Optimal Design for an Electrical Hybrid Micro Grid in Colombia Under Fuel Price Variation

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Abstract- In many ways, the availability of electrical energy is associated with the degree of development of a society. In spite of the recent technological advancements, many Latin-American countries remain with a wide number of towns isolated from the main grid of their electrical power systems. Colombia is one of these countries, and the implemented solutions rely mainly on the use of diesel generators. One possible solution approach includes the expansion of the existing infrastructure with the use of renewable energy sources in isolated microgrids. In this paper, three optimal designs for an isolated hybrid microgrid in the Colombian community of Unguía are proposed using an iterative optimization technique, the interior-point algorithm. The hybrid microgrid is composed by a diesel generator, photovoltaic panels, wind turbines, and batteries. In addition, each design is obtained for a given diesel generating cost. In each design the number of photovoltaic panels, wind turbines, and batteries for a given type of element are calculated. The unmet load and the power delivered by the diesel generator are calculated for each time interval. The optimization objective is to minimize the total system cost. The optimization results show that for a certain diesel cost, the system obtained only uses renewable energy and storage to supply load demand, although the diesel generator infrastructure is already in place, and no initial investment costs associated with diesel generation were assumed.

Keywords- Energy storage, Hybrid energy systems, Microgrids, Optimization, Renewable energy systems, solar energy, Wind energy.

1. Nomenclature

v	Wind speed [m/s].
P_R	Rated power of the wind turbine [W].
v_R	Rated wind speed specified for the wind turbine [m/s].
v_C	Cut-in wind speed specified for the wind turbine [m/s].
v_F	Cut-off wind speed specified for the wind turbine [m/s].
N_{wt}	Number of wind turbines.
P_{gen}	Power generated by renewable sources and diesel units [kW]
E_{bat}	Energy in the battery bank [kWh]
γ_{sd}	Self-discharge coefficient of the battery.
$E_{bat}(0)$	Initial charge of the battery [Wh]
η_b	Battery efficiency
N_{bat}	Number of batteries

P_{wt} Power delivered by each wind turbine [kW]

G Solar radiation [W/m^2].

η_{pv} Photovoltaic panel efficiency.

A_p Area of photovoltaic panel [m^2].

T_{pv} Temperature of photovoltaic panel [°C].

T_{cref} Reference temperature for the tests conditions of the photovoltaic panel [°C].

γ Variation temperature coefficient [%/°C]

P_{pv} Power delivered by each photovoltaic panel [kW]

N_{pv} Number of photovoltaic panels.

η_{DG} Efficiency of the diesel generator.

P_{DGr} Power delivered by the diesel generator including the generator efficiency [kW]

P_{DG} Power delivered by the diesel generator [kW]

P_{bat} Power exchanged between the battery bank and the grid [kW]

P_{load} Power demanded by load [kW]

P_{ns} Non-supplied demand [kW]

J Objective function value [COP]

x Decision variables vector

C_{Cpt} Yearly capital cost [COP]

C_{Mtn} Annualized operation and maintenance cost [COP]

C_{op} Cost of diesel operation [COP]

C_{DG} Diesel generating cost [COP/kW]

T Amount of hours in one year

T_c Optimization calculation period [h]

LOLP Overall probability that there will be a shortage of power

2. Introduction

According to [1], more than 1.2 billion of people suffer of poor quality or have no electricity access at all, and more than 80% of this population is from developing countries, mainly on rural areas or zones located far from generation or distribution centres. It can be argued that the availability of electricity is an important element to the development of society and the welfare of human beings [2]. However, these numbers show the existence of many towns and villages that remain disconnected from their own national electricity networks. Latin-America is no stranger to this phenomenon, and the reasons are usually related with the technical or economical unfeasibility of the required grid connections [3]. For Colombia, in particular, most of the population with electricity is concentrated in urban centres occupying an area of approximately 48% of the country. The zones without main grid access (denominated non-interconnected zones) represent roughly the remaining 52% of the territory [2]. In these zones, electricity is provided by isolated systems composed by some mixtures of small hydro power, solar panels, and mainly through the action AC generators connected to diesel engines (diesel generation plants). These diesel plants present drawbacks associated with the environmental impact, and transportation difficulties increase the already high costs of fuel, in spite of the subsidized program sponsored by government [2].

