20th International Conference on Renewable Energies and Power Quality (ICREPQ'22)
Vigo (Spain), 27th to 29th July 2022
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.20, September 2022

Sizing of a Scattered Housing Microgrid in a Remote Rural Area

R. Rodriguez[1, 2], G. Osma[1] and G. Ordoñez[1]

[1] Department of Electrical, Electronic and Telecommunications Engineering
Universidad Industrial de Santander, Bucaramanga (Colombia)
(57) (7) 634 4000, Ext. 2361
[2] FEMTO-ST, FCLAB, Univ. Bourgogne Franche-Comté, Belfort (France)
(33) (0) 3 84 58 36 00
e-mail: rusber.rodriguez@correo.uis.edu.co, gealosma@uis.edu.co, gaby@uis.edu.co

Abstract. Power solutions for remote rural regions are mainly based on generator sets or individualized generation systems per household. These solutions have low reliability and high financial and environmental costs, especially those involving fossil fuels. However, current solutions incorporate hybrid systems with renewable energy sources to reduce pollutant gas emissions and costs and increase the reliability and robustness of power generation. These hybrid systems can be considered micro-grid (MG) and could contribute to energizing remote non-interconnected areas. However, implementing MGs in these regions must challenge energizing dispersed households. Thus, both the sizing of the generation and distribution systems must be considered to guarantee the correct operation of the MG and a low cost. This paper explores coordinated sizing between the power sources and the distribution system to address the challenges of energizing remote areas with dispersed loads through MG. It presents a literature review on energization strategies for remote regions and proposes coordinated MG sizing. Finally, it applies coordinated sizing to a case study in Colombia. The sizing is approached as a mixed-integer nonlinear integer programming optimization problem and is solved by a particle swarm optimization (PSO) algorithm.

Key words. Dispersed loads, renewable energies, microgrid, remote areas, coordinated sizing.

1. Introduction

Worldwide, about 759 million people in rural households do not have an electrical supply. Of these, 60% are in areas categorized as non-interconnectable [1]. Consequently, the possibility of energizing such sites is restricted to isolated energy solutions. It implies that, in the medium term, they will not be interconnected to an existing power grid.

The main energization strategies consist of the installation of diesel generators. However, the evolution of renewable energy and distributed generation allows us to propose economically viable solutions based on hybrid generation systems. These generation systems could integrate energy storage, metering, and management and even be considered microgrids (MG) [2]. The MG energy planning and sizing for a remote region could face challenges such as the dispersion of dwellings (loads). Thus, it should address an electrical distribution network [3].

An MG's energy planning consists of applying a set of strategies oriented to the sizing and operation of the electrical system to meet the energy requirements and reduce the implementation, operation, and maintenance costs and the negative impact on the environment [4], [5]. Mainly, it focuses on the sizing of energy resources and the design of the electrical distribution network; likewise, it involves an energy dispatch strategy, which can be approached as an optimization problem [6].

Some researchers are focused on the sizing of isolated MG. For example, Akter *et al.* [7] designed an isolated MG with 100% renewable energy sources for the island of St. Martin, Bangladesh. The MG integrates photovoltaic cells (PV), a battery energy storage system (ESS), fuel cells (FC), and an electrolysis plant (EP). The design considers the annual load's growth until the project's expected life. Using MATLAB software, design optimization was addressed by mixed-integer linear programming. Likewise, Kumar *et al.* [8] Proposed an MG solution based on renewable energies in mountainous areas of India. It illustrates a detailed feasibility analysis of the proposed rural MG based on a hydrokinetic energy system with a hydroelectric pump as ESS.

In the same way, Muños *et al.* [9] analyzed the implementation of an MG for the islands of Old Providence and Santa Catalina, Colombia. On these islands, the power supply is by diesel generators. The research focuses on demand management strategies to diversify the energy matrix in remote rural areas. HOMER software was used to optimize and select the most convenient MG configuration from an economic and environmental perspective.

