# Optimization of Photovoltaic and Wind Energy Sources Sizing for Home Requirements in Non-interconnected Zones: A Colombian Case Study

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**Abstract:** This document proposes a sustainable strategy for implementing different Non-Conventional Renewable Energy (NCRE) Sources in Non-Interconnected Zones to satisfy the most significant energy demand in these areas. The proposed approach establishes an optimization model to minimize the Loss Probability of Power Supply (LPSP) and improve the cost-benefit ratio of electricity generation with NCRE, considering different constraints, such as demand, technology costs, available environmental resources, energy storage, and technical limitations. A genetic algorithm that minimizes an objective function dependent on the LPSP and the Levelized Cost of Energy (LCOE) is developed, considering the energy models of a hybrid system composed of solar panels, horizontal axis wind turbines, and an energy storage system. The meteorological conditions for the study area, such as radiation, wind speed, and temperature, are considered, as well as the technical specifications of different models of the systems, to arrive at a solution that allows selecting the best alternatives for a user who wants to implement renewable energy in his household.

**Key words:** Solar energy, wind energy, optimization, LPSP, LCOE

## 1. Introduction

The increase in the demand for electricity in the world is proportional to the population and industrial growth, added to the questioning of conventional sources of energy generation, leading humanity to a challenge of diversifying the sources of electric generation and implementing environmentally friendly technologies since in the world, more than 60% of the energy generated comes from polluting sources [1]. Colombia has one of the cleanest energy matrixes in the world: 66% Hydraulic, 28% Thermal, and 4% Minor, such as small hydroelectric and wind power plants [2]. However, despite being a privileged country due to its geographical position and diversity in the availability of renewable resources, there is not a high penetration of Non-Conventional Renewable Energy Sources (NCRES) other than hydro. In addition, about 66% of the territory is disconnected, which is equivalent to approximately 2 million inhabitants [3], thus generating that the primary source of generation in these populations are Diesel plants, which are not able to ensure a constant supply of energy to the different users [4].

This research proposes a methodology for analyzing the implementation of different NCRES in a Colombian Non-interconnected Zone, satisfying the most significant energy demand in these areas, according to the site's characteristics. An optimization model initially uses this information to maximize electricity generation with NCRES, considering different restrictions, such as demand, site conditions, energy storage, operating costs, and technical limitations. A case study is carried out for the zone, La Guajira, where there is a high potential for resources for using renewable energy, and its population is mainly disconnected from the national electricity grid. Therefore, a hybrid generation system is sized considering the energy demand and the energy sources from wind turbines, solar panels, and batteries.

## 2. Related Work

Research on optimization methods for energy sizing, applied to different case studies, is carried out to determine the most used electric generation sources and the most common methods for this type of work. Various authors, such as Tezer *et al.* [5] propose using Hybrid Renewable Energy Systems (HRES) to supply a continuous demand due to renewable energy problems. They present the use of different optimization methods considering variables such as cost minimization, the uncertainty of the energy produced, and the reduction of greenhouse gases. Here, heuristic methods, such as genetic and evolutionary algorithms, are mentioned. Anoune *et al.* [6] perform a literature review of different optimization methods for HRES, aiming to find the best cost-per-generated power ratio for isolated areas. Deng and Lv [7] review state-of-the-art optimization models for renewable energies, showing increasingly complete studies where storage systems, various sources, and analysis for different scenarios are considered. They establish that the most used planning objective is to minimize the cost. The constraints are improved according to the capacity ceiling, the electric demand, the requirement of real-time scheduling, and the deployment of flexible strategies, which aims to achieve the economy and technical detail of HERS.

Concerning indicators to narrow down different energy models, Mainali and Silveira [8] make a sustainability analysis of emerging technologies in the Indian context, identifying essential energy sources such as biomass and micro-hydroelectric; and establish indicators of maximum and minimum costs and some sustainable indicators to determine the status of energy resources. Ma et al. [9] conduct a techno-economic study to include different hybrid renewable energy sources in regional and urban spaces, providing an essential theoretical framework and analysis of different scenarios. Mohammadi et al. [10] use the criteria of minimum energy supply cost and maximum reliability to plan a renewable energy system for a self-sufficient household, considering the constraints of storage scarcity and inadequate electrical load.