The usage and participation of renewable energy sources in power systems are growing around the world, and his effects on different operational stages have been widely studied [4]–[9] . Amidst the Colombian electricity coverage scenario, renewable energy sources emerge as another useful tool for providing electricity to the non-interconnected zones. Though many initiatives have been explored in order to decrease the environmental and economic impact of fossil-based energy sources [10] in Colombia, the use of hybrid microgrid systems mixing diesel plants and renewable energy sources offers a promising alternative of solution for increasing the energy access in the country [2]. According to [11], microgrids are systems including loads and at least one element of distributed (small-scale) generation or storage and can operate isolated from the main electrical grid systems. In this context, the role of generation can be performed by renewable sources (like photovoltaic panels or wind generators) or the “conventional-type” small-scale generation units (small hydro-power or the mentioned diesel generators). The storage elements can be battery banks, electrical vehicles or hydro-pumped systems. The combined action generation and storage must be able of supply the energy demanded by the population of the non-interconnected zone.

In spite of microgrids use of the energy sources available in the non-interconnected area such as water currents, wind, solar radiation and biomass; they still have high initial investment costs compared to fossil fuel generators [2]. Also, the combination of infrastructure already in place with different uncertainties, objectives and constraints of the new elements may cause conflicting goals for the microgrid planning [12]. Thus, optimization methods are frequently required in order to design and select the right configuration for microgrid operation. Roughly speaking, the most commonly optimization techniques employed for microgrid design can be either based on iterative methods [13] or heuristic approaches [14]. However, heuristic methods have the disadvantage that they may converge to a local minima [12], [15]. Therefore, on this article three designs for a hybrid microgrid are proposed using different diesel generating cost in each design and employing an iterative optimization method called interior point [16]. The main goal of the optimization is the reduction of the total system costs, ensuring a service reliability of at least 80%. The Unguía community in the department of Chocó (Colombia) is set as the microgrid location.

This article is organized as follows: Section 2 summarizes some of the related work available in the literature. The study case is described in Section 3. The approach of the optimization problem is presented in Section

4, and Section 5 focuses on the results and their corresponding analysis. Finally, the conclusions are stated in Section 6.

3. Related Work

Whether for reaching the best possible design or for fulfilling the objective of an effective management of the electricity sources, optimization techniques perform an important role in hybrid microgrid development and operation [17]. The work of Fathima and Palanisamy [18] presents an laudable effort for defining and extending the concepts and models related with hybrid microgrids involving renewable sources, and a complete review of the state of the art in the use of optimization techniques in this context. The latter are classified into optimization for three main goals: storage elements operation, sizing of the elements and microgrid energy management and control.

The subject of the optimal sizing and design of microgrids has been also widely explored. As said before, usually the existent electrical infrastructure in the non-interconnected zones is expected to be integrated with renewable energy sources forming a hybrid microgrid. For this reason, issues like the economic feasibility and the long-term operation must be assessed in the microgrid design stage [12]. In this regard, Gamarra and Guerrero [12] present a complete review of the available technical literature in computational optimization techniques for microgrid planning and even propose a set of guidelines for the economic feasibility of the task. They classify the techniques as heuristic, traditional or software-based implementing some of the former approaches. As compiled in [19], heuristic optimization techniques involve Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Simulated Annealing (SA) and other alternatives such as Ant Colony Optimization (ACO) and Artificial Immune System (AIS) algorithm.

In particular, the work in [20] presents the use of PSO for the optimal design of microgrids in both isolated and grid-connected modes, performing also a robustness analysis for different operational conditions. In general, heuristic approaches are proposed for the task of finding a good enough solution over a large set of suitable solutions with a lesser computational burden than iterative methods; however, they cannot offer a guarantee of convergence towards the optimal solution [12]. In the software- based field of solutions, HOMER software is highly regarded as the tool most extensively used for microgrid modeling and design purposes [12]. An example of the use of HOMER is being given in [21], for the feasibility analysis of a hybrid microgrid for rural electrification in Ethiopia. However, the use of commercial software is limited in the possibilities of analysis, and that drawback could lead to limitations in the microgrid design. Traditional or iterative techniques describe the iterative procedure of finding the best possible value of a given objective function, having into account the models and constraints for a given problem until the fulfilling of some optimization criteria [12]. There are a lot of traditional optimization techniques applied to microgrid design and sizing, as shown in [12] and [19]. Some approaches involve the use of Model Predictive Control (MPC) [17], or the employment of sliding mode strategies based on Karush-Kuhn-Tucker (KKT) optimality conditions for linear programming (LP) problems [22]. Traditional iterative techniques could take a lot of computational effort. However, they are selected in this work because they can offer a guarantee of finding the optimal solution if the problem is formulated in a certain way as described in subsequent sections.