Although these researchers cover energy planning and sizing of isolated MGs, the topic of MGs in remote areas with dispersed loads is not common in the current literature. Consequently, this paper focuses on MG sizing for remote rural non-energized areas with scattered dwellings. Therefore, it proposes a coordinated sizing between the rated capacity of the sources and the distribution power network.

This strategy aims at sizing the power sources and the architecture of the power distribution network simultaneously. For this purpose, geographic and meteorological information about the region under study and the energy potential available from natural energy sources could be used. The proposal is applied in a remote rural region of Colombia that is used as a case study.

This paper is organized as follows: Section 2 describes the proposed MG coordinated sizing methodology for remote areas with dispersed loads. Section 3 presents the case study used to validate the sizing proposal, which corresponds to a remote non-energized region of Colombia. Section 4 exposes validation results. Finally, Section 5 summarizes the conclusions of the work and discusses the achievements, possible improvements, and future work.

2. Methodology

A coordinated sizing of an MG requires the knowledge of geographical and meteorological information of the study area. Also, general information on the costs per unit capacity of the energy sources and the distribution network. This coordinated sizing proposal considers a diesel generator, a small hydroelectric plant, a wind generator, a photovoltaic system, a battery bank as energy sources, and a single-phase low-voltage distribution system. Figure 1 presents the MG scheme that encompasses this methodology.

The strategy allows determining the capacity of each energy source, the geographic location of these sources in the study region, and the sizing and connections of the distribution network.

The methodological steps comprise *i)* the model of the energy sources, *ii)* the cost function approach, *iii)* the dispatch strategy for the energy sources, and *iv)* the optimization of the cost function. These steps are presented below:

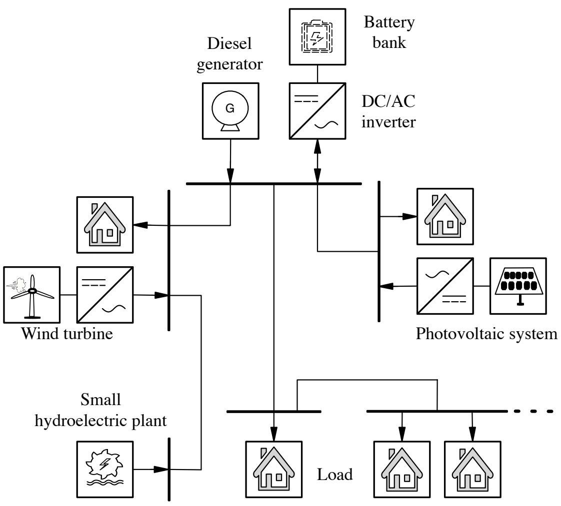

Fig. 1. Schematic of an isolated MG with dispersed demand.

A. Energy Sources Model

This proposal uses simple source models that relate nominal power and energy to MG operation and cost. The model used for each source is presented below.

It assumes that the PV system operates at the maximum power point for sizing purposes. The maximum power could be expressed in a simplified form as shown in Eq. (1) [10], here $P_{PV}(t)$ is the power delivered by the PV system, $G_a(t)$ is the incident solar irradiance, and $T_a(t)$ is the ambient temperature at t. $G_{a,0}$ and $T_{M,0}$ are the solar irradiance and module temperature at standard conditions, respectively. $P_{PV}^{M,0}$ is the nominal system power, $NOCT$ is the nominal operating temperature of the cells, and β is the temperature coefficient.

$$P_{PV}(t) = \frac{G_a(t)}{G_{a,0}} \cdot \left[P_{PV}^{\mathrm{M},0} + \beta \left(T_a(t) + G_a(t)\,\frac{NOCT - 20}{800} - T_{M,0}\right)\right] \tag{1}$$

The model shown in Eq. (2) is proposed by [11] for wind turbines since it relates the power generated with the power rate and the wind speed. Here, $P_{wind}(t)$ is the power generated by the wind turbine, and $V_{wind}(t)$ is the wind speed at t. P_n and V_n are the rate power and speed of the turbine, respectively. V_{min} and V_{max} are the minimum and maximum admissible wind speeds. The exponent k is used to adjust the shape of the wind system operating curve, and it is usually assumed to be 3.

