust it to the reality of Colombia, for example, the national and international physical distribution cost or the incentive proposed by the Act 1715 for electrification using non-conventional energy sources in Colombia.

2. Proposed methodology

In this methodology, the grid can be formed either from the diesel unit or from a master inverter. The diesel generation is only required when the energy produced by the photovoltaic source and the energy backup in the battery bank is lower than the demanded load. The following items summarize the key characteristics of the dispatch strategy used in this work to model PV-diesel with battery storage systems: (1) the system is considered DC-coupled (**Figure 1**) and (2) the load following strategy is adopted [1]. The diesel generators are only used to supply the load when

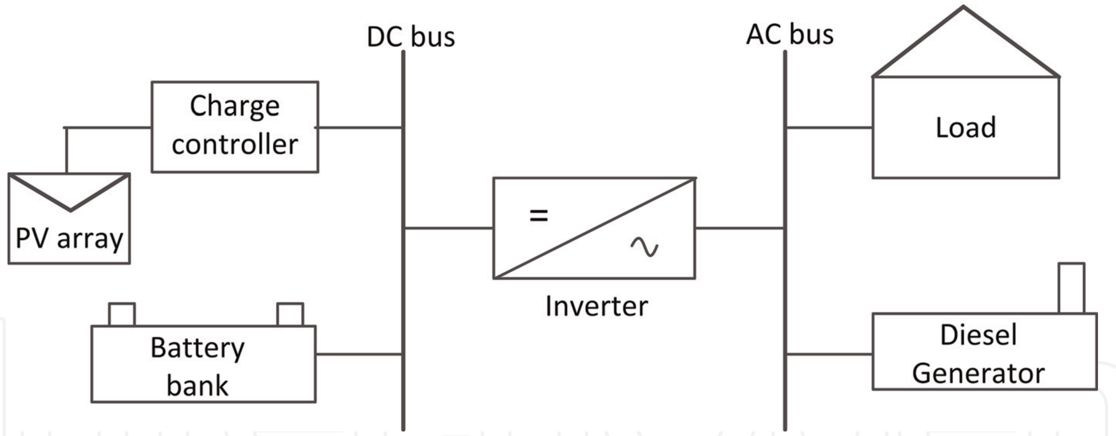

Figure 1.
Schematic diagram of a hybrid solar/battery/diesel generation system.

there is insufficient power from the PV source and the battery bank. Only the minimum DG unit required operates in every time step; (3) all DG units must operate over the minimum load ratio (δ_{min}) defined otherwise the DG unit must be turned off; (4) all DG units have the same nominal power capacity and operate at the equilibrium point at the same load ratio; (5) when diesel units are operating, the PV generation prioritizes the charge of the battery bank over the load; (6) only AC loads are considered; and (7) a maximum number of DG units are considered.

The proposed methodology is composed of the following steps: (1) a dispatch strategy algorithm, (2) calculation of economic indicators, (3) calculation of reliability indicators, (4) calculation of fiscal incentives, and (5) a PSO optimization process given an objective function which optimizes the number of components of the installation and a calculation of economic and reliability indicators for the best solution. The following subsections detail the steps of the methodology. **Figure 2** shows the schematic of the proposed methodology and the optimization process.

2.1 Dispatch strategy algorithm

Figure 3 shows the dispatch strategy flowchart used on the diesel-PV-battery model for a year which algorithm is described in detail below.

1. Obtain or generate inputs of the system: load profile (P_L), irradiance (G), and temperature (T) for the location in a year. Load profile can be obtained through a survey considering the uncertainties on the input data (38) and (39), and also load profile can also be obtained using measurement of the electrical demand. High-quality solar resource and meteorological data can be obtained by two approaches: high-accuracy instruments installed at a meteorological station and complex solar meteorological models which are validated using high-quality ground instruments.

2. Introduce the following technical information of each element of the system and initialize variables.

2.1. According to the available location and its restrictions, introduce the following technical information: $N_{DG,\ max}$ (maximum number of DG units), w_{DG} (rated power of the available diesel generator), δ_{min} (minimum load ratio [%]), f_0 (fuel Curve intercept coefficient [l/kW]), f_1 (fuel curve slope coefficient [l/kW]), N_{pv} (number of PV modules), $P_{pv_{stc}}$ (rated power of the