The use of optimal techniques in microgrids is also applied in the operational stage, for Energy Management System (EMS) development. With the goal of minimizing either the cost of the power generated from distributed units and storage, or the power distribution losses, Optimal Power Flow strategies have been explored [23], [24]. The inclusion of the power flow equations often lead to loss of convexity in the OPF problem formulation. This, in turn, requires the use of techniques and transformations, like semidefinite programming (SDP) relaxation [23], in order to get a convex problem with solution in polynomial-time complexity. As the aim of this paper falls in the design and planning stages of the microgrid, load flow equations are neglected and some simplistic models for generation and storage units are considered in order to obtain a linear optimization problem. This will reduce the computation time of the algorithms. However, exploration of the required techniques for operational stages of the Unguía microgrid will deserve consideration in future works.

The analysis of the fuel price has also been a sensitive topic in the microgrid design and sizing. In [25], Asano et al. evaluate the risk of investment in a microgrid system composed by renewable sources and combined heat and power (CHP); the system was designed for urban zones with distributed generation and volatility in the gas price was considered. The impact of both electricity and fuel price was studied also in [26], but from the point of view of an economic dispatch of a microgrid involving also electric vehicles (EV). And examining a broader field for discussing most of the economic aspects related with the installation investments and microgrid operation, Farzan et al.[27] present a prospective analysis of the possible sources of revenue for microgrids after accounting for various factors, fuel price included. In this sense, this paper aims to reflect the incidence of the fuel price in the optimal hybrid microgrid design and the planning for energy access in a rural zone in Colombia.

The topic of hybrid microgrid design in Latin-America has also been previously studied. The work in [3] describes the optimization of a hybrid microgrid energy system for an isolated town in the Amazonia region of Brazil; this town shares some characteristics with the proposed location of Unguia in Colombia. Also, some methodologies for the evaluation of the sustainable evolution of isolated microgrids in rural communities have been proposed, as shown in the work of Rahmann et al [28]. For the Colombian case, the work of Gaona et al [2] presents a survey of microgrid applications for electricity provision in rural isolated zones. Besides, they focus on the regulatory and energetic framework of Colombia for microgrid implementation, and this is the scenario for the development of the work in this paper.

4. Optimal Sizing Problem Approach

The optimization problem for the microgrid design is a linear problem, described as follows:

$$\underset{x}{minimize}\left(J(x)\right)$$

$$subject\ to:$$

$$h_i(x) = 0, \quad i = 1, \dots, m \tag{1}$$

$$g_j(x) \leq 0, \quad j = 1, \dots, p$$

Where x denotes the vector of decision variables, $J(x): \mathbb{R}^n \rightarrow \mathbb{R}$ is the cost function, $m = 2$ is the number of equality constraints $h_i(x)$, and $p = 5$ is the number of inequality constraints $g_j(x)$.

4.1 Decision variables

The degrees of freedom of the design are described in the vector of decision variables as:

$$x^T = [N_{pv} \quad N_{wt} \quad N_{bat} \quad P_{DG}(t) \quad P_{bat}(t)] \tag{2}$$

Where, N_{pv} is the number of photovoltaic panels, N_{wt} is the number of wind turbines, N_{bat} is the number of batteries, $P_{DG}(t)$ is the power delivered by the diesel generator at each hour, and $P_{bat}(t)$ is the power of charge or discharge of the batteries at each hour.

4.2 Objective function

The objective function for the optimization is the *Total Yearly Cost* of the system ($J(x)$), which is linear respect to the decision variables and is calculated as [29]:

$$J = C_{Cpt} + C_{Mtn} + C_{op} \tag{3}$$

$$C_{op} = \left(\sum_{t=1}^{T_C} C_{DG} P_{DG}(t)\right)\left(\frac{T}{T_C}\right) \tag{4}$$

In equation (3), C_{Cpt} denotes the yearly capital cost. This cost is assumed over the average lifetime span of the system elements. C_{Mtn} is the annualized operation and maintenance cost. The value of C_{op} represents the cost of diesel operation. C_{DG} is the diesel generation cost. The variable T is the amount of hours in a year and T_c is the optimization calculation period.