In summary, Genetic algorithms for HRES are the most used [11], wind and solar generation sources and storage systems are the most common in non-interconnected areas [12], [13], and the most used objective functions of optimization are the minimization of the Loss of Power Supply Probability (LPSP) and the Levelized Cost of Energy (LCOE) [14], [15].

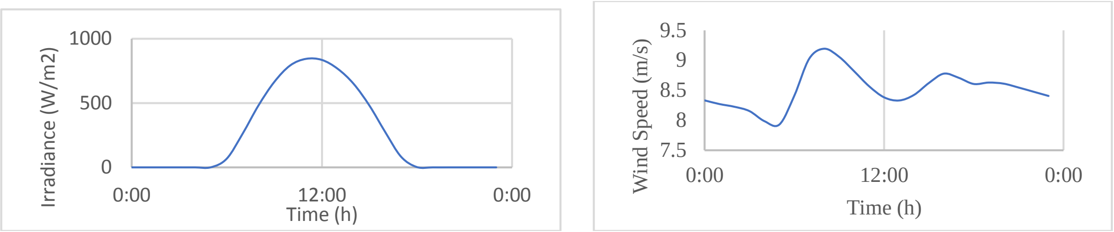
## 3. Proposed Optimization Approach

For this work, it is proposed to optimize an HRES with a configuration of wind and solar energy sources based on the environmental conditions of La Guajira, Colombia, the demand profile of a rural house, and the availability of the area of the site. For this case study, one-year data was simulated by the genetic algorithm. The proposed method performs a correct sizing of the sources, where a mathematical formulation is presented to optimize the system correctly, and each step is developed in the next.

### 3.1. Determine conditions at the location

Based on the selected location, wind speed and solar radiation data were collected for the last two years in Riohacha, the capital city of La Guajira [16]. Figure 1 shows the annual average solar radiation and wind speed ten meters above the surface.

Regarding the data collected, the solar resource presents an average of 6.2 hours of sun, which is a positive value compared to the world average, which is approximately 4 hours [17]. As the wind resource, the average wind speed oscillates between 8- 9 m/s [17], which is not usually the maximum power speed for a horizontal axis turbine; however, it is a speed that constantly generates energy from the wind resource.



(a) (b)

Fig. 1. Multi-annual average irradiance. b) Multi-annual average wind speed.

The consumption data were extrapolated from a dataset in Kaggle since the required data were unavailable for the specific area. However, these consumptions are related to the consumption in two homes with high energy demand in Houston, Texas, which could be approximated to the consumption of four houses in La Guajira. Therefore, the demand behavior for the first 100 hours is presented in Figure 2. It is observed that with these consumptions, a maximum demand value of approximately 4kW is reached, which means that the required demand is high at certain times.

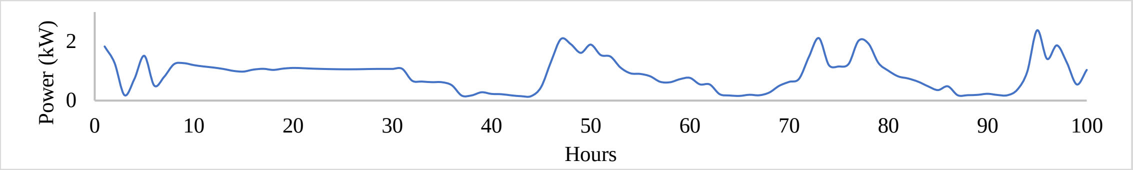


Fig. 2. Demand profile.

## 3.2. Technological characterization of generation sources

To solve the energy sizing problem, the indicators that are part of the objective function to be optimized are explained, considering how the different energy sources impact them.

### 3.2.1. Objective function indicators

The objective function is the minimization of the LPSP and LCOE indicators given a weighting for each of the mentioned variables, as is observed in equation 1, where $w_t$ is the weight of the technical indicator LPSP and $w_e$ is the weight of the economic indicator LCOE, the sum between $w_t$ and $w_e$ equals 1.

$$MinZ = w_t \times LPSP + w_e \times LCOE \tag{1}$$

Here, $w_t = 0.7$ and $w_e = 0.3$, where the technical indicator is more relevant than the economic one. These weights are defined as guaranteeing that the supply has greater importance than the cost of the system for this specific case.