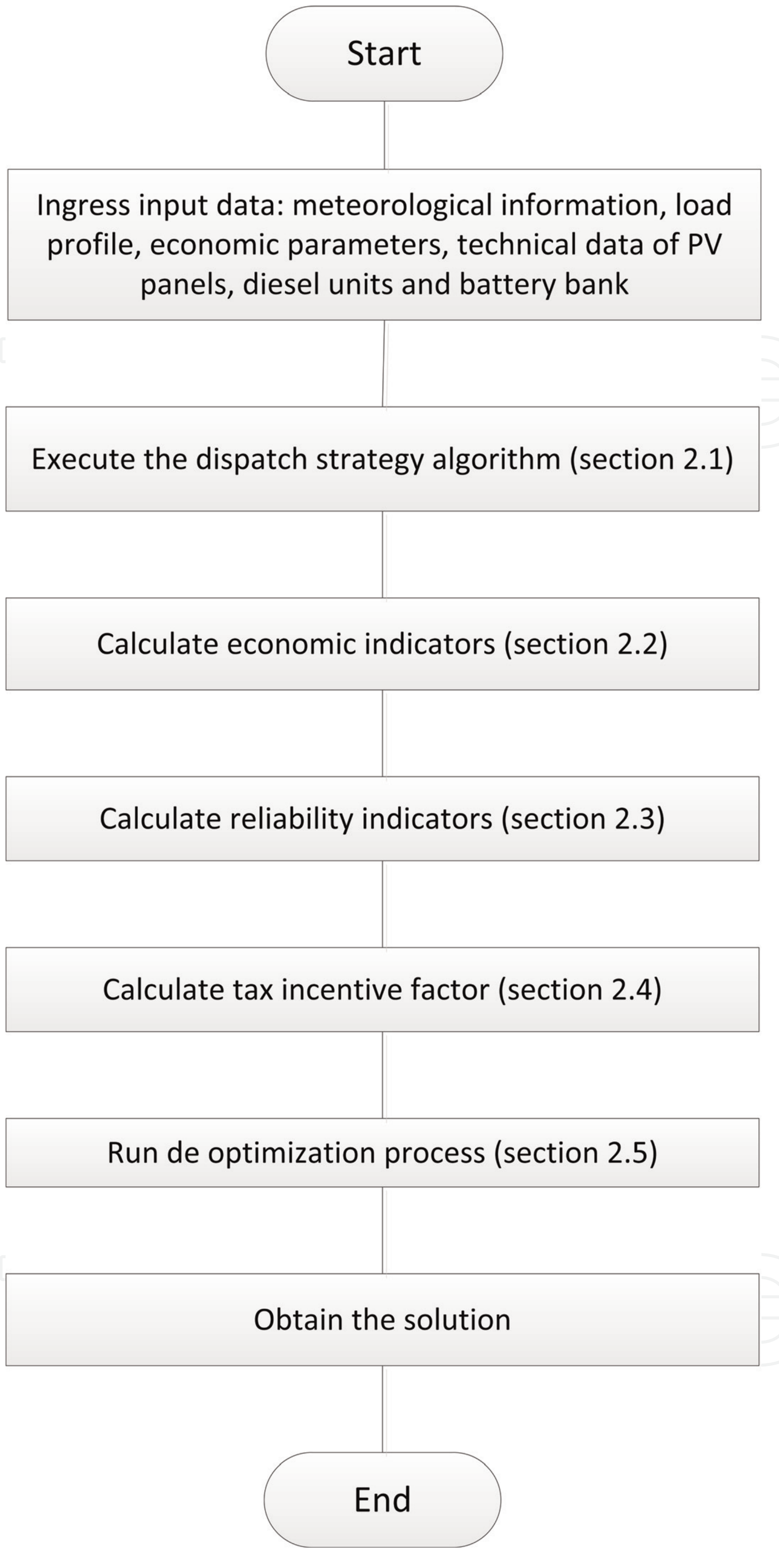

Figure 2.
Schematic diagram of the proposed methodology.

solar module in standard test conditions $[Wp]$), G_{stc} (global irradiance in standard test condition $[W/m^2]$), α_p (temperature coefficient of maximum power $[\%/°C]$), $NOCT$ (nominal operating cell temperature), T_{stc} (temperature of the cell standard test condition $[°C]$), T (cell's temperature), f_{pv} (derating factor of the solar module), η_{inv} (efficiency of inverters), N_{bp}

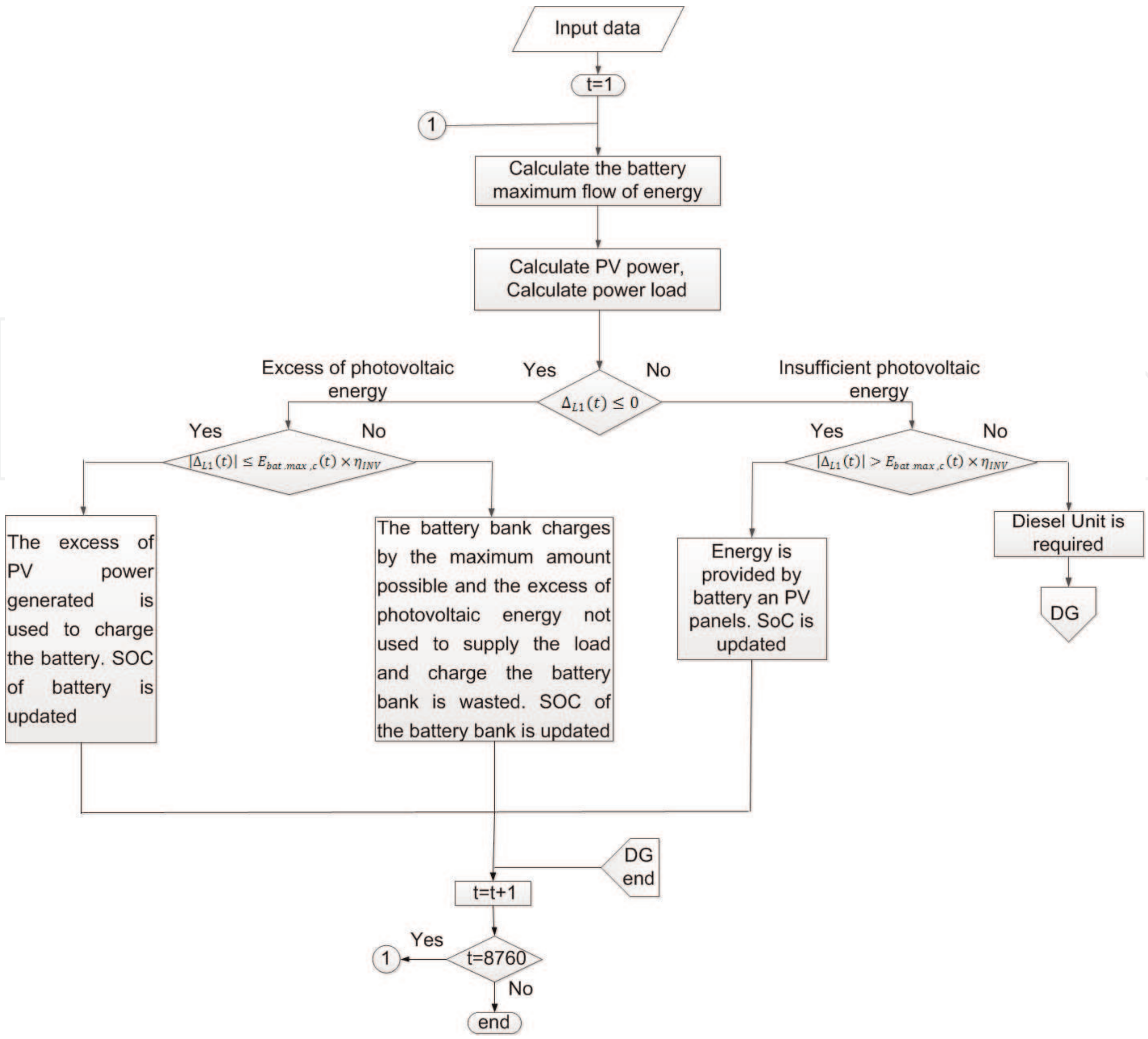

Figure 3.
Dispatch strategy flowchart.

(number of batteries in parallel), $E_{bcell,\,nom}$ (nominal capacity of one battery cell $[kWh]$), $V_{dc_{sist}}$ (DC voltage system [V]), E_{max} (maximum flow of energy to charge or discharge the battery bank $[kWh]$), $V_{dc_{bc}}$ (nominal voltage of each battery cell), $\eta_{bat,\,d}$ (discharge efficiency of the battery), $\eta_{bat,\,c}$ (charge efficiency of the battery), C_{rate} (capacity rate), DOD_{max} (maximum deep of discharge of the battery bank [%]), σ (self-discharge coefficient), w_{DG} (diesel rated power), and δ_{min} (diesel minimum load ratio).

2.2. Initialize the following variables: $\Delta_{L1} = 0$ (difference between PV energy generated and the energy demanded by the load), $t = 1$ (initial time instant, first hour of the year), $SOC(1) = SOC_{max}$ (state of charge (SOC) is initialized considering that the battery is full charged), $ENS = 0$ (energy not supplied), $PFT = 0$ (power time failure, $EW = 0$ (energy wasted), $P_{DG} = 0$ (diesel output power), $FC_{DG} = 0$ (consumption of the diesel generator, $N_{on} = 0$ (number of DG on), and $\delta = 0$ (diesel load ratio).