4.3 Constraints

4.3.1 Physical constraints.

The proposed elements for the design of the hybrid microgrid are described by the models presented in this section, which were taken from [22]. These models are simplified expressions commonly used for renewable energy sources in optimal microgrid design in order to decrease the computational burden.

The power delivered by the wind turbine (P_{wt}) is given by:

$$P_{wt} \begin{cases} P_r \frac{v^2 - v_C^2}{v_R - v_C^2}; & v_C \leq v \leq v_R \\ P_R; & v_R \leq v \leq v_F \\ 0; & v \leq v_C \ or\ v \geq v_F \end{cases} \tag{5}$$

The power delivered by the photovoltaic panel (P_{pv}) is given by:

$$P_{pv}(G,T) = \eta_{pv} A_p G\left[1 - \gamma\left(T_{pv} - T_{cref}\right)\right] \tag{6}$$

Where the term η_{pv} takes into account the total efficiency of the panels and DC/AC inverters. In addition, some effects such as mismatching and shading, which reduce the output power of the panel array, can be lumped into this factor. However, due to the small quantity of available data and the need to maintain a low model complexity (for the sake of computation requirements), this effects are neglected and the variable η_{pv} is assumed with a constant value of 15.3 %.

The power delivered by the diesel generator (P_{DGr}) is given by:

$$P_{DGr} = \eta_{DG} P_{DG} \tag{7}$$

In (7), P_{DGr} denotes the power delivered by the diesel generator taking into account the generator efficiency.

Using the previous models, the total power generated by both the renewable sources and diesel units, denoted by (P_{gen}), is given by the expression:

$$P_{gen} = N_{wt} P_{wt} + N_{pv} P_{pv} + P_{DGr} \tag{8}$$

Equations (5) - (8) presented the models of the generating units, but these equations are not included in the problem as optimization constraints. They only are used for calculating the output power of the different sources; the considered constraints are described in the next section.

4.3.2 Operational constraints

On the other hand, the first equality constraint of the optimization problem is the energy in the battery bank ($E_{bat}(t)$) composed by N_{bat} batteries, which fulfills the next equation at each hour *t*:

$$E_{bat}(t+1) = E_{bat}(t)(1-\gamma_{sd}) + \eta_b P_{bat}(t) \quad (9)$$

The second equality constraint is the power balance indicated in (10). It must be satisfied for all time intervals.

$$-P_{load}(t) + P_{gen}(t) - P_{bat}(t) + P_{ns}(t) = 0 \quad (10)$$

By definition, all the number of photovoltaic panels, wind turbines, batteries, the power delivered by diesel generator, and the unmet load must be represented by positive quantities:

$$N_{pv} \geq 0;\ N_{wt} \geq 0;\ N_{bat} \geq 0;\ P_{DG}(t) \geq 0; P_{ns} \geq 0 \quad (11)$$

Where the variable $P_{ns}(t)$ constitutes the value of the *Non-supplied* demand at each hour (the quantity of demand that is not being satisfied by the microgrid). The variable $P_{bat}(t)$ takes positive values when the batteries are charging and negatives when the batteries are discharging. The batteries are assumed as a group where all of them have the same level of charge. The energy in the battery bank must be kept between the allowed operational limits, $E_{bat-max}$ and $E_{bat-min}$, which are the maximum and minimum energy that can be stored on each battery respectively.

$$N_{bat}E_{bat-min} \leq E_{bat}(t) \leq N_{bat}E_{bat-max} \quad (12)$$

The charging and discharging power of the battery bank and power delivered by the diesel generator must remain below the operational limits. These limits are $P_{bat-max}$ for the charge or discharge of each battery, and P_{DG-max}.for the diesel generator In addition, unmet load must not exceed the demand at each hour.

$$P_{bat}(t) \leq N_{bat}P_{bat-max}, P_{bat}(t) \geq -N_{bat}P_{bat-max} \quad (13)$$

$$P_{DG}(t) \leq P_{DG-max}, P_{ns}(t) \leq P_{dem}(t) \quad (14)$$

Also, the diesel generating cost C_{DG} could be a decision variable for the optimization horizon. Considering this, a maximum and minimum quote, C_{DG-max} and C_{DG-min} respectively, are defined for this variable. Then the follow inequality constraint must be satisfied.

$$C_{DG-max} \leq C_{DG} \leq C_{DG-min} \quad (15)$$

4.3.3 Reliability constraints

The overall probability of occurrence of a shortage of power (LOLP) [31] is a metric related to the level of the system reliability. This is defined as the percentage of the total load demand that is un-supplied or non-served for the system over a given time period.

