Lexicographic Multi-objective Optimisation of Hybrid Power Generation Systems for Communities in Non-interconnected Zones

Edgar Ojeda-Camargo[1], John E. Candelo-Becerra[2]*, Alcides Santander Mercado[3]

[1]Faculty of Engineering, Universidad de la Guajira, Riohacha, Colombia, [2]Department of Electrical Energy and Automation, Universidad Nacional de Colombia, Sede Medellín, Colombia, [3]Department of Industrial Engineering, Universidad del Norte, Barranquilla, Colombia. *Email: jecandelob@unal.edu.co

ABSTRACT

Energy supply applications for populations in isolated areas have great importance in reducing poverty and environmental impacts. However, rural zones not connected to power grids require more studies related to select low cost and efficient technologies suitable to each size of community. This paper presents a lexicographic multi-objective optimisation model (LMOM) to select the best renewable energy technologies (solar and wind) of hybrid power generation systems (HPGSs) for communities located in non-interconnected zones. The model prioritises objective functions such as the generation cost, emissions of carbon dioxide (CO_2) and energy consumption in ton-equivalent petroleum (TEP). In addition, the model considers constraints related to the production cost, environmental sustainability, environmental conditions and reliability of the system. The results show that the model provides sustainable HPGSs adapted to the size of each community and the best renewable energy technologies are the central receiver system and the wind turbine with a 20-m tower.

Keywords: Renewable Energy, Rural Communities, Multi-objective Optimization
JEL Classifications: C61, Q42

1. INTRODUCTION

The use of clean energies has expanded in the last few years and it is an opportune moment for increasing the application of renewable energy worldwide (Obama, 2017). In particular, implementing renewable energies in rural zones is of great importance (Dhiman et al., 2017; Ley, 2017; Rahut et al., 2017), especially for the purpose of reducing poverty (Halsnæs and Garg, 2011; Herington et al., 2017; Ouedraogo, 2013; Pinedo, 2010). Rapid economic development means that natural resources are consumed, thereby generating high environmental impacts with a carbon footprint that could be mitigated by implementing more renewable energy sources (Cherni et al., 2007; Griggs and Noguer, 2002; Wolfram et al., 2016). However, the evaluation of renewable technologies in rural communities, designing economic

systems adjusted to the rural zones and the quantification of their advantages are still needed (Banerjee et al., 2017; Jadhav et al., 2017; Santoyo-Castelazo and Azapagic, 2014), especially for non-interconnected zones that require a more accelerated breakthrough to be powered by sustainable energy sources (Alfaro et al., 2017).

Some studies have worked on the optimal power flow management of interconnected networks (La Scala et al., 2014). Other have focused on multi-source networks to optimise the locations of renewable energy plants for electricity generation in non-interconnected zones (San Cristóbal, 2012). Other authors have presented some solutions to the problem based on multi-objective optimisation using the Pareto front, which solves only two objective functions (Koroneos et al., 2004). Another study focused on locating and sizing electricity generation systems

(Jordehi, 2015). Other authors examined multi-criteria decisions based on determining technical and non-technical characteristics in energy development in remote areas using diesel generators (Cherni et al., 2007). The multi-criteria decision method has also been used to select the best technology for wind energy generation compared with other technologies (Onar et al., 2015).

In the above references, the authors have not focused on solving multi-objective functions using generation costs and environmental impacts. Moreover, they have not prioritised the objective functions with constraints and less-used lexicographic multi-objective optimisation to find the best hybrid systems that guarantee reliability of hybrid power generation systems (HPGSs) for communities located in areas not connected to a power grid and less tested for indigenous communities. Therefore, in this work, a lexicographic multi-objective optimisation model (LMOM) is used to select the best renewable energy technologies for hybrid power generation systems (HPGSs) (solar and wind) applied to small, medium and large rural communities in non-interconnected zones. The model is formed by three objective functions: generation costs, environmental impacts of CO_2 and the environmental impact of ton-equivalent petroleum (TEP). The model also includes constraints related to the production cost, environmental sustainability, environmental conditions and reliability of the system. Furthermore, six types of renewable energy technologies were used to validate the model and select the best solar and wind combinations that work for HPGSs. Additionally, negative externalities have been evaluated to estimate the cost of the $kgCO_2/kWh$ produced by those technologies and include it in the total cost of production. The following types of renewable generation technologies were used to validate the model: a photovoltaic system (PVS), a cylindrical parabolic collector system (CPCS), a central receiver system (CRS), a mini-wind system (SMini_wind), a wind system with a 20-m tower (ST_20) and a wind system with a 50-m tower (ST_50).

The remainder of the paper has been divided into four sections. Section 2 presents the materials and methods of the research, in which the mathematical models of the solution technique and the validation test are described. Section 3 shows the results of the LMOM and the analysis, Section 4 presents the discussion and the conclusions and future research are in Section 5.

2. MATERIALS AND METHODS

This section includes the materials and methods applied to validate the LMOM. First, a description of the objective functions is presented. The lexicographic approach is then explained followed by a description of the validation test and the zone where it is applied.

2.1. Objective Functions and Constraints
The objective functions and their constraints are evaluated in order of importance as shown in Figure 1. The algorithm starts loading the main parameters in order to run all the processes. Then, the optimisation is performed in three stages: the first minimises the generation cost (Z_1), the second minimises the CO_2 emissions (Z_2) and the third minimises the TEP (Z_3). The