3. Calculate the battery model which expresses the equations in the function of the energy each hour:

(1) The maximum amount of energy that the battery bank can be discharged in one time step ($E_{bat,\,\max,\,d}(t)$ $[kWh]$) is as follows:

$$E_{bat,\ \max\_d}(t) = \max\left[0,\ \min\left[E_{max}, \left(SOC(t) - SOC_{min}\right)\right]\right] \tag{1}$$

(2) The maximum amount of energy that the battery can be charged in one time step ($E_{bat,\ \max,\ c}(t)$ $[kWh]$) is as follows:

$$E_{bat,\ \max\_c}(t) = \max\left[0,\ \min\left[E_{max}, \left(SOC_{max} - SOC(t)\right)\right]\right] \tag{2}$$

4. Calculate the hourly generated energy of the PV system ($P_{pv}(t)$ $[kWh]$). The PV power output for time step t is calculated using [14]:

$$P_{pv}(t) = N_{pv} \times P_{pv_{stc}} \times \frac{G(t)}{G_{stc}} \times \left(1 + \frac{\alpha_p}{100} \times (T(t) - T_{stc})\right) \times f_{pv} \tag{3}$$

5. Calculate the difference between PV energy generated and the energy demanded by the load ($\Delta_{L1}(t)$):

$$\Delta_{L1}(t) = P_L(t) - P_{pv}(t) \times \eta_{inv} \tag{4}$$

6. If $\Delta_{L1}(t) \le 0$, then the PV source can supply the load.

6.1. If $|\Delta_{L1}(t)| \le E_{bat.\ max,\ c}(t) \times \eta_{INV}$, the excess of PV energy generated ($E_{bat}(t)$), if any, is used to charge the battery bank, and the *SOC* of the battery is updated:

$$E_{bat}(t) = P_{pv}(t) - \frac{P_L(t)}{\eta_{INV}} \tag{5}$$

$$SOC(t+1) = SOC(t) \times (1 - \sigma) + E_{bat}(t) \times \eta_{bat,\ c} \tag{6}$$

Go to step 10.

6.2. Else, the battery bank is fully charged; SOC is updated. There is excess of energy that cannot be used supplying the load or charging the battery, so energy wasted (EW) is calculated.

$$E_{bat}(t) = E_{bat.\ max,\ c}(t) \tag{7}$$

$$SOC(t+1) = SOC(t) \times (1 - \sigma) + E_{bat}(t) \times \eta_{bat,\ c} \tag{8}$$

$$EW(t) = P_{pv}(t) - \frac{P_L(t)}{\eta_{INV}} - E_{bat}(t) \tag{9}$$

Go to step 10.

7. If $\Delta_{L1}(t) > 0$, the photovoltaic source is insufficient to supply the load.

7.1. If $\Delta_{L1}(t) < E_{bat,\ \max,\ d}(t) \times \eta_{INV}$, the battery bank discharge to supply the lack of energy. SOC of the battery is updated.

$$E_{bat}(t) = \frac{P_L(t)}{\eta_{INV}} - P_{pv}(t) \tag{10}$$

$$SOC(t+1) = SOC(t) \times (1 - \sigma) - E_{bat}(t) \times \eta_{bat,\ d} \tag{11}$$

Go to step 10.

7.2. Otherwise, diesel generation is required. Go to step 8.

8. Diesel generation is necessary. Photovoltaic energy is used to charge the battery bank, and the diesel generation is used to supply the load. The energy stored in the battery bank and energy generated by the diesel unit is used to supply the load at night.

8.1. **Case 1:** $P_L(t) < \delta_{min} \times w_{DG}$. Since the DG units cannot operate under the minimum load ratio, δ_{min}, all DG units must be turned off ($N_{on}(t) = 0$, $\delta(t) = 0; P_{DG}(t) = 0$). The generated PV energy and the energy available in the battery bank are used to supply the load, while the energy not supplied (ENS) and the power time failure (PTF) are counted:

$$E_{bat}(t) = E_{bat.\,max\,,\,d} \tag{12}$$

$$SOC(t+1) = SOC(t) \times (1-\sigma) - E_{bat}(t) \times \eta_{bat\_d} \tag{13}$$

$$ENS(t) = P_L(t) - \left(P_{pv}(t) + E_{bat}(t)\right) \times \eta_{inv} \tag{14}$$

$$PFT = PFT + 1 \tag{15}$$

Go to step 10.

8.2. **Case 2:** $P_L(t) \geq \delta_{min} \times w_{DG}$ && $P_{pv}(t) > 0$. The photovoltaic energy is used to charge the battery bank. The diesel generation supplies the load.

8.2.1. **Case 2.1:** $P_{pv}(t) \geq E_{bat.\,max\,,\,c}(t)$. The battery bank charges at its maximum ratio, and the excess of energy is used to supply the load with the diesel generation.

$$E_{bat}(t) = E_{bat.\,max\,,\,c}(t) \tag{16}$$

$$SOC(t+1) = SOC(t) \times (1-\sigma) + E_{bat}(t) \times \eta_{bat,\,c} \tag{17}$$

$$P_{DG}(t) = \min\left(N_{dg,\ max} * w_{dg}, P_L(t) - \left(P_{pv} - E_{bat}(t)\right) \times \eta_{inv}\right. \tag{18}$$

$$N_{on}(t) = \left\lceil \frac{P_{DG}(t)}{w_{dg}} \right\rceil \tag{19}$$

$$\delta(t) = \frac{P_{DG}(t)}{N_{on}(t) \times w_{DG}} \tag{20}$$

Go to step 9.

8.2.1.1. **Case 2.1.1:** $P_L(t) > \left(P_{pv}(t) - E_{bat}(t)\right) \times \eta_{inv} - P_{DG}(t)$. Diesel generation is not sufficient to supply the load; the energy not supplied is accounted:

$$ENS(t) = P_L(t) - \left(P_{pv}(t) - E_{bat}(t)\right) \times \eta_{inv} - P_{DG}(t) \tag{21}$$

$$PFT = PFT + 1 \tag{22}$$

Go to **step** 9.

8.2.1.2. **Case 2.1.2:** $\delta(t) < \delta_{min}$. If the load ratio of the DG unit is lower than the minimum load ratio allowed, then just one DG unit ($N_{on}(t) = 1$) works operating at the minimum load ratio ($\delta(t) = \delta_{min}$), and the excess of PV energy generated is wasted:

$$P_{DG}(t) = N_{on}(t) \times \delta(t) \times w_{DG} \tag{23}$$

$$EW(t) = P_{pv}(t) - E_{bat}(t) - \frac{P_L(t) - P_{dg}(t)}{\eta_{inv}} \tag{24}$$

Go to **step** 9.

8.2.2. **Case 2.2:** $P_{pv}(t) \leq E_{bat.\,max\,,\,c}(t)$. All photovoltaic energy is used to charge the battery bank:

$$E_{bat}(t) = P_{pv}(t) \tag{25}$$

$$P_{DG}(t) = \min\left(N_{dg,\ max} * w_{dg}, P_L(t)\right) \tag{26}$$

$$SOC(t+1) = SOC(t) \times (1-\sigma) + E_{bat}(t) \times \eta_{bat,\,c} \tag{27}$$

$$N_{on}(t) = \lceil \frac{P_{DG}(t)}{w_{dg}} \rceil \tag{28}$$

$$\delta(t) = \frac{P_{DG}(t)}{N_{on}(t) \times w_{DG}} \tag{29}$$

8.2.2.1. **Case 2.2.1:** $P_L(t) > P_{DG}(t)$. The DG is insufficient to supply the load; the energy not supplied is accounted:

$$ENS(t) = P_L(t) - P_{DG}(t) \tag{30}$$

$$PFT = PFT + 1 \tag{31}$$

8.3. **Case 3:** $(P_L(t) \geq \delta_{min} \times w_{DG}$ && $P_{pv}(t) \leq 0$). At night, the battery bank and the DG units are used to supply the load.