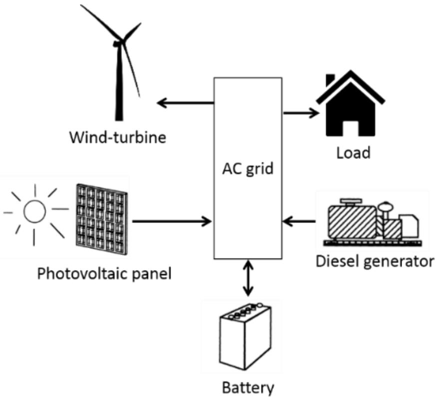
$$LOLP = \frac{\sum_{t=1}^{T_c} P_{ns}(t)}{\sum_{t=1}^{T_c} P_{load}(t)} \leq 0.2 \quad (16)$$

Variable T_c in equation (16) denotes the total time intervals taken into account for the design. In this case, there are 744 time intervals, equivalent to a month of operation. A LOLP level of 0.2, or 20% is defined as a restriction of the optimization problem. The inequality constraints of optimization set in (1) are proposed in equations (11)-(16), which also are linear with respect to the decision variables.

5.Study Case Description

The Unguía community is located in the northern of the Chocó department, as shown in Fig.1a. The town has a total area of 1307 km^2 and an estimated population of 15200 inhabitants [32], with around 30% of them concentrated in the urban area. This location was selected because of its environmental characteristics that make it a suitable region for the implementation of a hybrid power system integrating wind and solar renewable sources, as shown in [33]. A scheme of the proposed microgrid for this community, is illustrated in Fig.1b; this microgrid is composed by two 475 kVA diesel generators, a battery bank, solar panels, and wind turbines. The diesel generating units represent the conventional infrastructure currently-used to provide energy supply in Unguía.

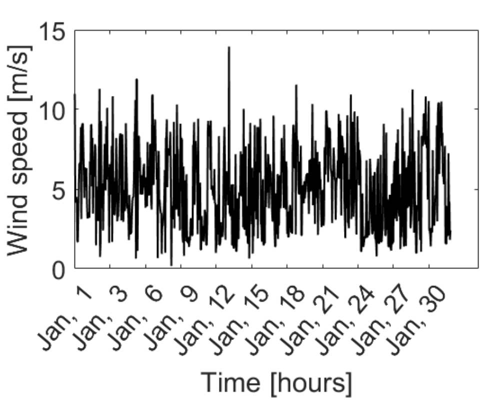
a.)



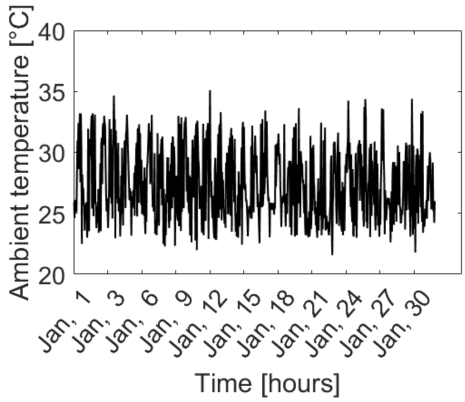
b)

Fig. 1. Location of Unguía (a) and scheme of the proposed hybrid microgrid (b).