Figure 1: Flowchart of the optimisation model
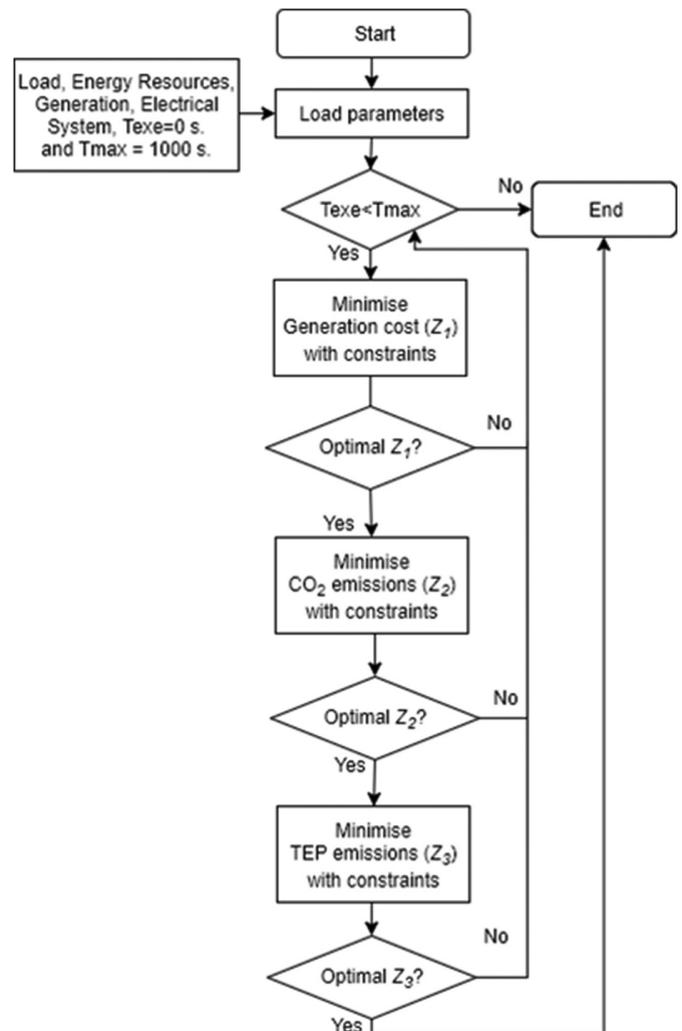
constraints are considered in the minimisation of each objective function. The algorithm repeats these three stages until all the objective functions are minimised or the execution time (T_{exe}) is greater than the final time (T_{max}). In the following subsections, the mathematical formulation of the model and the lexicographic approach are described.

2.1.1. Generation cost function
The first objective function Z_1 corresponds to the minimisation of the generation costs, represented in kWh over the lifecycle of the selected HPGS as shown in Eqs. (1) and (2). Herein, the term i corresponds to the power generation technology, j is used to evaluate each community classified by size and t represents the period of time evaluated. $C_{i,j,t}$ is the power generation cost, $X_{i,j,t}$ represents the power produced in kWh and $P_{i,j,t}$ is the equivalent emissions cost of 1 kg CO_2 used to generate power:

$$Z_1 = Min\left(\sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{t=1}^{T}\left(C_{i,j,t}+P_{i,j,t}\right)*X_{i,j,t}\right) \quad (1)$$

For this objective function, some constraints are considered to study the different configurations of the power generated for

the communities. The first constraint corresponds to the power balance, where the power generated by the electricity energy system ($X_{i,j,t}$) (must be equal to or greater than the power consumed by the community j during the evaluated period of time t $(D_{j,t})$:

$$\sum_{i=1}^{n} X_{i,j,t} \geq D_{j,t} \quad \forall j,t. \tag{2}$$

Furthermore, load demand constraints for each community in time t are used in the optimisation model. At this point, the consumption must be equal to or lower than the current power demand to guarantee stability of the power network as shown in Eq. (3). Herein, the term $Cs_{j,t}$ is the maximum power load consumed by each community j in the period t. This constraint is used to obtain enough power production and guarantee the continuous stability and reliability of the electricity service:

$$D_{j,t} \geq Cs_{j,t} V_{j,t} \tag{3}$$

The search for the best HPGS must consider that the load is equal to the same power demand previously defined at each period t to set a fixed value for the algorithm that searches the power generation that balances the power demand as expressed in Eq. (4). Herein, the term $f(D_{j,t})$ is the fraction of the maximum load in percentage value (%) that represents the energy consumption of each community (j):

$$Cs_{j,t} = f(D_{j,t}) \,\forall_{j,t}. \tag{4}$$

The power produced by the HPGS with technology i in time t must be defined also as a constraint that restricts power production according to the technical and environmental conditions as shown in Eq. (5). Herein, the term R represents a number with a large value that enables the technology y_i to generate electricity according to the energy potential of the studied zone, subjected to the power of each system:

$$X_{i,j,t} \leq Ry_{i} \forall_{i,j,t}. \tag{5}$$

A power production constraint is also considered in the formulation for each wind technology that is part of the best HPGS to guarantee that the exceeded power demand is produced by the solar energy system as shown in Eq. (6):

$$\sum_{i=1}^{n} X_{i,j,t} = (1-\alpha) D_{j,t} \,\forall i,t. \tag{6}$$

In the model, the parameter alfa and the option $1-\alpha$ that represents the participation factors of the solar and wind sources are integrated in the constraints. For the tests performed in the research, the parameter was assumed as 0.5, which represents a power production of 50% by the solar energy system and 50% by the wind energy system; this condition can be changed according to the energy potential and the renewable energy resources available at each zone, reducing or increasing the participation of the energy system. One of the conditions defined for the problem is that the electricity generation system must cover 90% of the power demand (including the different losses) and the remaining power (10%)

must be used to supply the power grid or accumulate in batteries for future demand.

When the power produced by the HPGS is higher than the power demand, the excess must either supply the power grid or accumulate in batteries for future demand. This was defined as a constraint in the mathematical formulation of the optimisation model as shown in Eq. (7):

$$IR_t = \sum_{i=1}^{n} \sum_{j=1}^{m} X_{i,j,t} - \sum_{j=1}^{m} Cs_{j,t}, \forall t \tag{7}$$

A binary constraint was also considered in the mathematical model to select the wind and solar energy technology with the term $y_{i,t}$ as shown in Eq. (8):

$$\sum_{i=1}^{3} y_{i,t} = 1, \forall i,t \, and \, y_{i,t} = \{0,1\}. \tag{8}$$

The value 1 indicates an active generator and 0 an inactive generator. The term i represents the technology used to produce electricity and t represents the time of the evaluation, where y_1 is the SMini_wind, y_2 is the ST_20, y_3 is the ST_50, y_4 is the PVS, y_5 is the CPCS and y_6 is the CRS.

A non-negative constraint is applied to the objective function that considers the power generation $X_{i,j,t}$ as shown in Eq. (9). Thus, the electricity generation system will only provide positive power for the network:

$$X_{i,j,t} \geq 0 \,\forall_{i,t} \tag{9}$$

2.1.2. Objective function of CO_2 emissions
The second objective function Z_2 is proposed to optimise the total emissions of CO_2 generated over the lifecycle by the best HPGS, where $E_{i,j,t}$ is the equivalent emission of CO_2 in kg released into the atmosphere with the production of 1 kWh (i.e., kgCO$_2$/kWh):

$$Z_2 = \text{Min}\left(\sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{t=1}^{T} E_{i,j,t} X_{i,j,t}\right) \tag{10}$$

The second objective function is subjected to the same constraints defined for the first objective function. Moreover, the minimum value of the generation cost over the lifecycle of the electricity generation system is considered a constraint that represents the optimal value of the first objective (Z_1^*) function by the lexicographic approach as shown in Eq. (11), where $C'_{i,j,t}$ represents both the production cost and the emission cost:

$$\sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{t=1}^{T} C'_{i,j,t} X_{i,j,t} = Z_1^* \tag{11}$$