8.3.1. **Case 3.1:** $(P_L(t) - E_{bat.\,max\,,\,d}(t) \times \eta_{inv} \geq \delta_{min} \times w_{DG})$. Battery bank is discharged at maximum rate, and DG units generate the remaining energy necessary to supply the load.

$$E_{bat}(t) = E_{bat.\,max\,,\,d}(t) \tag{32}$$

$$P_{DG}(t) = \min\left(N_{dg,\ max} * w_{dg}, P_L(t) - E_{bat}(t) \times \eta_{inv}\right. \tag{33}$$

$$SOC(t+1) = SOC(t) \times (1-\sigma) - E_{bat}(t) \times \eta_{bat,\,d} \tag{34}$$

$$N_{on}(t) = \lceil \frac{P_{DG}(t)}{w_{dg}} \rceil \tag{35}$$

$$\delta(t) = \frac{P_{DG}(t)}{N_{on}(t) \times w_{DG}} \tag{36}$$

8.3.1.1. **Case 3.1.1:** $(P_L(t) \geq P_{DG} + E_{bat}(t) \times \eta_{inv})$. The diesel **generation** and the energy provided by the battery bank are not sufficient to supply the load; the energy not supplied is accounted.

$$ENS(t) = P_L(t) - P_{DG}(t) - E_{bat}(t) \times \eta_{inv} \tag{37}$$

$$PFT = PFT + 1 \tag{38}$$

8.3.2. **Case 3.2:** $(P_L(t) - E_{bat.\,max\,,\,d}(t) \times \eta_{inv} < \delta_{min} \times w_{DG})$. Just one DG unit works operating at the minimum load ratio ($N_{on}(t) = 1$, $\delta(t) = \delta_{min}$). The battery bank provides the insufficient energy to supply the load.

$$P_{DG}(t) = N_{on}(t) \times \delta(t) \times w_{DG} \tag{39}$$

$$E_{bat}(t) = \frac{P_L(t) - P_{DG}(t)}{\eta_{inv}} \tag{40}$$

$$SOC(t+1) = SOC(t) \times (1-\sigma) - E_{bat}(t) \times \eta_{bat,\, d} \tag{41}$$

9. The fuel consumption $FC_{DG}(t)$ is calculated by [15, 16]:

$$FC_{DG}(t) = N_{on}(t) \times w_{dg} \times f_0 + P_{DG}(t) \times f_1 \tag{42}$$

10. Increase the time step ($t = t + 1$). If $t \leq 8760$, and return to step 3. Else END.

After run the previous algorithm; economic and reliability indicators should be calculated using the following procedure.

2.2 Economic indicators

An economic analysis is required to determine the optimum cost and benefit ratio of HRES. These systems generally require high capital investment, even though they have low operation and maintenance (O&M) costs and less fuel costs in comparison with systems relaying only on fossil fuels. In this study, the annualized cost of the system (ACS) and the cost of energy (COE) are considered as the economic criteria to evaluate the feasibility of this hybridized system configuration.

The annualized cost of the system (ACS) is the sum of the annualized capital cost (CC), the annualized replacement cost (RC) and the annualized cost of maintenance (OM) [7, 17–19]. In [17], the annualized cost of the system is defined as

$$ACS = \sum_{i=1}^{N_c} (CC_i + RC_i) \times CRF(i_r, R) + O\&M_i) \tag{43}$$

where N_c is the number of components; in this study there are three components (PV modules, battery banks, DG units). Subscript i is used to describe the cost of each component. The capital recovery factor ($CRF(i_r, R)$) can be defined as a ratio used to calculate the present value of an annuity (a series of equal annual cash flows) in the function of the real interest rate (i_r) and the lifetime of the project (R) [17]. The capital recovery factor is calculated by

$$CRF(ir, R) = \frac{i_r \times (1+i_r)^R}{(1+i_r)^R - 1} \tag{44}$$

The real interest rate is used to convert between one-time costs and annualized costs. By defining the real discount rate, the inflation rate effect is factored out of the economic analysis. All costs, therefore, become real costs, which are in defined in terms of constant dollars. The real interest rate is calculated by

$$i_r = \frac{i_n - i_f}{1 + i_f} \tag{45}$$

where i_n and i_f are the nominal interest rate and expected annual inflation rate, respectively.

The capital cost for each component is described as follows:

$$CC_{pv} = c_{pv} \times N_{pv} \times P_{pv_{stc}} \tag{46}$$

$$CC_{bat} = c_{bat} \times N_{bat} \times E_{bcell,\,nom} \tag{47}$$

$$CC_{DG} = c_{DG} \times N_{DG} \times w_{DG} \tag{48}$$

where c_{pv} is the cost per Watt peak installed of photovoltaic power in [USD/Wp]; this cost includes the cost of the module, the electronic power equipment required (charge controller and inverter), and the installation cost (engineering, transportation, balance of system equipment as cable, mounting rack, electrical protection, etc.). c_{pv} varies according to the project location and site conditions; it can range from 3 to 10 USD/Wp. The cost per unit of the battery system, c_{bat}, in [USD/Wh], includes the average cost of the battery cell and the installation cost of the battery system. The parameter c_{DG} in [USD/kW] is the cost per unit of diesel generation installed and also includes the cost of the diesel generator unit and the associated installation costs.

The replacement cost is calculated for each element. The replacement cost of the photovoltaic system is assumed null, as the photovoltaic modules have a life cycle superior to the lifetime of the project and it is assumed in this model that the charge controllers and inverters do not need replacement during the lifetime of the project. The replacement cost of the battery system and the DG unit can be calculated as

$$RC_{bat} = \gamma_{bat} \times CC_{bat} \times K_{bat}\left(i_r, L_{pv}, y_i\right) \tag{49}$$

$$RC_{DG} = \gamma_{DG} \times CC_{DG} \times K_{DG}\left(i_r, L_{DG}, y_i\right) \tag{50}$$

where γ_{bat} and γ_{DG} are derate factors of the initial capital cost invested for the battery system and the diesel genset, respectively, as some cost necessary during the installation are no longer needed during the replacement (civil works, battery rack, electrical protections, fuel tank, etc.). $K_i\left(i_r, L_i, y_i\right)$ is the single payment present worth [17], which is defined by

$$K_i\left(i_r, L_i, y_i\right) = \sum_{n=1}^{y_i} \frac{1}{\left(1+i_r\right)^{n \times L_i}} \tag{51}$$

where L and y are the useful lifetime and the number of replacements of the component during the lifetime of the project, respectively. The number of replacements of each component is a function of useful lifetime of the component and the lifetime of the project ($y_i = \lfloor \frac{R}{Li} \rfloor$).