The LCOE is the ratio between the total energy production of the power system to build and operate it over its lifetime and the average total cost of the system over that lifetime, represented by equation 2. The LCOE can also be considered the minimum cost necessary to sell electricity at the breakeven price over the plant's life [18].

$$LCOE = \frac{TLCC \times CRF}{\sum_{t=1}^{8760} E_{ca\,(t)}} \tag{2}$$

where, $TLCC$ is the total life cycle cost in USD, $CRF$ is the capital recovery factor, and $E_{ca}$ is the energy consumption over time.

The reliability of the power supply depends on the Loss of Power Supply Probability (LPSP) of the HRES that is incapable of feeding the load demands, represented by equation 3. LPSP =1 refers to an electrical load never being powered, while LPSP = 0 refers to a continuously powered electric load [19].

$$LPSP = \frac{\sum_{t=1}^{8760}\left[E_{ca(t)} - E_{gen(t)}\right]}{\sum_{t=1}^{8760}\left[E_{ca(t)}\right]} \tag{3}$$

where $E_{gen}$ is the sum of solar, wind, and battery bank contribution. If $LPSP < 0$, then the energy generated is more significant than the power demanded; while, if $LPSP > 0$, the demand exceeds the generation.

The constraints are related to different behaviors. $E_{pv}(t) + E_{wt}(t) > E_{ca}(t)$ determines that if the wind and solar energy generation is greater than the demand, the battery enters a charge state; and, if $E_{pv}(t) + E_{wt}(t) < E_{ca}(t)$ represents that if the wind and solar energy generation is less than the consumption, the battery enters a discharged state.

Equation 4. explains the Capital Recovery Factor (CRF), where $\alpha$ is the lifetime of renewable systems, and $ir$ is the interest rate.

$$CRF = \frac{ir\,(1 + ir)\alpha}{(1 + ir)\alpha - 1} \tag{4}$$

Equations 5, and 6 explain the Total Life Cycle Cost (TLCC) for wind and photovoltaic energy, respectively, where $N_{wt}$ is the number of wind turbines, $N_{pv}$ is the number of solar panels, $C_{c,}$ is the initial capital cost, and $O\&M$ is the operation and maintenance cost.

$$TLCC_{wt} = N_{wt} \times C_{c,wt} \times \left(1 + \frac{O\&M_{wt}}{CRF}\right) \tag{5}$$

$$TLCC_{pv} = N_{pv} \times C_{c,pv} \times \left(1 + \frac{O\&M_{pv}}{CRF}\right) \tag{6}$$

The equation 7 explains the Total Life Cycle Cost (TLCC) for the battery, where $E_{b,max}$ is the total storage capacity of the battery bank, $I_{bb}$ is the initial cost for each kWh of capacity in the battery bank, $M_{bb}$ is the maintenance cost per kW installed in a year, $F_{max}$ is the maximum charge and discharge rate over one hour, and $CR$ is the annual battery replacement cost.

$$TLCC_{bb} = E_{b,\max} \times I_{bb} + \left(\frac{CR \times E_{b,\max}}{CRF}\right) + \left(\frac{M_{bb} \times F_{\max} \times E_{b,\max}}{CRF}\right) \tag{7}$$

Defined as a percentage variable, $LPSP = 0\%$ means that the energy production satisfies the demand profile as long as a value of $100\%$ means that the system does not meet the total load demand. The value of $LPSP_{max} = 10\%$ was established for the case study since it is a reliable value for the supply loss [20].

Other constraints are related to the site area where the system would be installed, the roof area limits the number of panels, $A_{pv}N_{pv} \leq A_{house}$, and the number of turbines is limited by the land area, $5\pi D_{wt}^2 N_{wt} \leq A_{land}$. Where, $A_{pv}$ is the area of the solar panel, $N_{pv}$ is the number of solar panels, $A_{house}$ is the area of the house, $D_{wt}$ is the diameter of the turbine, $N_{wt}$ is the number of turbines and, $A_{land}$ is the area of the land.