$$P_{wind}(t) = \begin{cases} 0 & V_{min} > V_{wind}(t) > V_{max} \\ P_n\left(\dfrac{V_{wind}^k(t) - V_{min}^k}{V_n^k - V_{min}^k}\right) & V_{min} \le V_{wind}(t) < V_n \\ P_n & V_n \le V_{wind} \le V_{max} \end{cases} \tag{2}$$

It uses the gravitational potential energy model shown in Eq. (3) to define the electric power of the small hydropower plant [8]. Here $P_{HP}(t)$ is the plant's power output, and $Q(t)$ is the water flow rate set at t. ρ is the density of water, g is the gravitational constant, η_{HP} is the energy conversion efficiency, and $(y_1 - y_2)$ is the head difference or drop from the intake to the turbine.

$$P_{HP}(t) = \eta_{HP} \cdot \rho \cdot Q(t) \cdot g \cdot (y_1 - y_2) \tag{3}$$

The genset is the backup system if the renewable energy sources cannot supply the demand and the battery bank is discharged. The operation is restricted between a minimum power value P_{GEN}^{min} and maximum P_{GEN}^{max}. The genset can be out of operation if it remains in such a state for a long time. In a general way, the operating constraint of the genset is $P_{GEN}^{min} \le P_{GEN}(t) \le P_{GEN}^{max}$ or $P_{GEN}(t) = 0$. It is usual to take the values of $P_{GEN}^{min} = 30\%$, P_{GEN}^{max}=95% of the rated capacity [12].

It uses the fuel consumption model (4) proposed by Muselli *et al.* [13]. Here $Q_{diesel}(t)$ is the fuel consumption, and $P_{GEN}(t)$ is the power of the genset at t. P_{GEN}^{N} and Q_{diesel}^{N} are the nominal power and fuel consumption values. Also, the operating power and fuel consumption are directly related.

$$Q_{diesel}(\mathrm{t}) = 0.22 \cdot Q_{diesel}^{N} + 0.78 \cdot \frac{P_{GEN}(t) \cdot Q_{diesel}^{N}}{P_{GEN}^{N}} \qquad (4)$$

The battery bank should ensure power balance and supply or absorb energy appropriately. The state of charge (SOC) of the battery bank is determined from Eq. (5) [12]. Since charging and discharging cycles reduce the lifetime of batteries, it is advisable to maintain the $SOC(t)$ between a range SOC_{min} and SOC_{max}.

$$SOC(t) = SOC(t-1) + \eta_{ESS} \cdot P_{ESS}^{ch}(t) - \frac{P_{ESS}^{dis}(t) \cdot \Delta t}{\eta_{ESS}} \qquad (5)$$

Here $SOC(t)$ is the state of charge at t, $SOC(t-1)$ is the state of charge at an earlier time Δt and η_{ESS} is the charging and discharging efficiency of the battery bank. It is usual to take the values of $SOC_{min} = 35\%$, $SOC_{max} = 90\%$, and $\eta_{ESS} = 0.9$.

B. *Cost Function*

The cost function includes the initial investment C_{acq}, the operation and maintenance costs $C_{O\&M}$, the cost associated with the environmental impact C_{env} and the cost of the distribution system C_{dist} including the acquisition and distribution energy losses. The environmental impact is evaluated as a penalty for the emission of pollutant gases. Equation (6) estimates the total financial cost.

$$C_{total} = C_{acq} + C_{O\&M} + C_{env} + C_{dist} \qquad (6)$$

The equipment acquisition cost is annualized using a rate of return to obtain an equivalent annual cost per piece of equipment. The operation and maintenance costs are directly related to the energy generated and the installed power of the energy sources. In the case of distribution lines, this cost depends on the voltage level and the length of the line and is evaluated as a percentage of the acquisition cost. Likewise, energy losses due to the Joule effect in the wires are associated with a penalty cost corresponding to the energy cost [4].