2.1.3. Objective function of TEP
The third objective function Z_3 is defined as the minimisation of TEP consumed over the lifecycle by the best possible HPGS as shown in Eq. (12), where $M_{i,j,t}$ is the TEP produced for each 1 kWh:

$$Z_3 = \text{Min}\left(\sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{t=1}^{T} M_{i,j,t} X_{i,j,t}\right) \qquad (12)$$

Likewise, this objective function is subjected to the initial constraints previously defined for the first objective function. The minimum value of the generation cost over the lifecycle of the electricity generation system is considered a constraint that represents the optimal value of the first objective function (Z_1^*) by the LMOM. Moreover, the minimum emissions of power produced by the HPGS shown in Eq. (10), or the second objective function (Z_2^*), is considered a constraint for this third function as shown in Eq. (13):

$$\sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{t=1}^{T} E_{i,j,t} X_{i,j,t} = Z_2^* \qquad (13)$$

2.1.4. Lexicographic optimisation

The theory of the multi-objective decision is a great tool for prioritising different goals in decision making (Cheng, 2013) and lexicographic optimisation has been used widely to solve different problems (Jones and Jimenez, 2013). For example, it has been used to find the best solutions for the functioning of several industrial plants to minimise operating costs, emissions and the loss of assets (Choobineh and Mohagheghi, 2016), and to find the compensation in the electricity market and guarantee the security of some conventional systems (Aghaei et al., 2011). It has also been used to find compensation for economic, environmental and energy factors involved in the development of forest energy plantations (Lonergan and Cocklin, 1988). Therefore, the three objective functions, with all the constraints as planned in the research, can be solved by prioritising the objective functions and using the lexicographic optimisation technique.

Let the functions $f_1(X), f_2(X), \dots, f_n(X)$ be subjected to a set of initial constraints. They can be written in an order of priorities to be solved. If $X_1^*, X_2^*, \dots, X_j^*$ are values such that f_j is optimal in and subjected to the initial and additional constraints such that X_j^*, $f_{j-k}(X) = f_{j-k}\left(X_{j-k}^*\right), \forall k \le j-1$ then the problem can be solved as a lexicographic optimisation (Castro-Gutierrez et al., 2009). This is due to the existence of conflicts among the objective functions that will make an improvement to one of them result in deterioration of another. This approach establishes that the objective function with the higher priority is solved first; next, low priority objectives are considered to solve the complete problem. Therefore, the first aim is to prioritise the generation cost, then the CO_2 emissions and, finally, the TEP (Lonergan and Cocklin, 1988) to obtain the best electricity generation system (Dufo-López et al., 2011).

2.2. Generation Systems

For communities located in non-interconnected zones, it is preferred to use autonomous power generation systems. Therefore, in this study, wind and solar energy systems are proposed based on the characteristics shown in Table 1.

The SMini_wind, ST_20, ST_50 and PVS were modelled with data obtained from the HOMER Energy software (Hybrid Optimization of Multiple Energy Resources). The CPCS was modelled with local solar radiation provided by the Institute of Hydrology,

Table 1: Summary of the costs and category of the impacts for the environment

No.	Generation technology	Abbreviation	Rated power (kWh)
1	Mini-wind systems	SMini_wind	38
2	Wind systems with a 20-m tower	ST_20	38
3	Wind systems with a 50-m tower	ST_50	38
4	Photovoltaic system	PVS	38
5	Cylindrical parabolic collector system	CPCS	20
6	Central receiver system	CRS	1 MW

Meteorology and Environmental Studies (IDEAM). The CRS was modelled with hourly solar radiation data obtained from the Meteonorm software version 7.

With these models, the Windelsol software version 1.0 was used to find the optimal parameters and elements of the power plant and design the field of heliostats. Finally, the data is introduced in the system advisor model (SAM) software to model the annual production of the renewable energy power plant. These systems were designed to estimate the variables to feed the optimisation model and facilitate the analysis of non-interconnected zones with varied climate and geographic features, including the presence of high wind and solar potential.

Figure 2 shows the CPCS with its main components and broken down into five stages due to its complexity. The first stage corresponds to the design conditions of the plant. The second stage is the determination of the characteristics of the meteorological resources available. The third stage is done to know the sizing of the Rankine cycle. The fourth stage corresponds to the sizing of the solar field. Finally, the fifth stage simulates the electrical production.

Figure 3 shows the design of the CRS with the possibility to supply electricity to the power grid. These systems were projected with a lifecycle of 25 years (Hernández-Moro and Martínez-Duart, 2013) while considering the growth rate of the Colombian population (DANE, 2009). They were designed and contextualised to the region according to the existing energy potential and located in the zone called the "sun belt" (Meisen and Krumpel, 2009).

The levelised cost of energy (LCOE) was estimated with the energy systems generating over the lifecycle of each technology, which is optimised in the first objective function of the model. Then, a factor is applied to increase around 10% of the generation (SunFields Europe, 2011) and, thus, avoid overloading the system. With the components of the system, the effect of the carbon released into the environment was analysed according to two impact criteria, CO_2 emissions and TEP, with the LCA as shown in Figure 4 (Rúa Lope, 2009). These variables are optimised by the last two functions of the model over the lifecycle of the selected technologies to form the best HPGS.

Regarding the lifecycle, a complete identification and quantification of resources was carried out, starting with the acquisition of the