### 3.2.2. Energy sources

For the estimation of the electric generation of the selected sources, the mathematical models for the generation of solar panels $P_{pv}(t)$ proposed by Maleki et al. [17], the wind generation proposed $P_{wt}(t)$ by Woolmington et al. [19] and the charging and discharging model of the batteries $E_b(t)$ proposed by Maleki et al. [17], are considered.

where the total energy of the system is dependent of the number of turbines $N_{wt}$, the number of solar panels $N_{pv}$, and the number of batteries $N_{bb}$.

## 3.3. Implement the optimization strategy

The selected optimization strategy for HRES sizing is a Genetic Algorithm (GA) based on the literature analysis shown in previous sections. The GA starts creating an initial random population composed of $p$ individuals with $n$ chromosomes. Each chromosome represents the number of wind turbines, solar panels, and batteries. The first three chromosomes correspond to three different types of wind turbines $(N_{wt1} - N_{wt3})$. The following four chromosomes correspond to the considered four types of PV units $(N_{pv1} - N_{pv4})$, and the last chromosome, $N_{bb}$, represents the number of batteries in the storage system. The proposed solution is composed of 8 chromosomes (n = 8).

The parameters and characteristics chosen for the algorithm are shown in the following Tables. Table 1 for the attributes of the types of solar panels and the parameters of the wind turbines, and for batteries the following parameters are considered: $S_b$=1.35kWh, $\eta_{bat}$ = 85%, $DOD$ = 0.8, $F_{max}$ = 0.08, $\sigma$ = 0.0002, and $I_{bb}$ = 996.3 with an $M_{bb}$ = 5.

Table 1 Solar panels and Wind turbines parameters

| Solar panels | | | | | Wind Turbines | | | |
|---|---|---|---|---|---|---|---|---|
| Parameter | Model 1 | Model 2 | Model 3 | Model 4 | Parameter | Model 1 | Model 2 | Model 3 |
| $P\ [W]$ | 0.26 | 0.105 | 0.27 | 0.42 | $P\ [W]$ | 1 | 2.1 | 3.3 |
| $Area\ [m^2]$ | 1.74 | 0.72 | 1.64 | 2.48 | $Vci\ [m/s]$ | 2.5 | 3.5 | 2.5 |
| $Efficiency$ | 0.2066 | 0.146 | 0.165 | 0.17 | $Vco\ [m/s]$ | 18 | 25 | 18 |
| $NOCT\ [°C]$ | 45 | 45 | 44 | 45 | $Vr\ [m/s]$ | 12 | 11 | 12 |
| $T_{ref}[°C]$ | 25 | 25 | 25 | 25 | $Cc\ [USD]$ | 6040 | 12684 | 24825 |
| $N_T[°C]$ | -0.0034 | -0.0034 | -0.0041 | -0.0031 | $O\&M\ [USD]$ | 30.2 | 63.42 | 99.3 |
| $C_c[USD]$ | 550 | 283.5 | 729 | 1134 | $Swept\ Area\ [m^2]$ | 2.54 | 7.1 | 19.95 |
| $O\&M\ USD$ | 5.5 | 2.835 | 7.29 | 11.34 | | | | |

## 4. Results

Seven simulations are presented from the genetic algorithm results, as shown in Table 2.

Table 2. Simulations for the optimization approach

| Iteration | Npv | Nwt | Nbb | Tpv | Twt | Z | LPSP | LCOE |
|---|---|---|---|---|---|---|---|---|
| 0 | 18 | 8 | 9 | 3 | 2 | 0.0197 | 0.002 | 412.08 |
| 1 | 11 | 4 | 10 | 1 | 1 | 0.01259 | 0.00476 | 208.30 |
| 2 | 16 | 3 | 10 | 1 | 1 | 0.01202 | 0.00683 | 162.91 |
| 3 | 17 | 3 | 10 | 1 | 1 | 0.01201 | 0.00677 | 163.72 |
| 4 | 18 | 3 | 10 | 1 | 1 | 0.012 | 0.00671 | 164.601 |
| 5 | 19 | 3 | 10 | 1 | 1 | 0.012 | 0.00665 | 165.41 |
| 6 | 20 | 3 | 10 | 1 | 1 | 0.012 | 0.00659 | 166.22 |

Iteration 6 is the one that minimizes Z, complying with that LPSP < 10% and decreasing the LCOE, which is the ratio of costs per generation, concerning the other solutions. Figure 3(a) shows a one-year behavior of the system. For better understanding, Figure 3(b) shows the first 100 hours of the generation sources' behavior to supply the case study's demand.