For the case of the genset, the maintenance cost also depends on the installed power, while the operating cost depends on the fuel consumption. In the case of remote regions, the cost of fuel could be up to ten times higher than that of large-scale electric power systems, depending on the distance from the fuel source and transportation constraints.

Table I presents acquisition and O&M costs provided by Timilsina [4] and Kosmadakis *et al.* [14] for some distributed generation sources.

Table I. - Equipment acquisition and O&M costs.

EQUIPMENT	ACQUISITION COST	O&M COST
Genset	550 USD/kW	2.0% of C_{acq}
Wind turbine	2 150 USD/kW	2.6% of C_{acq}
PV system	1 500 USD/kW	1.1% of C_{acq}
Small hydropower plant	2 456 USD/kW	1.6% of C_{acq}
Battery bank	380 USD/kWh	1.2% of C_{acq}
Distribution line	5 000 USD/km	0.5% of C_{acq}

C. *Sources Dispatch Strategy*

The objective of the dispatch strategy is to guarantee the power balance of the MG by prioritizing supply from renewable energy sources [15]. It is expected to avoid the genset supply as much as possible. For this purpose, it defines operating limits for the sources depending on the operating conditions and load demand. Figure 2 presents the dispatch strategy.

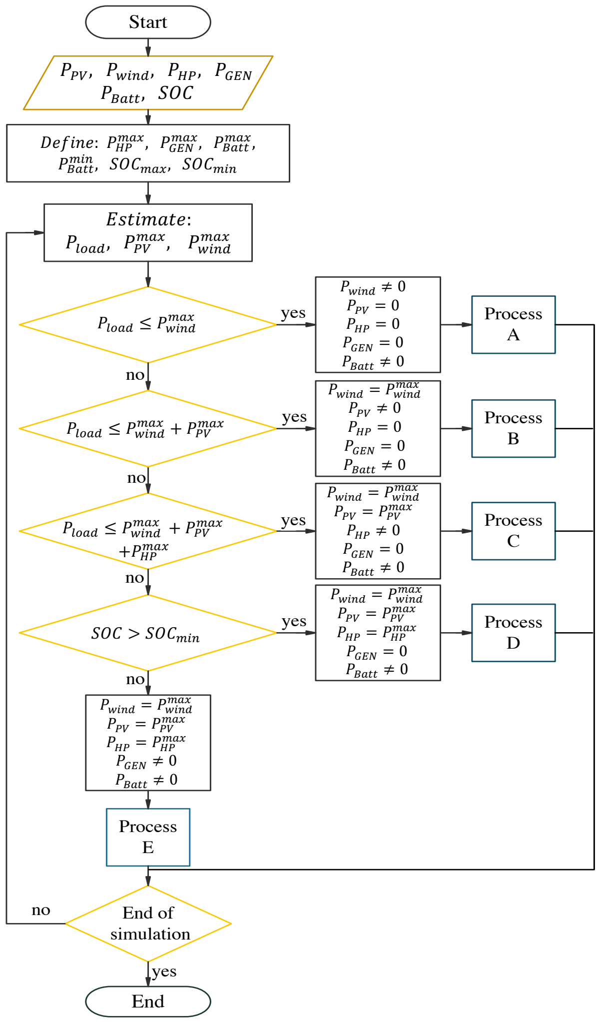

Fig. 2. Energy sources dispatch strategy.

Here, P_{load} is the power demanded by the dwellings. P_{PV}^{max} and P_{wind}^{max} are the maximum power that the PV system and the wind turbine could generate according to the current weather conditions, respectively. P_{Batt} is the power from or to the battery bank.

