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Assessment of Power Generation Alternatives Through a Fuzzy Multiobjective Mixed Integer Long-Term Planning Model: Case Study of Non-Interconnected Areas of Colombia

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This paper presents a fuzzy multiobjective mixed-integer linear programming (FMOMILP) model for the optimal long-term energy planning of a power generation system for the case study of non-interconnected areas of Colombia. The proposed model determines: the optimal planning of power generation, selecting between solar photovoltaic, biomass gasification, wind turbines, small hydro, grid extension, and diesel engines alternatives; the type of fuels; and the plant locations so as to meet the expected electricity demand, while satisfying the fuzzy objectives concerns: the minimization of the total power system cost and CO_2 emissions and take into consideration design, operational, and efficiency constraints.
In order to capture more accurately the spatial and technical characteristics of the problem, the underlying geographical area is divided into a number of individual sub-zones. Two real case study concerning San Andres and La Macarena energy planning problem demonstrates the applicability of the proposed approach.
Finally, in the case of San Andres Island, the results indicate that the environmental objective favours the use of solar photovoltaic and wind turbines systems, while economic objective favours to continue using diesel plants. On the other hand, in the case of La Macarena, the environmental objective favours the use of small hydro, solar PV and the transmission, while the economic favours the biomass gasification.

1. Introduction

Nowadays, nearly 1.4 billion people still lack access to electricity (87 % of whom live in rural areas), and one billion has access only to untrusted networks of electricity. It is estimated that the capital investment needed to provide modern energy services to this population is on the order of $40 \cdot 10^9$ US$/y until 2030. This represents about 3 % of the total investment in energy worldwide that is expected for this period (Grynspan, 2011).
In the Colombian case, approximately 421,000 households do not have electricity service, 57 % of which are not connected to the national grid (SIN per its initials in Spanish) (UPME, 2012). Most of these households are located in non-interconnected areas, which are characterized by low population density (4 %), public services limited and undeveloped, people’s basic needs unsatisfied, and cover almost 66 % of the national territory including nearby 1,200 settlements, 16 departments, 91 towns and 2 million people (Castro, 2010).
With the aim of supplying the lack of electricity in non-interconnected areas solutions with diesel generation (Diesel-Gen) have been established, which are not sustainable in the long term, from an economic and environmental point of view (Rosso-Cerón, et al., 2015). Nevertheless, the implementation of renewable energy technologies for the generation of electricity in situ in developing countries is presented as a solution for these people who do not have this service (Zerriffi, 2011).
The decision about choosing energy supply alternatives in rural populations has traditionally been from technical and economic criteria, leaving in the background environmental issues (Rojas, 2012), energy resources, and demand forecasting. Consequently, current research focuses on the extension of the proposed model to incorporate uncertainty, and analysis of several alternative scenarios to provide with further insight into the influence of key parameters into the overall power system.

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Regarding the latter point, fuzzy multiobjective model like the criteria decision method facilitates information management of unavailability required data (parameters) over the midterm decision horizon, they are assumed to be ambiguous and vague (fuzzy) uncertainties in nature (Torabi and Hassini, 2009), all are defined by their possibility distributions (the semantic interpretation of the degree of membership handled will be the degree of possibility), that is, the problem of MOMILP with fuzzy parameters we address uses the possibility theory. Logically this requires working with models based on the estimation of the possible values that can reach the magnitudes involved in it, and therefore, the results will contain a greater or lesser degree of imprecision and uncertainty.

Therefore, with the goal of planning energetic future and sustainable development in two isolated regions (San Andres Island and La Macarena) of non-interconnected areas of Colombia, this work assesses solar photovoltaic (PV), biomass gasification, wind turbines, small hydro, grid extension, and diesel systems through a spatial FMOMILP multi-period long-term model. The planning horizon (2015–2024) consists of ten annual periods within the time horizon and the base year is 2014. Their objectives concern the minimization of the total power system cost (economic objective) and CO_2 emissions equivalent (environmental objective) and take into consideration design, operational, and efficiency constraints.

The remainder of this paper is organized as follows. In Section 2, we define the problem and present the cases of study. In Section 3, we describe the model equations, indices, parameters, decision variables and the hybrid method proposed for solving the problem. In Section 4, we present and discuss our computational results, which indicate that in the case of San Andres Island, the environmental objective favours the use of solar PV and wind systems, while economic objective favours the use of diesel plants. On the other hand, in the case of La Macarena, the environmental objective favours the use of small hydro, solar PV and the transmission, while economic favours the biomass gasification (in this case with residual crops from plantain). Finally, in Section 6, we conclude our paper and present some future research directions.

2. Problem Statement and Cases of Study

The model incorporates regional disparity disaggregating the target area into urban and rural areas. Urban areas correspond to large cities, like San Andres Island (demand: 273 GWh per year and supply by using diesel generation) and rural areas are isolated places or small towns, like La Macarena (demand: 2 GWh per year and supply by using diesel generation). Both are differentiated according to their location within or outside the areas where interconnection to the electricity grid will be available in the future. A general representation of the energy system is shown in Figure 1.