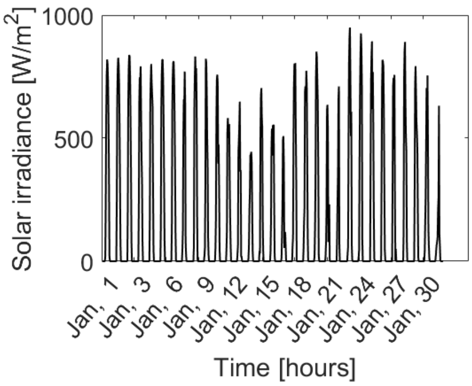
The weather data were extracted from the databases of the Colombian Institute for Hydrology, Meteorology and Environmental Studies (IDEAM) [34] and the National Centre for Coffee Research from Colombia (Cenicafe) [35]. However, the measurements data series of wind speed and temperature had gaps for some time-lapses. Therefore, the month of January was selected as the source of information because it presented a most complete set of full data than the other months. Missing data were generated by simulation, assigning Weibull [36] and Kernel [37] probability density functions for the wind and temperature or irradiance data, respectively. However, a more extended series of data should be explored in subsequent works, and several efforts are being focused on the data measurement and extraction in Unguía. Electricity demand data were taken from the Institute for Planning and Promotion of Energy Solutions for Non-interconnected Zones of Colombia (IPSE) [30]. Figure 2 depicts the weather variables and load demand for January 2015 at Unguía.



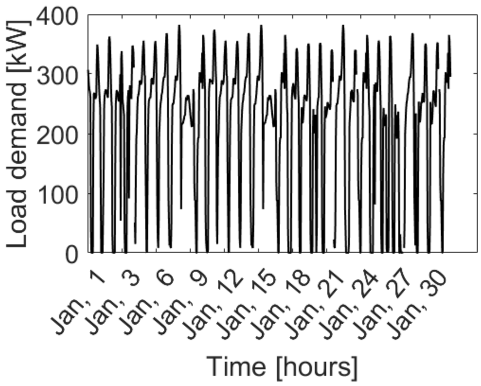
a. Wind speed data.



b. Ambient temperature data.



c. Solar irradiance data.



d. Load demand data.

Fig. 2. Climatological variables and electricity demand for January of 2015 at Unguía.

The technical specifications of the microgrid elements are presented in Table 1. Initial cost values of each element were taken from references [31] and [22] and were converted from euros into Colombian pesos (COP) with a rate of exchange of 3384,4 COP/euro (rate of exchange at July, 26th of 2016). The project lifespan was assumed as 20 years with a yearly interest rate of 5% [32].

For the sake of comparison, and for the purpose of this paper, three different values are going to be assumed for the diesel generating cost C_{DG}: at first, \$ 681.7 COP/kWh, which, according to [39], is the average value of diesel cost in Colombia. In order to observe the consequences of the variations in the behavior of this variable, a diminishing trend in diesel cost was assumed. Reductions of 10 times and 100 times of the average generating cost were investigated, resulting in explored values of \$ 68.2 COP/kWh and \$ 6.8 COP/kWh, respectively. The full optimization was performed for the three values of diesel cost.

Table 1. Technical characteristics of microgrid elements [31]-[22].

Photovoltaic panel	
Rated power	200 [W]
Surface	0.808×1.580 [m]
Nominal cell temperature (NOCT)	45 [°*C*]
Efficiency	15.3%
Temperature coefficient	0.006 [%/°*C*]
Annualized investment cost	333 [€/kW]
Annualized maintenance cost	2 % of investment cost
Wind turbine	
Rated power	1000 [W]
Cut-in wind speed:	2.5 [m/s]
Rated wind speed	11 [m/s]
Cut-off wind speed	53 [m/s]
Annualized investment cost	400 [€/kW]
Annualized maintenance cost	2 % of investment cost
Battery	
Rated capacity	1350 [kWh]
Rated voltage	12 [V]
maximum discharge level	80%
Efficiency	100%
Self-discharge coefficient	0.002
Annualized investment cost	39.04 [€/kWh]
Annualized maintenance cost	2 % of investment cost
Diesel generator	
Number of units	2
Rated power of each unit	475000 [VA]

6. Results and Analysis

A flow chart of the optimization process is illustrated on Fig.3. It is composed by several steps: the first one is related to the input data acquisition or estimation. The input data are the hourly time series of load demand, wind speed, solar irradiance and ambient temperature for the calculation period, which is one month for this case.

The time series data are the inputs for the element models at the second stage. The outputs of the models are the power delivered by each renewable element and the power demanded by system.

Then, on the third stage is the optimization process, which takes the decision of how many elements of renewable generation and storage are required for the adequate system operation, minimizing a set cost function. Also, the optimization uses a dispatch strategy for the diesel generator and the storage system, setting the power delivered by diesel, the power of charge and discharge in battery bank and the unmet load at each hour. This process involves the calculation of the variables $P_{bat}(t)$, $P_{DG}(t)$ and $P_{ns}(t)$.