The fixed mount PV systems do not have moving parts, so operating and maintenance costs consist of regular cleaning and monitoring of performance, the annual operation, and maintenance cost can be estimated as a percentage of the PV system total investment, ρ_{pv}, usually between 1 and 2% [20].

$$O\&M_{PV} = \rho_{pv} \times CC_{pv} \tag{52}$$

In a similar way, the annual operation and maintenance cost for the battery system can be calculated as percentage of the total investment cost of the battery system. This cost can vary according to the technology of the battery bank. For example, the cost of operation and maintenance for vented lead-acid batteries is higher than maintenance-free sealed lead-acid batteries or Li-ion batteries. The percentage of the total investment cost, ρ_{bat}, can vary between 1 and 3%.

$$O\&M_{bat} = \rho_{bat} \times CC_{bat} \tag{53}$$

The operation and maintenance cost for the diesel system components is divided in two values: a fixed cost, expressed as a percentage of the diesel initial investment,

ρ_{DG}, and a variable cost associated to the cost of fuel, f_C, in [$/gal], and the annual fuel consumption. The annual operation and maintenance cost of the diesel system can be calculated by

$$O\&M_{DG} = \rho_{DG} \times CC_{DG} + f_C \times \sum_{t=1}^{8760} FC(t) \quad (54)$$

The cost of energy (COE) can be defined as the average cost per kWh of useful electrical energy produced by the system [21]. It can be obtained as the ratio between the annualized cost of the system and the effective load served in 1 year. The economic model assumes that the yearly effective load served is constant over the lifetime of the project. COE can be calculated as follows:

$$COE = \frac{ACS}{\sum_{t=1}^{8760} (E_L(t) - ENS(t))} \quad (55)$$

2.3 Reliability indicators

The dependency on nature and unpredictability of solar resources has a great impact on energy production which leads to unreliable power supply during cloudy days. A system is reliable if it can supply the required power to the electrical load within a specific time period.

The loss of power supply probability (LPSP) is the most widely used method to evaluate the reliability in hybrid system, therefore is selected, in this work, as reliability criteria. The LPSP be calculated as the ratio of power supply deficit to the electric load demand during a certain period of time (normally a year). A ratio equal to zero means all load demand, during the period of time, is served by system (53). LPSP is given by

$$LPSP = \frac{\sum_{t=1}^{8760} ENS(t)}{\sum_{t=1}^{8760} E_L(t)} \quad (56)$$

A method that takes into account the weight of reliability in the economic model includes a component of the cost of electricity interruptions or cost of load (C_{loss}) [17]. The cost of electricity interruptions can be estimated in different ways, for example, looking at the customer's willingness to pay for an expansion or at production losses at industries affected, or at the level of compensations, which makes shortages acceptable. In [17], for 2009, the cost ranges from 5 to 40 USD$/kWh for industrial users and 2–12 USD$/kWh for domestic users.

The cost of electricity lost for non-interconnected zone can vary with respect the reference cost and could be difficult to estimate, as depends on the willingness of users to pay for a more robust system. The cost of electricity not supply (C_{loss}) in [USD/kWh] is an input parameter in the economic model. The annualized cost of energy not supplied can be calculated as

$$AC_{loss} = C_{loss} \times \sum_{t=1}^{8760} ENS(t) \quad (57)$$

$LPSP$ and AC_{loss} are calculated for each possible combination considered during the sizing methodology.

2.4 Fiscal incentives

Under the Colombian Renewable Energy Law, new clean energy projects will receive up to 50% tax credits, but they can only be applied during the first 5 years. In this work, when the fiscal incentives are considered, it is assumed that the company will receive the 50% of the tax credit equally distributed over the first 5 years of the project. In general, investment tax credits can be calculated as

$$i = \sum_{j=1}^{5} i_j = 0.5 \tag{58}$$

$$i_1 = i_2 = i_3 = i_4 = i_5 = 0.1 \tag{59}$$

In a similar way, it is assumed that the effect of depreciation is equally distributed each year, and the useful life for accelerated depreciation purposes is 5 years; then

$$d = \sum_{j=1}^{5} d_j = 1 \tag{60}$$

$$d_1 = d_2 = d_3 = d_4 = d_5 = 0.2 \tag{61}$$

Assuming an effective corporate tax income rate of 33% and under the previous consideration, the tax reduction factor Δ for the purpose of this work is given by

$$\Delta = \frac{1}{(1-t)} \times \left[1 - t \times \left(\sum_{j=1}^{T1} \frac{i_j}{(1+i_r)^j} + \sum_{j=1}^{T2} \frac{d_j}{(1+i_r)^j}\right)\right] \tag{62}$$

wheret is the effective corporate tax income rate, $T1$ is the maximum number of years to apply the investment tax credit, $T2$ is the useful life of the power-generating facility for accelerated depreciation purposes (in year) = 5, i is the investment tax credit, and d is the depreciation factor expressed as percentage of investment cost over $T2$ year.

Fiscal incentives granted by the Colombian Act 1715 only apply to not conventional energy source installation and its components. In this way, the incentive tax factor only applies to the capital cost of photovoltaic and battery components:

$$\begin{aligned} ACS_{adj} = {} & \left[\left(CC_{pv} + CC_{bat}\right) \times \Delta + CC_{DG} + RC_{bat} + RC_{DG}\right] \times CRF(i_r, R) + O\&M_{pv} \\ & + O\&M_{bat} + O\&M_{DG} \end{aligned} \tag{63}$$

2.5 Objective function: optimization process

The objective of this work is sizing hybrid power generation systems (solar-diesel) battery-backed, in non-interconnected zones, which minimizes the total cost of the solution and maximize the reliability of supply. To minimize the total cost of the system, the following objective function is used:

$$Cost = \frac{ACS_{adj} + AC_{loss}}{\sum_{t=1}^{8760} (E_L(t) - ENS(t))} \tag{64}$$

This work aims to develop an optimization model for sizing an energy system to supply the energy demand on an off-grid location. The optimization of these systems could be complex, since many variables are naturally stochastic depending mostly on the characteristic of the solar resource and the load profile of the selected location. The objective is to minimize the total cost of the solution and maximize the reliability of the supply.

As a result of the optimization problems, the following information are obtained: (1) amount of photovoltaic modules and therefore the total photovoltaic power in kWp, (2) amount of diesel generation units and the total diesel energy power in kWp, (3) amount of battery cell required and total capacity of the energy storage system in kWh, (4) energy flow in the system showing the different states of the system according to the dispatch strategy described in this work, (5) discriminated cost of each technology in terms of initial capital required and O&M cost, (6) annualized cost of energy of the best solution, and (7) amount and cost of energy not supplied and LPSP.

3. Case study

"Santa Cruz del Islote" in Bolivar, Colombia, was used as a location for the case study. This rural community is selected to evaluate the optimization model developed in this work.

3.1 Meteorological inputs and load profile

The monthly global irradiance over the horizontal and over the plane of the array was calculated using a MATLAB routine developed in this work and then compared with results obtained from Solargis. **Table 1** shows the results obtained.