The strategy dispatches renewable energy sources first. It gives the following order of priority: the wind turbine, the PV system, and the small hydropower plant. The surplus energy from renewable sources charges the battery up to SOC_{max}. Process A implies that the load demand is less than the wind turbine's power. Then the wind turbine supplies the load and charges the batteries. In the same sense, processes B and C imply that the demand could be met by combining aerogenerator and PV sources and aerogenerator, PV, and hydropower sources, respectively.

Process D corresponds to the load demand being greater than the renewable generation, but the batteries have enough charge to supply the missing load. In the case of process E, the load demand is greater than the renewable generation, and the batteries are discharged. Therefore, the genset starts to supply the missing load and charge the batteries.

D. Optimization Algorithm

The coordinated sizing proposal is implemented in MATLAB software. It uses the PSO algorithm to integrate the dispatch strategy to solve the optimization problem. Figure 3 presents the procedure for solving the sizing optimization problem for the MG. Figure 4 shows the procedure for the evaluation of the cost function.

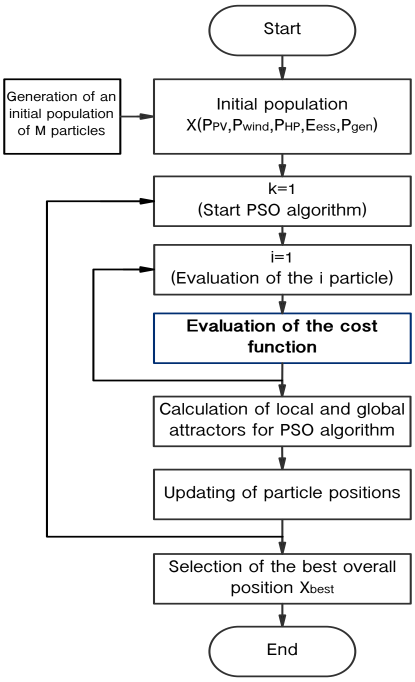

Fig. 3. Methodology for solving the MG sizing optimization problem.

3. Case Study

To apply the strategy proposal, a non-interconnected rural region at GMS N 6° 13' 12'' O 73° 50' 60' in Cimitarra, Colombia, was used as a case study. The region is approximately 636 240 m^2 and integrates seven dwellings. Only the dwelling closest to the access road has the electrical supply from the local distribution network.

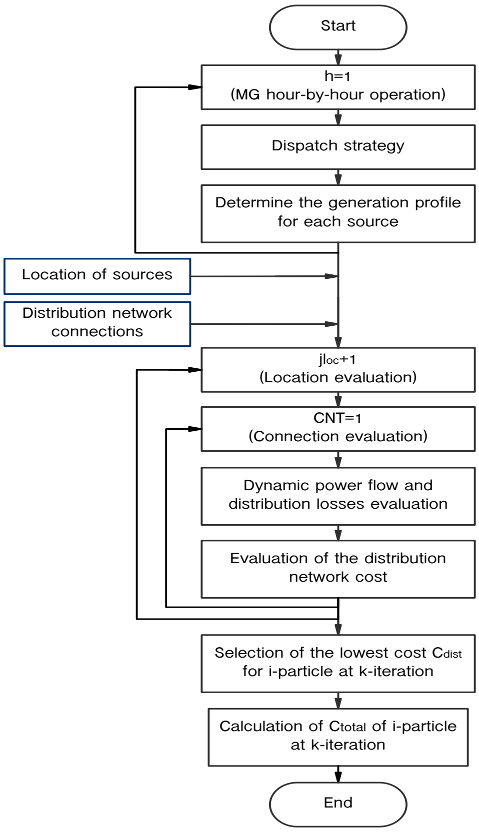

Fig. 4. Methodology for the cost function evaluation.

The energized house is the location reference of the case study. The geographical information of the region was obtained using Google Earth software. Meteorological information was obtained from the NASA database through the Prediction of Worldwide Energy Resources (POWER) Project. The PVSyst software was used for hourly data synthesis.

The study area was modeled using a 100 x 100 position matrix representing the location of 10 m x 10 m sub-zones. The position rows and columns represent the geographical location of a sub-zone. The model allows storing the region's geographical and meteorological parameters in layers. Figure 5 presents the case study's altitude profile and the dwellings' position using the position matrix model.