Figure 2: Diagram of the cylindrical parabolic collector system plant
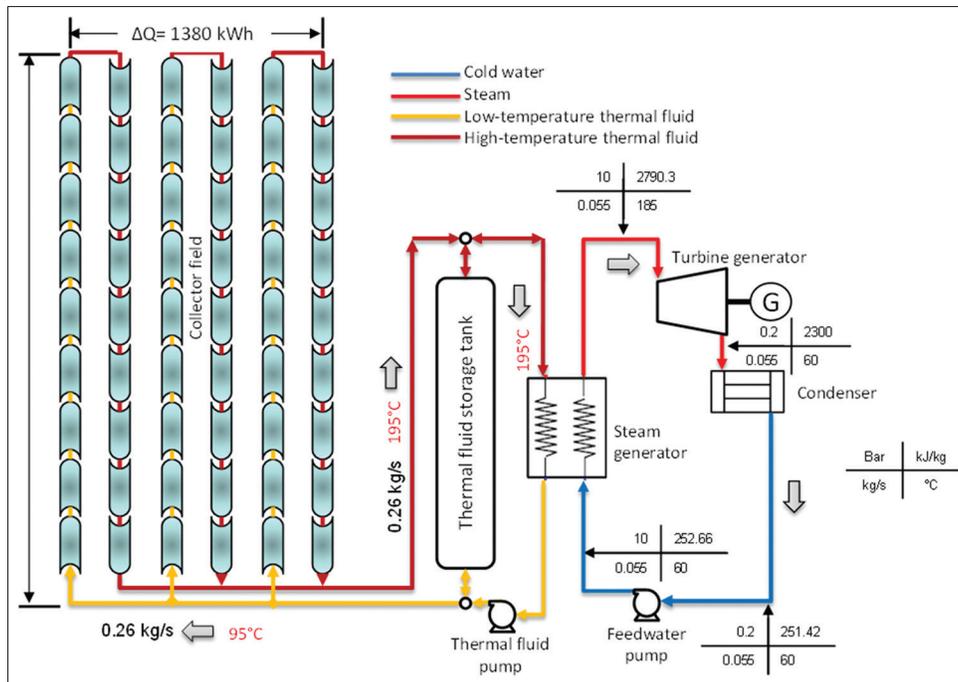
Figure 3: Diagram of the solar plant with a central receptor
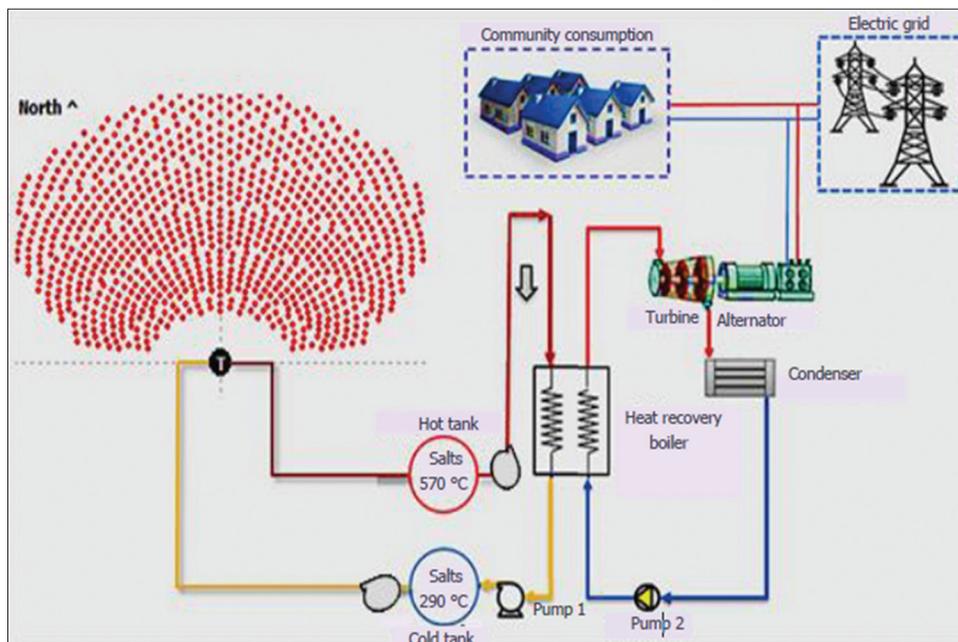
raw materials, passing through the manufacture while considering transport, evaluating the use, engaging the recycling and taking into account the final disposal of each technology used in the model. Moreover, real data were collected from the non-interconnected zone to validate the proposed model and also the negative externalities related to the power generated by each energy system technology were considered (Longo et al., 2008; Saman et al., 2014; Schleiniger, 2016).

2.3. Estimation of the Generation Costs, CO_2 and TEP

Table 2 shows the generation costs, the emission in tons of CO_2 and the TEP estimated with the designed systems. The prices

of CO_2 emissions (McHenry, 2009; Rugtveit, 2012) were taken from the website of the European CO_2 Trading System (http://www.sendeco2.com/es/), an organisation subject to the European Union Emission Trading Scheme (EU ETS), which constitutes the European Directive on CO_2 trading.

2.4. Sample Selection

Figure 5 shows the department of La Guajira in Colombia with the middle and upper zones, where the study was conducted. This region has a great rural length and a population of 1 million, distributed over a 20,848 km² in the northern part of Colombia and divided into the lower, middle and upper

Figure 4: Phases of the LCA
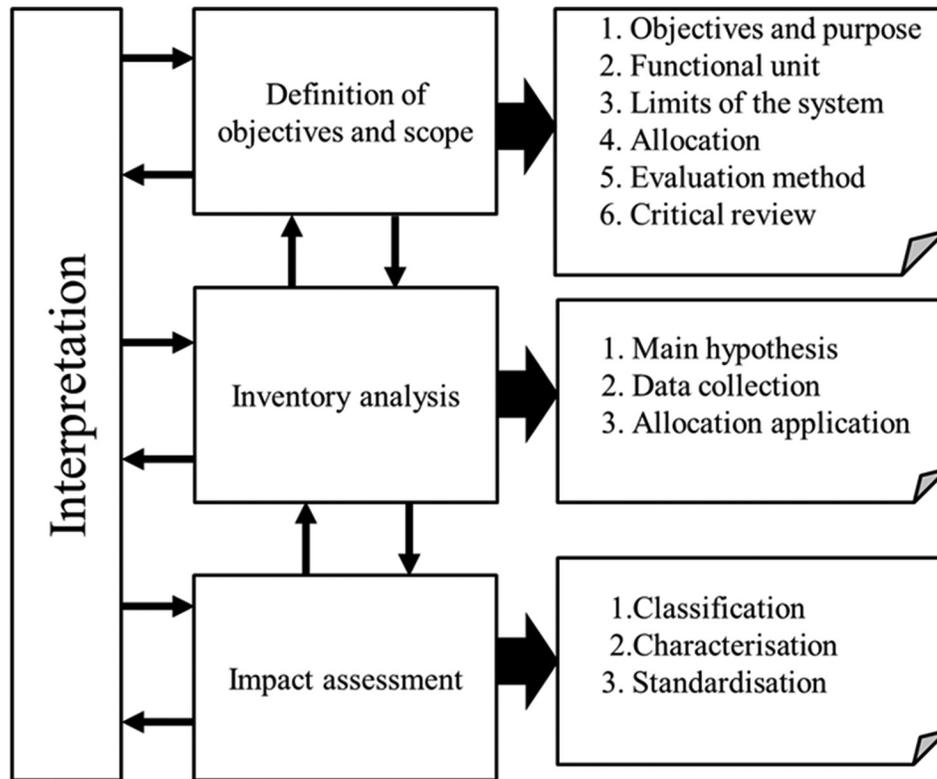
Source: Based on the NTC-ISO 14040(Rúa Lope, 2009)