	Global horizontal irradiation [kWh/m^2] Solargis	Global horizontal irradiation [kWh/m^2] calculated	Dev [%]	Global tilted irradiation [kWh/m^2] Solargis	Global tilted irradiation [kWh/m^2] calculated	Dev [%]
Jan	183.6	182.0	−0.88%	201.9	198.6	−1.65%
Feb	175.6	174.2	−0.81%	186.9	184.3	−1.41%
Mar	194.3	193.0	−0.68%	198.5	196.2	−1.14%
Apr	177.2	176.1	−0.65%	175	172.9	−1.17%
May	166.4	165.2	−0.70%	160.1	158.8	−0.83%
Jun	161.9	160.8	−0.71%	153.6	152.6	−0.65%
Jul	173.2	172.0	−0.69%	165.3	163.9	−0.84%
Aug	171.7	170.6	−0.65%	167.8	166.1	−1.03%
Sep	160.9	159.8	−0.70%	162	160.1	−1.17%
Oct	155.8	154.4	−0.91%	162.4	159.5	−1.79%
Nov	149.1	147.7	−0.96%	160.5	157.1	−2.13%
Dec	161.2	159.7	−0.93%	177.8	174.1	−2.09%
Year	2030.9	2015.3	−0.77%	2071.8	2044.1	−1.34%

Table 1.
Meteorological input parameters (monthly).

The difference can be accounted to the simplicity of the transposition model used in our MATLAB routine; nevertheless the results are good enough for the purpose of this work.

The load profile data was obtained from the National Monitoring Center (CNM) of the IPSE [22]. **Table 2** shows the input data used to generate the daily load profile curve. **Figure 4** shows the daily load profile for a week generated by a MATLAB routine developed in this work.

3.2 Technical inputs

This subsection describes the technical inputs required by the photovoltaic, diesel, and battery model employed in the optimization model developed in this work.

Hour	Power [%]	Uncertainty factor [%]	Hour	Power [%]	Uncertainty factor [%]
h	α_{power}	α_{unc}	h	α_{power}	α_{unc}
0	7.78	10	12	0.96	10
1	7.68	10	13	2.88	10
2	7.40	10	14	5.67	10
3	7.20	10	15	5.86	10
4	6.34	10	16	3.75	10
5	1.15	10	17	1.54	10
6	0.00	0	18	0.96	10
7	0.00	0	19	6.24	10
8	0.00	0	20	8.65	10
9	0.00	0	21	8.65	10
10	0.00	0	22	8.65	10
11	0.38	10	23	8.26	10
Yearly average daily energy demand [kWh], $E_{AV,\,day}$					520.5

Table 2.
Daily load profile for "Santa Cruz del Islote" July 2018.

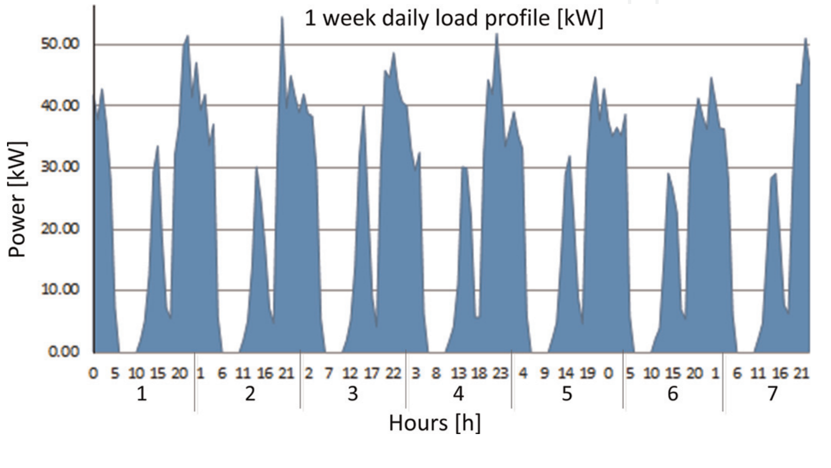

Figure 4.
Daily load profile for a week generated for "Santa Cruz del Islote."

3.2.1 Photovoltaic module technical data

A monocrystalline PV module of 300 Wp, reference JKM300M-60, from the company JINKO SOLAR, is used. **Table 3** shows the technical characteristics of the PV module selected. The cost per Wp installed presented in **Table 3** includes other costs not related to the price of the PV modules as the cost of charge controller, the PV inverters, and the mounting structure. Also this price includes indirect cost associated to the PV installation as engineering study costs, logistic costs, and certification costs. The cost per Wp presented is taken as reference and is provided by experts consulted in companies of energy sector.

3.2.2 Diesel genset technical data

The input data required by the diesel generation model is presented in **Table 4**. This information is collected from expert opinions on companies in the energy

Symbol	Description	Value
$P_{pv_{stc}}$	Maximum power [Wp]	300
V_{mpp}	Maximum power voltage [V]	32.6
I_{mpp}	Maximum power current [A]	9.21
V_{oc}	Open-circuit voltage [V]	40.1
I_{sc}	Short-circuit current [A]	9.72
η_{pv}	Module efficiency (%)	18.33
α_P	Power temperature coefficient [%/°C]	−0.39
α_V	V_{oc} temperature coefficient [%/°C]	−0.29
α_I	I_{sc} temperature coefficient [%/°C]	0.05
$NOCT$	NOCT [°C]	45
c_{PV}	Cost per Wp installed [USD/Wp]	2
ρ_{PV}	Fixed OM factor as ratio of the PV CC	0.01
f_{PV}	Photovoltaic derating factor	0.85
η_{INV}	Inverter efficiency	0.9

Table 3.
PV module technical inputs.

Diesel input data		
Symbol	**Description**	**Value**
$N_{DG,\ max}$	Maximum number of DG unit	5
δ_{min}	Minimum load ratio allowed	0.3
L_{DG}	Lifecycle [years]	10
ρ_{DG}	Fixed OM value as percentage of the diesel initial investment [%]	0.1
f_C	Fuel cost [USD/l]	0.8

Table 4.
Diesel model technical inputs.

sector. This information must be validated each time the optimization model is used since it can vary depending on the studied case.

Table 5 shows a database of diesel generation units with the cost per kW and the fuel curve parameters. This table was built using information supplied by the Colombian Regulation Commission of Energy and Gas (CREG—Comisión de Regulación de Energía y Gas) in [23]. The cost per kW presented in **Table 5** includes the direct and indirect costs related to the installation of a Diesel plant in non-interconnected zones.

DG power [kW]	Cost per kW installed [USD/kW]	Derate factors of the initial capital cost invested [%]	1/2 load 1 hour in liters	Full-load 1 hour in liters	f_0 [L/kWh]	f_1 [L/kWh]
10	2724.09	31.83	1.4	2.6	0.020	0.240
20	1697.26	32.43	3.4	6.05	0.037	0.265
25	1540.12	31.63	3.6	6.4	0.032	0.224
30	1934.44	23.00	6.8	10.96	0.088	0.277
40	1654.09	23.71	8.69	15.12	0.056	0.321
50	1434.92	25.12	9.825	16.63	0.060	0.272
60	1343.75	25.26	10.96	18.14	0.063	0.239
70	1788.83	18.13	11.43	19.77	0.044	0.238
80	1686.08	18.56	11.9	21.4	0.030	0.237
100	1723.40	17.24	12.85	23.06	0.026	0.204
125	1587.11	17.92	18.9	34.4	0.027	0.248
150	1572.63	17.55	22.3	41.2	0.022	0.252
200	1373.73	19.32	29.11	54.43	0.019	0.253

Table 5.
Diesel genset unit database.