Dwelling 1 is the only one with an electrical supply and has induction motors to oxygenate pools used for fish farming. A maximum unit demand and daily demand profile for all dwellings were taken following the local design standard [16].

The electrical load of the motors was determined according to the nameplate data for a 190 W cooling system, a 1 657 W blower, and a 1 657 W splash. The daily demand profile of the motors was determined according to the operating schedules provided by the homeowner. Figure 6 presents the demand profile of a dwelling and the motors. The maximum power per dwelling is 0.8 kW, and for motors is 3.5 kW. Daily demand is 68.3 kWh for all households and 36.0 kWh for motors.

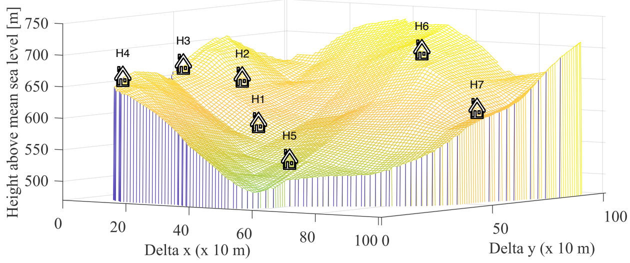

Fig. 5. Elevation profile of the case study remote region.

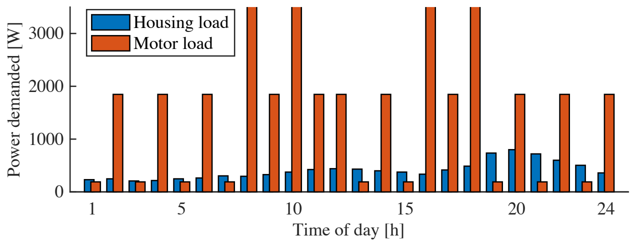

Fig. 6. Case study housing and motor daily demand profiles.

The energy and fuel loss costs are defined based on local tariffs. Thus, the cost for energy loss is set at 0.17 USD/kWh and diesel at 0.60 USD/l.

4. Results

The coordinated sizing proposal was applied in the case study. The results show the selection of the energy mix for the MG. Likewise, the coordinated sizing determined the rated values of the sources, the location concerning the position matrix, the dimensioning and connections of the distribution network, and the MG's cost.

Tables II shows the nominal values and location of the sources.

Table II. - Energy source ratings.

SOURCE	RATED CPACITY	LOCATION (Row, column)
Genset	3.0 kW	(52, 53)
Wind turbine	0.0 kW	---
PV system	0.8 kW	(14, 65)
Small hydropower plant	4.1 kW	(24, 51)
Battery bank	105 kWh	(57, 70)

Note that a nominal power of 0 kW was found for the wind turbine. It indicates that installing a wind turbine is not recommended for the study region. On the other hand, the hydropower plant has the highest nominal power, which follows the hydropower potential of the study region.

Regarding the location of the sources, the genset corresponds to housing 1 and the battery bank to housing 2. The PV system and the hydropower plant are in different sites according to the region's energy potential benefit.

Table III summarizes the annualized costs. For the genset, 96% of $C_{O\&M}$ is for fuel consumption. Figure 7 shows the distribution system connections.

Table III. - MG annualized cost.

EQUIPEMENT	COST	
	ACQUISITION	O&M
Genset	224 USD	988 USD
PV system	153 USD	13 USD
Hydropower plant	1 346 USD	161 USD
Battery bank	7 035 USD	477 USD
Distribution network	1 616 USD	81 USD
Total cost of MG		12 094 USD