Table 2: Summary of the costs and categories of environmental impact

Technologies (n)	Costs			Impact	
	$/kWh	**$ equivalent tCO$_2$/kWh**	**Total**	**tCO$_2$/kWh**	**TEP/kWh**
SMini_wind	864	0.323	864.323	1.94E-05	5.66E-06
ST_20	660	0.371	660.371	2.23E-05	6.34E-06
ST_50	676	0.504	676.504	3.03E-05	8.58E-06
PVS	860	0.806	860.806	4.85E-05	1.51E-05
CPCS	867	0.829	867.829	4.99E-05	2.36E-05
CRS	768	0.385	768.385	2.32E-05	5.35E-06

Table 3: Classification of the indigenous communities

Size	Number of inhabitants	Segment
Up to 50 people	Small communities (10 users)	S1
Between 51 and 150 people	Medium communities (20 users)	S2
More than 151 people	Large communities (39 users)	S3

Guajira (Puerta, 2004). The population studied in the research was selected because the communities are located in non-interconnected zones and have low resources (Leal González et al., 2003; PMA-OXFAM-CLUSTER SAN-PNUD, 2014) and also because this region has a high potential for wind and solar energy (Pinto et al., 2004).

The sample size was estimated as shown in Eq. (14) (Aguilar-Barojas, 2005), where n_p is the sample considered from the population to validate the energy systems, N is the total population considered in the middle and high Guajira, z is the confidence level defined as 95% according to the standard deviation of 1.96, p considers the probability of being chosen and equal to 0.5 with

a $q = 1 - p$ and e is the error considered in the calculation of the sample (5%):

$$n_p = \frac{z^2 * p * q * N}{e^2 (N-1) + z^2 * p * q} \tag{14}$$

The sample size required under this formulation and the described parameters is 381 households. With this sample, we proceeded to calculate the current and future power demand on a household basis. Communities were classified as small, medium or large, as presented in Table 3, for the purpose of adapting the design of the HPGS to the communities' needs (43, 44).

The renewable energy systems were designed according to the power demand of the selected communities and with an annual projection of population growth (DANE, 2005a), and considering the lifecycle of the technologies under study. In this case, the energy demand of the communities will have an increasing trend as shown in Figure 6 (DANE, 2005b).

Figure 5: Distribution of the communities in the middle and upper Guajira.

Source: adapted from Google Earth®

Figure 6: Tendency of annual demand of populations in the non-interconnected zones
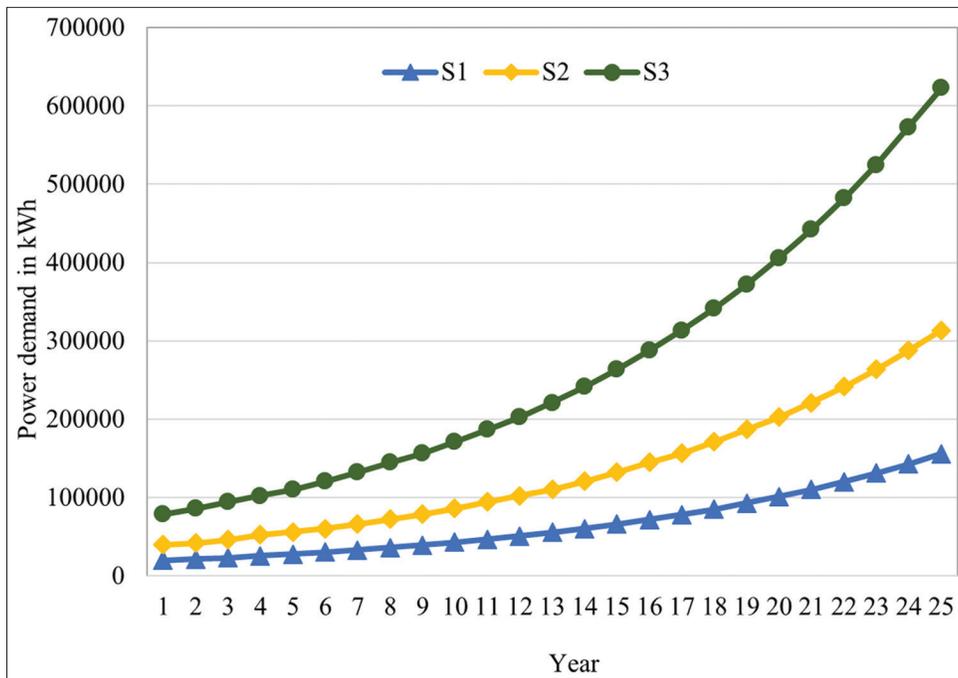

3. RESULTS AND ANALYSIS

To perform the simulations, we used a computer with an Intel Core 2 Duo @ 3.16 GHz and 8 GB RAM, under 64-bit with Windows 8.1. The program used for optimising the objective functions is the General Algebraic Modeling System (GAMS) and, to solve the high complex problem, the IBM ILOG CPLEX Optimizer, which allows flexibility for the solution with mixed integer programming (MIP). For the lifecycle analysis, the SimaPro software was used, which allows to calculate the environmental, social and economic impacts of the renewable technologies used for the analysis of carbon footprint. The objective functions were evaluated considering a maximum of 1,000 seconds to obtain the best renewable energy technologies for the HPGS.

The following results show that the best renewable energy technologies for the HPGS applied to communities located in non-interconnected zones are the ST_20 and CRS. Other technologies were discarded by the LMOM as they were not feasible or represented very high values for the objective functions. Thus, the results for the ST_20 and CRS are presented in the following ways: (1) The results for the generation costs; (2) the results for the CO_2 emissions; and (3) the results for the TEP emissions.