Battery bank input data		
Symbol	**Description**	**Value**
V_{dcbc}	Battery voltage [V]	2
V_{dcsist}	DC system voltage [V]	48
C_{rate}	Capacity rate [h]	5
η_{bat_c}	Charge efficiency	0.9
η_{bat_d}	Discharge efficiency	1
σ	Self-discharge rate	0.000083
L_{bat}	Lifecycle [years]	10
δ_{bat}	Factor of the initial capital cost invested for the battery bank	0.7
ρ_{bat}	Fixed OM factor as ratio of the battery bank initial investment	0.02
DOD_{max}	Maximum depth of discharge	0.5

Table 6.
Battery bank technical inputs.

3.2.3 Battery bank technical data

In this chapter book, vented lead-acid battery banks only are considered. This kind of battery cells are often selected for large energy storage banks due the low cost, low maintenance, and high cycle stability. **Table 6** shows the input data required by the battery bank. The battery bank charge and discharge efficiency and the self-discharge ratio is taken from [24]. The maximum depth of discharge is set in 0.5 since the battery bank can accomplish 3000 cycles during its life service

Battery cell capacity [Ah] at C10	Battery cell capacity [kWh] at C10	Battery cell voltage [V]	# of cycles at 50% DOD	Price per unit [USD] (€)	Price per kWh [USD/kWh] (€)
280	0.56	2	3000	114.00	203.57
350	0.7	2	3000	135.00	192.86
420	0.84	2	3000	153.00	182.14
520	1.04	2	3000	161.00	154.81
620	1.24	2	3000	186.00	150.00
730	1.46	2	3000	210.00	143.84
910	1.82	2	3000	234.00	128.57
1070	2.14	2	3000	303.00	141.59
1220	2.44	2	3000	330.00	135.25
1370	2.74	2	3000	361.00	131.75
1520	3.04	2	3000	389.00	127.96
1670	3.34	2	3000	426.00	127.54
1820	3.64	2	3000	460.00	126.37
2170	4.34	2	3000	538.00	123.96
2540	5.08	2	3000	664.00	130.71
2900	5.8	2	3000	744.00	128.28
3250	6.5	2	3000	834.00	128.31
3610	7.22	2	3000	906.00	125.48
3980	7.96	2	3000	981.00	123.24
4340	8.68	2	3000	1056.00	121.66
4700	9.4	2	3000	1097.00	116.70

Table 7.
Battery cell database.

System inputs parameters		
Symbol	**Description**	**Value**
R	Time of the project [years]	20
i_r	Real interest rate [%]	8.08
c_{loss}	Cost of energy loss [USD/kWh]	0.2
Δ	Fiscal incentive factor	0.9038

Table 8.
System input parameters.

PSO input parameters		
Symbol	**Description**	**Value**
$N_{PV\,l}$	Lower bound number of PV modules	0
w_{DGl}	Lower bound nominal power of diesel	0
$N_{B_p\,l}$	Lower bound number of battery cell in parallel	0
$E_{bcell,\,nom\,l}$	Lower bound nominal capacity of battery cell [kWh]	0
$N_{PV\,u}$	Upper bound number of PV modules	20,000
w_{DGu}	Upper bound nominal power of diesel unit in [kW]	200
$N_{B_p\,u}$	Upper bound number of battery cell in parallel	10
$E_{bcell,\,nom\,u}$	Upper bound nominal capacity of battery cell [kWh]	9.40
Max_{it}	Maximum number of iterations	50
$nPop$	Population size	200
w	Inertia coefficient	1
w_{max}	Inertia coefficient max	0.9
w_{min}	Inertia coefficient min	0.5
c_1	Personal acceleration coefficient	2.5
c_2	Social acceleration coefficient	1.5

Table 9.
PSO input parameters.

according the datasheet. Other values as maintenance cost, ρ_{bat}, and the fraction of reposition cost, δ_{bat}, are set according to the recommendation of experts in the energy sector.

The main characteristics and price of the battery cells of the reference used in this work are presented in **Table 7**. The information was obtained from inquiries to local companies.

3.2.4 System inputs

The system input parameters are shown in **Table 8**. The cost of energy lost is assumed in 0.2 USD/kWh. This value depends on the necessities and characteristics of the users of the select location. The interest rate considered in this work is 8.08% taken in [25].

Fiscal incentive factor is calculated applying an effective corporate tax income rate of 33%. The resulting incentive factor is 0.938.

The parameters for the PSO algorithm and the boundaries for each decision variable are shown in **Table 9**.

4. Results of the case study

Table 10 summarized the obtained results after applying the proposed sizing methodology. The best cost achieved was 0.2090 USD/kWh being the lowest obtained. The optimization results deliver no only the design (number of components) but also economic and reliability indicators.

Component	Design	Unit	Indicator	Value	Unit
N_{pv}	13	Units	CC_{pv}	7800.00	USD
$P_{pv_{stc}}$	3.9	[kWp]	CC_{DG}	48257.99	USD
w_{DG}	25	[kW]	CC_{bat}	3864.00	USD
N_{DG}	2	Units	$O\&M_{pv}$	78.00	USD/year
P_{DG}	50	[kW]	$O\&M_{DG_f}$	4825.80	USD/year
N_{b_p}	1	Units	$O\&M_{DG_v}$	26884.74	USD/year
N_{b_s}	24	Units	$O\&M_{DG}$	31710.54	USD/year
N_{bat}	24	Units	$O\&M_{bat}$	77.28	USD/year
$E_{bcell,\ nom}$	1.04	[kWh]	RC_{DG}	7019.48	USD
$E_{bat,\ n}$	24.96	[kWh]	RC_{bat}	1243.60	USD
			FC	38406.77	[1]
			ACS_{adj}	38737.05	USD/year
			$LPSP$	1.25	%
			COE_{adj}	0.26	USD/kWh
			AC_{loss}	475.03	USD/year
			$LPVG$	0.00	%
			$Cost$	0.21	USD/kWh

Table 10.
Results of the case study.

5. Conclusions

In this work, an optimization methodology was developed and described in detail to help sizing HRSE integrated by photovoltaic and diesel generation with energy storage.

The main features of the sizing methodology developed were as follows: (a) it allows the simulation of hybrid renewable systems and the evaluation of its economic and reliability integrated by diesel and photovoltaic generation with energy storage, (b) the dispatch strategy developed prioritize the use of renewable energy among other energy sources, and (c) fiscal incentives granted by the Act 1715 of 2014 in Colombia were considered on the calculation of the cost of energy using the fiscal incentive factor.

The reliability of the system was included in the objective function of the PSO algorithm through the annual cost of the energy not supplied. Also a fiscal incentive factor was used to include the financial benefits granted by the Act 1715 of 2014 in Colombia to non-conventional renewable source of energy. The results were obtained after simulating the energy flow of the system for 1 year with 1-hour resolution.