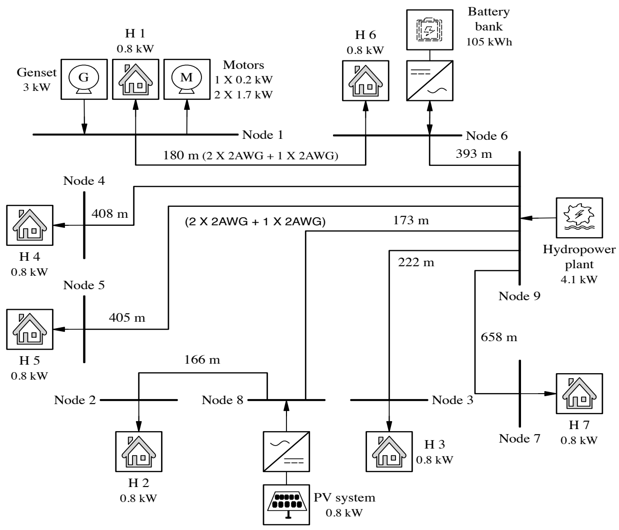

Fig. 7. MG distribution network connections for the case study.

Figure 8 presents the energy distribution of the MG. Note that the genset is connected to the motors node to meet peak demands. However, the genset is on 19% of the year. The most significant number of connections concurs in Node 9, which corresponds to the hydropower plant since this is the one that supplies the most energy to the loads.

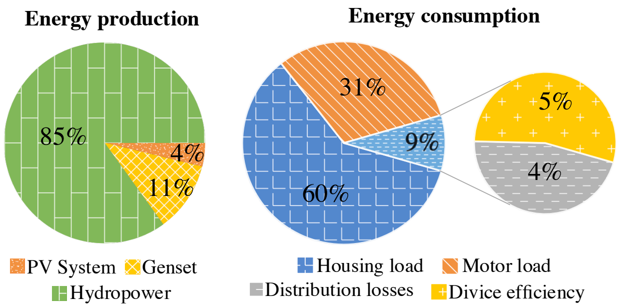

Fig. 8. Energy distribution for the study MG.

The results in the study case show that the sizing proposal could be applied to other regions with similar conditions. It is enough to update the data according to the case. Compared to further investigations, this proposal stands out because it simultaneously sizes the sources and the distribution network.

For example, Muños *et al.* [9] sized the energy sources but did not focus on the distribution network. Likewise, Huang *et al.* [15] presented an optimal sizing based on energy management, but it does not integrate the distribution system. Although planning an MG that combines the sizing of the sources, the distribution network, and energy management in a coordinated and simultaneous way requires a high computational cost, these investigations show us the progress towards a world with energy coverage for all.

5. Conclusions

This paper proposes a coordinated MG sizing strategy for energizing non-interconnected areas with scattered dwellings. The proposed strategy is approached as an optimization problem that simultaneously integrates the power sources' sizing and distribution network. The coordinated sizing is applied to a rural area in Colombia.

The dispersed demand condition implies that the dwellings to be energized are considerably distant from each other, between 100 m and 1000 m. Furthermore, implementation costs are higher than typical because some remote regions have limited transport and access routes, making on-site components more expensive.

Applying the coordinated sizing strategy to the case study offers consistent results and complies with the design and operation restrictions established for the study region. However, it should be applied to more real case studies and test systems. Results could be compared, and aspects to be strengthened could be determined, such as demand management strategies and the distribution networks.

It is recommended to take advantage of the position matrix for future work since it can store information in layers such as protected or inaccessible regions and information about shaded areas. It is also recommended to strengthen the reliability of meteorological data. Similarly, the distribution network design must be fortified to ensure the viability of the implementation and the lowest cost.

Acknowledgement

The authors wish to thank the Department of Electrical, Electronics and Telecommunications Engineering (Escuela de Ingenierías Eléctrica, Electrónica y de Telecomunicaciones), the Vice-Rectorate for Research and Extension (Vicerrectoría de Investigación y Extensión) from the Universidad Industrial de Santander. Moreover, to ECOS Nord, an internationalization program has allowed collaborative work between the Université Bourgogne Franche-Comté, the FEMTO-ST Institute, and the Universidad Industrial de Santander to enhance development of science and knowledge.

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