Figure 7: Cost of the ST_20 and CRS technologies during their lifecycles for the three community sizes
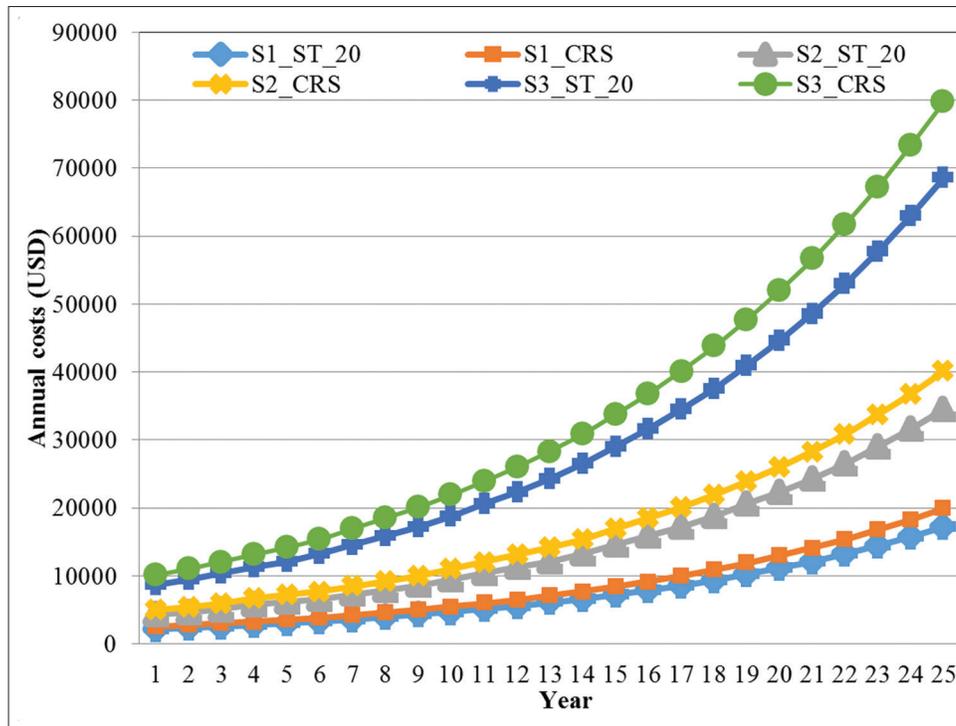
3.1. Generation Cost Function

The result of the generation cost function summarises the best combinations identified in GAMS in which MIP and CPLEX were used. Therefore, Figure 7 shows the annual cost of generation through the entire lifecycle of ST_20 and CRS for the three sizes of communities (S1, S2 and S3). Herein, the terms S1_ST_20, S2_ST_20 and S3_ST_20 represent the curves of the annual costs of the ST_20 technology during the lifecycle for the community sizes S1, S2 and S3, respectively. In the same way, the terms S1_CRS, S2_CRS and S3_CRS represent the annual costs of the CRS technology for the community sizes S1, S2 and S3, respectively. The same terms are used for the rest of the figures presented in this section of the paper.

All curves presented in this figure show the same growth tendency, which is related to increasing load demand through the years; thus, the annual growth for each segment of the population is explained by the growth rate of the population projected in Figure 6. Therefore, both generation technologies have similar increasing cost tendencies in the selected combination of renewable energies for the HPGS.

However, when comparing the costs of technologies, the CRS technology produces greater values than the ST_20 technology because the CRS requires components that represent higher costs and those are reflected in the results of the curves. The design of the energy systems for community S1 is lower compared with that for community S2 and even more for community S3 because power demand and population growth lead to increased costs over the last years of the lifecycle.

Furthermore, the minimum generation cost obtained with this function is Z_1 = 2,731,818 USD through the lifecycle of the two

chosen technologies. This is the optimal value among all possible combinations through the lifecycle of each selected technology to create the best HPGS. As the systems were designed to obtain a power greater than the energy consumed, the remaining energy can be used to cover future demands of the communities. However, the more power that the generation system produces to meet increasing demand the more that the system wears out and the more the production cost increases.

Figure 8 shows the power production obtained with the LMOM through the entire lifecycle of ST_20 and CRS, considering the three community sizes (S1, S2 and S3). In this figure, both CRS and ST_20 produce the same power to supply the demand as each generation technology was designed to supply 50% of total demand and the complete power demand is covered by the available energy resources. As previously stated, the percentage can be managed to evaluate different combinations of renewable resources and determine their participation according to the total power demand; however, this evaluation will be performed in future research.

Power production is increased consistent with population growth (DANE, 2005). To meet the power demand, the electricity generation system was designed by the lifecycle of each technology. The capacity was increased 20% (two standard deviations), where 90% represents the consumption of the population and the lost possibilities of the system or any other unexpected event. The remaining 10% of the total generation capacity is used to cover future demand or to supply the power grid. This must be established as the minimum power delivered because power consumption could decline under energy savings policies, which would leave a greater amount of energy to be sent to the power grid.