As the optimization calculation requires the definition of cost function and the constraints, the acquisition, maintenance and operation costs of the system elements must be provided, as well as the limit capacities of them and the reliability requirements of the system. As shown in section 4, both the objective function and the constraints for the optimization are linear with respect to the decision variables presented in equation (2) which were considered as real-valued. This guarantees the existence of a global minimum point for the problem. Three scenarios with different diesel generation costs were evaluated, and the optimal design was obtained in each case.

The optimization problem was implemented in the software Matlab® R2015b for its solution. The characteristics of the computer in which the problem was implemented are: Intel Core i7-4790K processor, 32 Gb RAM. The optimization was solved using the Mosek solver [33] in Matlab. Mosek uses *interior-point* algorithm [16] as optimization technique. The memory capacity (ϑ) needed to solve the problem is related to the square of the number of decision variables n, i.e.:

$$\vartheta = f_r\, n^2 \tag{17}$$

Where f_r is a factor that depends on the number of inequality constraints p, and the equality constraints number denoted by m.

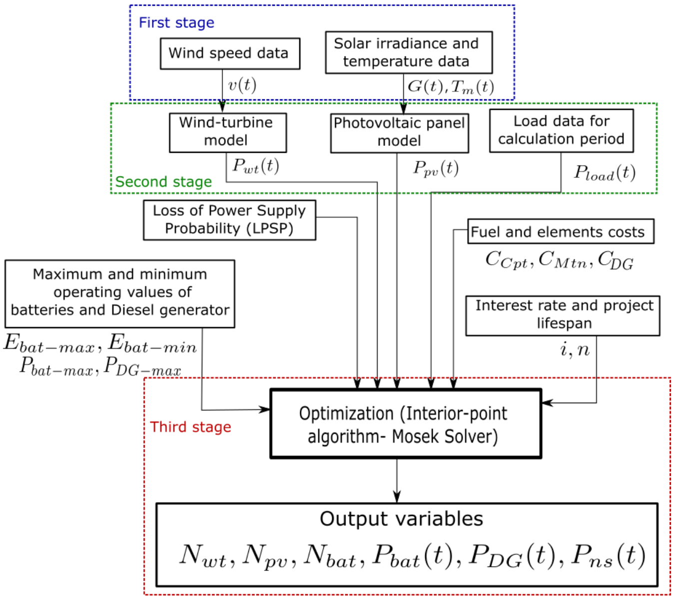


Fig. 3. Flow chart of the implemented algorithm.

Table 2 summarizes the optimization results. The maximum simulation time for the three solved optimizations was 5.9 seconds.

Table 2. Optimization results for different diesel generating cost.

	Design 1	**Design 2**	**Design 3**
Diesel price [COP/kWh].	$681.7	$68.2	$6.8
$\mathbf{N_{wt}}$	648	191	0
$\mathbf{N_{pv}}$	1998	699	0
$\mathbf{N_{bat}}$	2616	0	0
Diesel usage	0%	65.0%	100 %
Installed power [kW]	1837.8	1224.9	950
Objective function value: Yearly system costs [MCOP]	142.6	121.9	12.8

Both the power delivered by each source and the total demand are illustrated in Fig.4 and Fig.5 for the first week of January, for designs 1 and 2 respectively (these are the designs employing renewable sources). On the other hand, design 1 is the only one proposing battery bank usage. The energy stored on the battery bank is being shown in Fig.6.

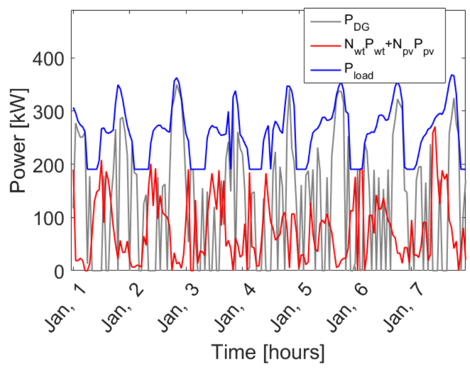


Fig. 4. Power generation and load demand of the system for design 2.