Dispatch strategy was described in detail, prioritizing the use of renewable resource over diesel generation to supply the load. Also diesel generation cannot be used to charge the battery bank. This condition was based on the fact that, in off-grid areas, the complications associated to supply the fuel and the maintenance of DG units are commonly underestimated.

It is expected that this work will help the process of designing HRES in non-interconnected areas, thus contributing to the development of these locations and improving the life quality of the population living on these places.

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References

[1] Salas V, Suponthana W, Salas RA. Overview of the off-grid photovoltaic diesel batteries systems with AC loads. Applied Energy. 2015;**157**:195-216. DOI: 10.1016/j.apenergy.2015.07.073

[2] Shaahid SM, Elhadidy A. Opportunities for utilization of stand-alone hybrid (photovoltaic + diesel + battery) power systems in hot climates. Renewable Energy. 2003;**28**: 1741-1753. DOI: 10.1016/S0960-1481 (03)00013-2

[3] Shaahid SM, El-Amin I. Techno-economic evaluation of off-grid hybrid photovoltaic-diesel-battery power systems for rural electrification in Saudi Arabia—A way forward for sustainable development. Renewable Energy. 2009; **13**:625-633. DOI: 10.1016/j.rser.2007. 11.017

[4] Tsuanyo D, Azoumah Y, Aussel D, Neveu P. Modeling and optimization of batteryless hybrid PV (photovoltaic)/ diesel systems for off-grid applications. Energy. 2015;**86**:152-163. DOI: 10.1016/ j.energy.2015.03.128

[5] Jeyaprabha SB, Selvakumar AI. Optimal sizing of photovoltaic/battery/ diesel based hybrid system and optimal tilting of solar array using the artificial intelligence for remote houses in India. Energy and Buildings. 2015;**96**: 40-52. DOI: 10.1016/j.enbuild.2015. 03.012

[6] Belmili H, Haddadi M, Bacha S, Almi MF, Bendib B. Sizing stand-alone photovoltaic–wind hybrid system: Techno-economic analysis and optimization. Energy Review. 2014;**30**: 821-832. DOI: 10.1016/j.rser.2013.11.011

[7] Luna-Rubio R, Trejo-Perea M, Vargas-Vázquez D, Ríos-Moreno GJ. Optimal sizing of renewable hybrids energy systems: A review of methodologies. Solar Energy. 2012; **86**(4):1077-1088. DOI: 10.1016/j. solener.2011.10.016

[8] Erdinc O, Uzunoglu M. Optimum design of hybrid renewable energy systems: Overview of different approaches. Renewable and Sustainable Energy Reviews. 2012;**16**(3):1412-1425. DOI: 10.1016/j.rser.2011.11.011

[9] Ahmad Khan A, Iqbal M, Qaisar S, Anpalagan A. A compendium of optimization objectives, constraints, tools and algorithms for energy management in microgrids. Renewable and Sustainable Energy Reviews. 2016; **58**:1664-1683. DOI: 10.1016/j.rser.2015. 12.259

[10] Siddaiah R, Saini P. A review on planning, configurations, modeling and optimization techniques of hybrid renewable energy systems for off grid applications. Renewable and Sustainable Energy Reviews. 2016;**58**:376-396. DOI: 10.1016/j.rser.2015.12.281

[11] Prakash P, Khatod DK. Optimal sizing and siting techniques for distributed generation in distribution systems: A review. Renewable and Sustainable Energy Reviews. 2016;**57**: 111-130. DOI: 10.1016/j.rser.2015.12.099

[12] Mandelli S, Brivio C, Colombo E, Merlo M. A sizing methodology based on levelized cost of supplied and lost energy for off-grid rural electrification systems. Renewable Energy. 2016;**89**: 475-488. DOI: 10.1016/j.renene. 2015.12.032

[13] Haghighat Mamaghani A, Avella Escandon SA, Najafi B, Shirazi A, Rinaldi F. Techno-economic feasibility of photovoltaic, wind, diesel and hybrid electrification systems for off-grid rural electrification in Colombia. Renewable Energy. 2016;**97**: 293-305. DOI: 10.1016/j.renene.2016. 05.086

[14] Hatata AY, Osman G, Aladl MM. An optimization method for sizing a solar/wind/battery hybrid power system based on the artificial immune system. Sustainable Energy Technologies and Assessments. 2018;**27**:83-93. DOI: 10.1016/j.seta.2018.03.002

[15] Mohammed A, Pasupuleti J, Khatib T, Elmenreich W. A review of process and operational system control of hybrid photovoltaic/diesel generator systems. Renewable and Sustainable Energy Reviews. 2015;**44**:436-446. DOI: 10.1016/j.rser.2014.12.035

[16] Ameen AM, Pasupuleti J, Khatib T. Simplified performance models of photovoltaic/diesel generator/battery system considering typical control strategies. Energy Conversion and Management. 2015;**99**:313-325

[17] Kashefi Kaviani A, Riahy GH, Kouhsari SM. Optimal design of a reliable hydrogen-based stand-alone wind/PV generating system, considering component outages. Renewable Energy. 2009;**34**(11):2380-2390. DOI: 10.1016/j.renene.2009.03.020

[18] Fathima AH, Palanisamy P. Optimization in microgrids with hybrid energy systems—A review. Renewable and Sustainable Energy Reviews. 2015;**45**:431-446. DOI: 10.1016/j.rser.2015.01.059

[19] Chauhan A, Saini RP. A review on integrated renewable energy system based power generation for stand-alone applications: Configurations, storage options, sizing methodologies and control. Renewable and Sustainable Energy Reviews. 2014;**38**:99-120. DOI: 10.1016/j.rser.2014.05.079

[20] Hernández-Moro J, Martínez-Duart JM. Analytical model for solar PV and CSP electricity costs: Present LCOE values and their future evolution. Renewable and Sustainable Energy Reviews. 2013;**20**:119-132. DOI: 10.1016/j.rser.2012.11.082

[21] Zhang J, Huang L, Shu J, Wang H, Ding J. Energy management of PV-diesel-battery hybrid power system for island stand-alone micro-grid. Energy Procedia. 2017;**105**:2201-2206. DOI: 10.1016/j.egypro.2017.03.622

[22] CNM-IPSE [Internet]. 2018. Available from: http://www.ipse.gov.co/ [Accessed: 11 July 2019]

[23] Comisión de Regulación de Energía y Gas [Internet]. 2014. Available from: http://www.creg.gov.co/ [Accessed: 11 07 2019]

[24] Yang H, Zhou W, Lu L, Fang Z. Optimal sizing method for stand-alone hybrid solar–wind system with LPSP technology by using genetic algorithm. Solar Energy. 2008;**82**(4):354-367. DOI: 10.1016/j.solener.2007.08.005

[25] Castillo-Ramíre A, Mejía-Giraldo D, Molina-Castro JD. Fiscal incentives impact for RETs investments in Colombia. Energy Sources. 2017;**12**(9):759-764. DOI: 10.1080/15567249.2016.1276648