**Figure 8:** Power production in kWh for the ST_20 and CRS for the three community sizes
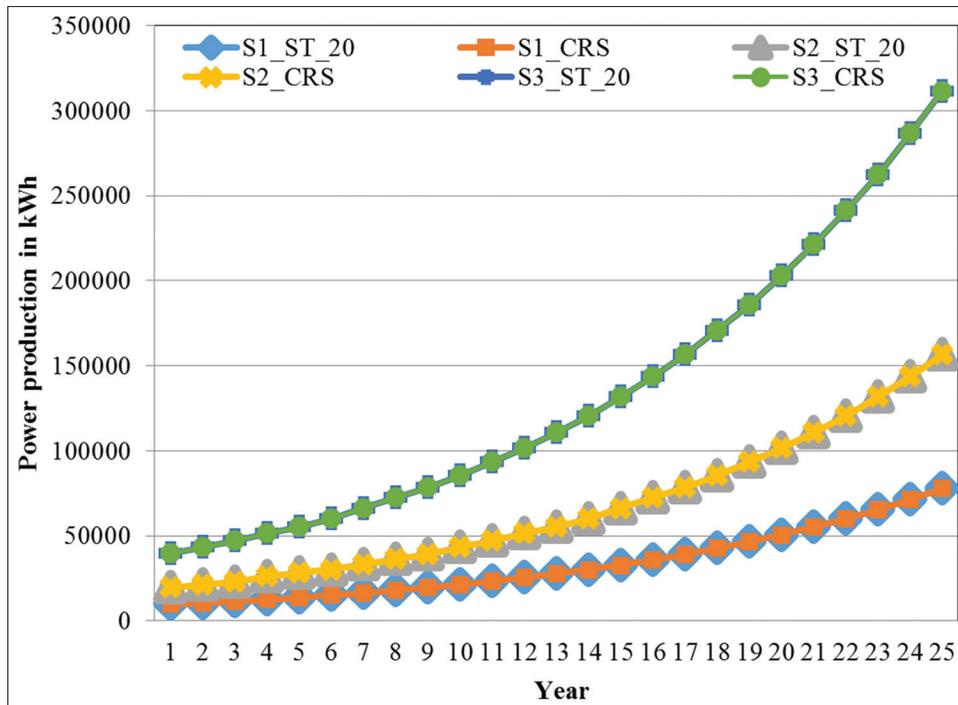
Figure 9: Associated emissions to the ST_20 and CRS for each segment over the lifecycle
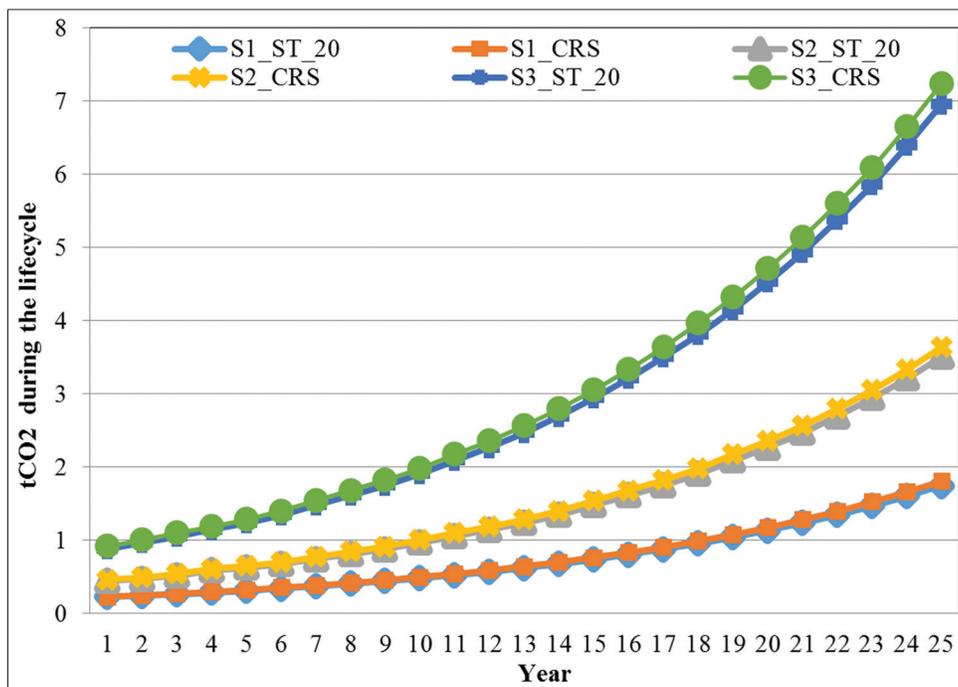
Therefore, the results for the first function obtained a total of 11,701,971 kWh through its lifecycle for the three segments of the population with a relatively low cost of USD 0.23 (23 cents) per kWh. This value is competitive compared with other research performed in Colombia (Flórez et al., 2009; SunFields Europe, 2011). Likewise, it was found on an international level by some studies that these costs are competitive (ATKEARNEY, 2010; Breyer et al., 2009; Hernández-Moro and Martínez-Duart, 2013).

3.2. CO$_2$ Emissions
Figure 9 shows the CO$_2$ emissions through the entire lifecycle of the ST_20 and CRS for the three sizes of communities (S1, S2 and S3). This figure shows an increasing trend of the CO$_2$ emissions over the lifecycle of the selected technologies that contemplates the worn components, replacement of equipment and the increasing cost of materials for operations and maintenance. The LMOM found that the CRS minimises CO$_2$ emissions throughout the lifecycle, preserving the constraints defined for the first function

Figure 10: TEP associated with the ST_20 and CRS for each type of community
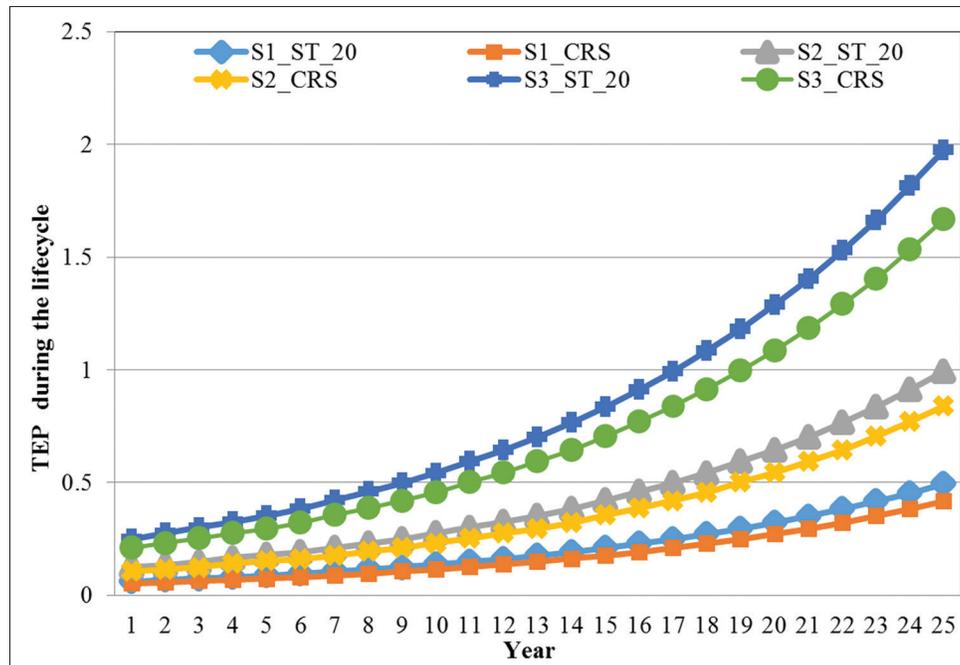
or the generation cost. Furthermore, when power production increases to supply the growing demand, the generation system becomes more worn out and the emissions increase.

Therefore, the results of function 2 obtained an optimal value of = 266,204 kg CO_2 while considering all the power produced through the lifecycle for each evaluated community size. The estimated emissions of 1 kWh generated by the proposed generation system are around $3.23E-02$ $kgCO_2/kWh$, whereas for the Colombian power grid it is around 0.2717 $kgCO_2/kWh$ (UPME, 2009). Minimal emissions are obtained with the first technology (ST_20) being friendlier on the environment (low-altitude tower, minimal impact and medium power supply system). The second one is of a high-power supply system, able to generate energy on a large scale with little impact on the environment and, especially, minimal land use.

3.3. TEP Emissions
Figure 10 shows the TEP emissions through the entire lifecycle of the ST_20 and CRS for the three sizes of communities (S1, S2 and S3). In this case, this becomes a factor of the annually produced energy over the entire lifecycle because the more the technology is used to supply electricity for the population the faster its deterioration, which increases future consumption. The system presents a short increase in power consumption, justified precisely by its components (mainly the tower), which require a greater consumption of TEP during the manufacturing process. However, this system generates power with a smaller amount of CO_2 emission than the CRS. Furthermore, the TEP emissions produced by the CRS are lower than those produced by the ST_20 and different to those reported in Figure 9, where higher CO_2 emissions were produced by the ST_20 technology.