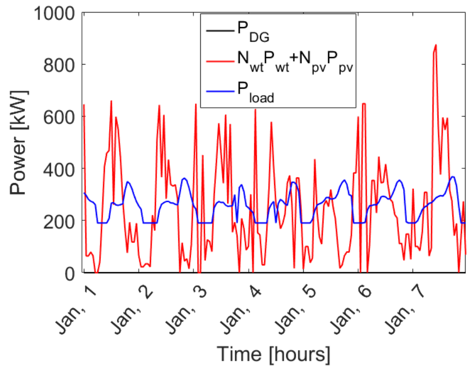


Fig. 5. Power generation and load demand of the system for Design 1.

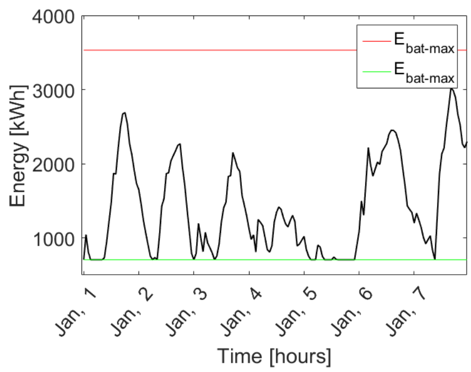


Fig. 6. Battery bank energy for Design 1.

From Table 2, it can be concluded that the optimization solution is sensitive to high variation of the diesel generating cost. With a diesel cost of $ 681.7 [COP/ kWh], which is the case of design 1, the obtained system only uses renewable generation. Decreasing the diesel cost 10 times, to $ 68.2 [COP/kWh], the design uses a combination of renewable sources and diesel, as can be seen on Fig.4. And if diesel price decreases 100 times with respect to the initial price evaluated for design 1, the resulting system generates a microgrid system only using diesel generation (no renewable units).

The energy in battery bank for design 1, illustrated in Fig.5, varies according the changes in generation load balance of the system. For large generation periods the batteries absorb the excess of energy in the microgrid until they reach their maximum value, as it occurred on the afternoon hours of January 1st and 2nd. Also, batteries deliver the stored power when the generation is low as it happened for the first hours of January 1st and 2nd.

Furthermore, considering an average value of diesel generating cost in Colombia as $681.7 [COP/kWh], the design found was composed only by renewable sources and batteries. The total installed capacity of this design is the capacity of the renewable sources plus the nominal power of the two diesel generators already installed in Unguía. However, the optimization result indicates that these diesel generators are not used due to their high operating cost. In this case, a better solution approach would be to build an entirely new microgrid infrastructure for renewable sources, if the diesel cost is set at the value proposed in [39].

7. Conclusions

Three designs of a hybrid Diesel-PV-Wind-Battery microgrid were evaluated for the Unguía community in Colombia. The planning of the configuration and the total costs of operation of the hybrid microgrid was performed using the interior-point optimization algorithm. The examined designs guarantee a level of system reliability of 80% while minimizing the system cost.

The designs obtained for the different set diesel cost values vary drastically, but, in some sense, they reflect the expected behavior according to decreasing of the diesel generation cost. For a diesel generation cost of 100 times lower than the average value of diesel cost in Colombia, a system with only diesel generation was selected. However, in order to reach these latter result, extreme reductions in the diesel generation cost were assumed, and this decrement on diesel cost has a low probability of occurrence in real markets. Meanwhile, a design based totally on renewables was found with the average cost value of diesel-based generation. It is fair to acknowledge that some optimistic values for renewable energy sources were assumed.

Taking into account the average diesel generating cost in Colombia, it is a better decision to install a new generation system based on wind and solar renewable energies and battery storage at the Unguía community than continue operating the diesel generation system. Therefore, a rigorous estimation of diesel price is recommended, for example a time series of the price could be taken instead of a constant price as in this case in order to obtain more realistic results.

On the other hand, it can be said that this work will encourage the developments of the microgrids in Colombian communities with no electricity access or with limited access through systems based on fossil fuels. The example shows a marked reduction in the usage of diesel generation, and also a decreasing behavior in the total system costs if renewable technologies are included in the microgrid system. In this sense, it would be interesting to investigate the effects of factors such as the pollutant emissions in the optimization for future microgrid designs, in order to encourage a deeper use and penetration of renewable energy sources for electrification in non-interconnected zones.

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