From the above, the algorithm selects as the best solution 20 solar panels of type 1, 3 wind turbines of type 1, and 10 batteries, this giving a result of LPSP equal to 0.7% and a LCOE of 166.22USD/kWh per year, where concerning the initial solution the LPSP worsens, but the cost decreases significantly. For this reason, it is evident in the different iterations that the algorithm always tries to reduce the number of turbines and increase the number of panels since the turbines have the highest cost.

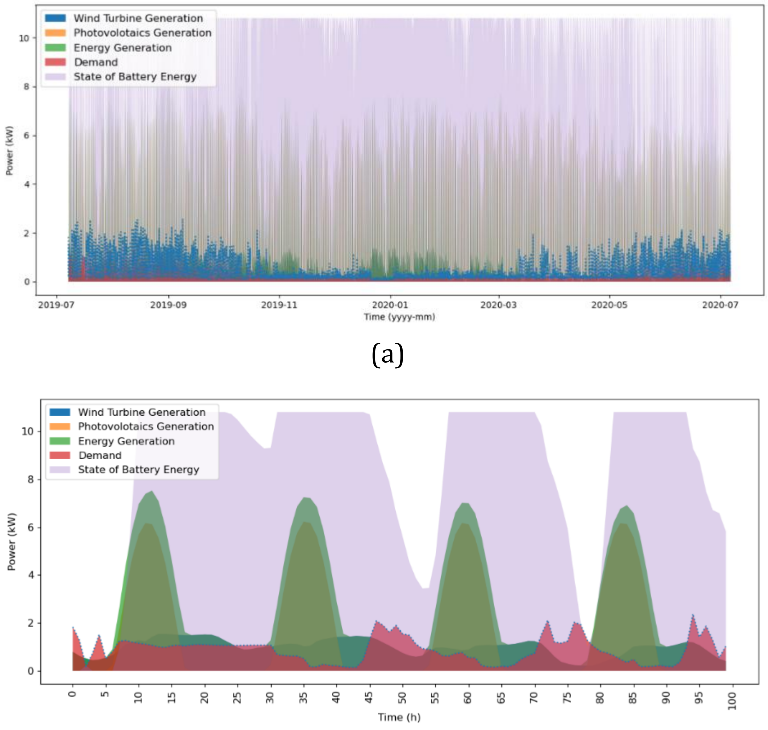


Fig. 3. a) One-year behavior of the better solution. b) First 100 hours behavior of the better solution.

## 5. Conclusions

This work shows the importance of using renewable energies to supply the energy demand in non-interconnected areas, such as some localities of La Guajira, Colombia. It is determined that, according to the results of the proposed optimization approach, different resources can become more important depending on the context. It is evidenced that more than five wind turbines without the need of solar panels can supply the demand; however, the cost per kWh generated by wind turbines is much higher than that of the solar panel; this shows that relating technical indicators such as LPSP and economic indicators such as LCOE allow finding techno-economically viable solutions. In addition, the work shows that the use of genetic algorithms for the resolution of sizing problems allows reaching achievable results in shorter times, since only by generating a population of 1000 individuals the global optimum can be reached about the 27000 possible combinations that would have to be considered with other types of solutions, such as the case of brute force methods, among others.

## Conflict of Interest

The authors declare no conflict of interest.

## Author Contributions

Santiago Bernal-del Río, Riccardo Mereu, Gilberto Osorio-Gómez conducted the research; Santiago Bernal-del Río, Riccardo Mereu, Juan Carlos Rivera, Gilberto Osorio-Gómez analyzed the data; Santiago Bernal-del Río, Gilberto Osorio-Gómez wrote the paper.

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