Therefore, the third function provided an optimal value of = 68.39 TEP consumed over the lifecycle of the two selected technologies.

This value is restricted by the optimal results obtained with the objective functions and , demonstrating the low consumption of energy that both systems have.

4. DISCUSSION

The results showed how the proposed LMOM selected two renewable energy technologies for a HPGS applied to communities located in non-interconnected zones. The model considered objectives as generation costs and environmental impacts based on the power production. This design allows the use of wind and solar energy sources according to the local energy resources and the consumption of habitants in the non-interconnected zones (Manzano-Agugliaro et al., 2013; Santoyo-Castelazo and Azapagic, 2014; Sood et al., 2012). By classifying communities based on population, the proposed power generation systems are adapted to each community.

The results showed that the best HPGS is formed with renewable energy technologies, such as the ST_20 and CRS, because they are the most economic options through the lifecycle for the size of the evaluated communities located in non-interconnected zones. This system was obtained after simulating the nine possible combinations of three solar and three wind energy technologies with GAMS, where each technology presented different generation costs, CO_2 emissions and TEP. The ST_20 system was the most economic choice among of the wind energy options because the main components are not expensive and the wind at 20 m has great energy potential. The CRS offers large power potential with the radiation registered at the zone and can produce electricity on a large scale with minimal land use and at low cost compared with the ST_20 and other systems. In this function, the annual costs through the lifecycle of each selected technology show an ascendant behaviour, experiencing an average annual increase of 1.33% during the 25 years for each grouped community. The above

is valid and coherent with the projected demand, which increases with population growth.

The slight increase in generation costs found in the results is a reasonable value, considering that if the production increases annually, then the systems need to increase the power while, over time, they deteriorate and fail, demanding new investments in equipment to replace components and operations and maintenance over the lifecycle of each system. These expenses are implicit in the LCOE of the optimised HPGS. Besides, the operation costs turn into a factor of the annually produced energy, which means that the more energy produced due to the increase in demand the greater the wear on components and, thus, generation costs. However, when production is increased while preserving the same energy resources, production costs decrease over time.

The optimisation model was evaluated considering a forecast power demand with population growth, showing a slight tendency to increase the costs of electricity and with the possibility to supply to the power grid. The electricity production requirements for the indigenous Wayuú communities were based on their population size: small, medium or large. The costs of production in the first function are adjusted to the regional budget. La Guajira has important resources to improve the living conditions of the poorest and most vulnerable population in the territory and these solutions provided good options for those currently without electricity service.

These electricity generation systems were designed to estimate the LCOE and, with the LCA, CO_2 emissions and the TEP over the lifecycle of each technology (Dufo-López et al., 2011). These values must be adjusted with the optimisation model, considering the prioritisation of goals (Chang et al., 2012; Cheng, 2013; Jones and Jimenez, 2013; Kamiri and Attarpour, 2012), to identify the best technical options of HPGS designed to supply the consumption of rural communities located in non-interconnected zones or to supply the power grid. The CRS and CPCS need to be designed with low generation cost to guarantee economic sustainability and to result in minimal damage to the environment.

The second and third functions of the model and that minimise the two impact categories evaluated (CO_2 and TEP) validate the selected HPGS in the first function (ST_20 and CRS). The results are a consequence of both technologies being comparatively friendly with the environment among all six evaluated (in relation to energy production based on the burning of fossil fuel, their difference is very meaningful). This is a reasonable valuation because the more time the technologies are used the more the energy production increases, the more the components wear out and the more elevated the emissions sent into the atmosphere, with an increase of the energy consumption in TEP over its lifecycle.

The results show that there are no other technological options to replace the ST_20 and CRS because of their minimal values found in functions 2 and 3. The CRS system shows a greater production of $kgCO_2/kWh$ in proportion to ST_20. These results are inverted in the third function in which the ST_20 presents a greater consumption of TEP/kWh (this is due mainly to the manufacture of a 20-m tower) compared with the CRS.

The results of the model are focused on determining the best technical options for the HPGS, which must cover the projected power balance with a low generation costs and reduced environmental impact as identified in the LCA of each technology. It can be observed that the costs increased slightly in the CRS compared with the ST_20 because the CRS generates a greater amount of energy annually, thus increasing the costs.

The CO_2 emissions in the second objective function are higher for the CRS than for the ST_20, which is consequent with the previous analysis and because of the characteristics of the CRS components. The condition of the second function is inverted in the third, where the CRS appears with the lowest energy consumption in TEP compared with the ST_20 due to the tower components of this last system. However, on average with these technologies over their lifecycles, there would be a savings of 15.99, 32.09 and 63.98 tons of CO_2 into the atmosphere compared with the fossil fuel energies produced by S1, S2 and S3, respectively (UPME, 2009).

The CRS and ST_20 technologies are the best options to implement HPGS for communities located in non-interconnected zones. This result is repeated for the studied communities, obtaining a minimal cost and reduced environmental impact. This result allows supporting the economic, social and environmental aspects for the communities and with a high probability of generating electrical energy for future interconnections to the power grid.

The proposed method is applicable to other problems with similar characteristics, where prioritising is required to determine optimal HPGS with multiple objectives and constraints related to the generation cost and environmental impact. The first function minimises the generation cost and the last two optimise the emissions of CO_2 and TEP over the lifecycle of the selected technologies. These solutions are oriented to the sustainable improvement of living conditions for communities that inhabit the non-interconnected zones with wind and solar potential and to contribute to reducing CO_2 emissions (Mitchell et al., 2005).

5. CONCLUSION

This paper presented an LMOM to select the best renewable energy technologies for HPGSs applied to rural communities located in non-interconnected zones. The LMOM is used to prioritise three objective functions that minimise the generation cost, CO_2 emissions and the consumption of energy in TEP. Validation of the method was conducted through nine combinations of technologies (three solar and three wind technologies) and applied to the design of HPGSs for rural communities of small, medium and large size. For this paper, the demand for energy in these communities was estimated.

The results showed that the LMOM prioritised the three objective functions and determined the best HPGS for each community tested in the research; that is, the proposed method is useful to solve this type of problem when applied to non-interconnected zones. Three optimal HPGSs were designed for each technology and the results show that the best technologies for the communities are the CRS and ST_20. In future work, the model can be adapted

and tested with other renewable energy sources in other places and more functions can be adapted for other social indicators. In addition, other power generation systems can be adapted to the method to evaluate their sustainability and functioning in non-interconnected zones.

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