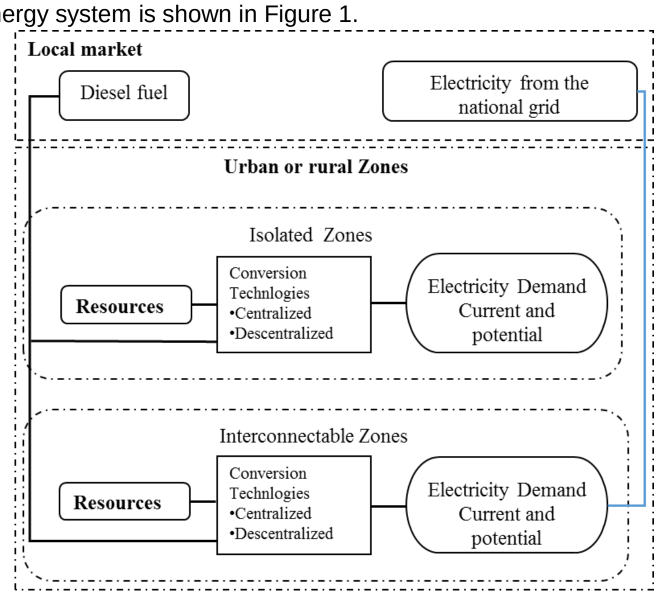

Figure 1: Generic superstructure for non-interconnected areas electrification systems

The design of the energy system provides the most suitable combination of energy resources and conversion technologies to meet a certain quantity of electricity demand under a set of goals and constraints. The solution should determinate which, where, and when new generation units should be constructed over a long range planning horizon (Meza et al., 2007). In addition, the spatial fuzzy multi-period long-term planning model considers two objectives: the minimization of the total power system cost (Considering: capital expenditures, operational expenditure, transmission and fuel costs) and CO_2 emissions (environmental impact objective).

The model also takes into account design, operations, and efficiency constraints such as operational constraints, design constraints and budget constraint.

3. Mathematical Formulation

In this section, FMOMILP objective function and the main equations of the model are presented. All the parameters were obtained from the National Monitoring Centre, Unified Information System, the Regulation Commission of Energy and Gas, the International Energy Agency (IEA) and NASA meteorological data base.

Model parameters

$\widehat{D_{z,b,t}}$ Energy demand (kWh)
$\widehat{DP_{z,t}}$ Peak demand (kW)
$DB_{z,b,t}$ Block duration
ρ_z Reserve margin
$F_{z,p}$ Capacity factor
$A_{z,p}$ Availability factor
$ICa_{z,p}$ Initial available capacity (kW)
$\widehat{Camax}_{z,p}$ Maximum capacity to be added (kW)
$\widehat{Camin}_{z,p}$ Minimum capacity to be added (kW)
$Trmax_z$ Max. capacity to transmit from SIN (kW)
$\widehat{FuRmax}_{z,r,t}$ Maximum amount of fossil fuel available in the domestic market (fossil fuel unit)
$\widehat{InvCo}_{z,p,t}$ Unit investment costs. (USD/kW)
$\widehat{FixCo}_{z,p,t}$ Unit fixed costs (USD/kW)
$\widehat{VarCo}_{z,p,t}$ Unit variable costs (USD/kWh)
$\widehat{FuCo}_{z,r,t}$ Unit cost of fossil fuel t USD/ fossil fuel unit)
$\widehat{TrCo}_{z,t}$ Unit O&M costs of new transmission lines (USD/kWh)
$\widehat{InvTr}_{z,t}$ Unit investment costs of new transmission lines (USD/kW)
$\widehat{BugCo}_z$ Total budget for new capacity (USD)
$\widehat{PriR}_{z,r,t}$ Local primary resource (resource units)
$\widehat{Rw}_{z,r,p}$ Consumption factor of primary resource (primary resource units/kWh)
$\widehat{Ex}_{z,r}$ Exergy factor of the primary energy resource
$\widehat{Em}_{z,p}$ CO_2 emission factor ($kgCO_2/kWh$)

Sets

z zone
p power generation plants
r primary resource
b load block (peak, off peak)
t, v time period (2015-2024)

Sub-sets

iso ⊆ z Isolated Zones (San Andrés,)
inc⊆ z Interconnectable Zones (La Macarena)
renr⊆ r Non fuels resource (Solar, Wind, Water)
fulr⊆ r Fuels resource (Diesel, Biomass)
fosr⊆ r Fossil resource (Diesel)
renp⊆ p Non fuel plant (SmallHydro, BioGen, SolarPV, WindGen)
fulp⊆ p Fuels plants (DiselGen)

Decision variables

$EnG_{z,p,b,t}$ Energy generated (kWh)
$FuR_{z,r,t}$ Amount of fossil fuel acquired in the domestic market (Fossil fuel units)
$ETr_{z,b,t}$ Amount of energy transmitted (kWh)
$CaT_{z,p,t}$ Available capacity (kW)
$PoG_{z,p,t}$ Power generated (kW)
$CaA_{z,p,t}$ Capacity to be added (kW)
$PriF_{z,r,p,t}$ Fuel available for being consumed
$PriF_{z,r,t}$ Total fuel available for being consumed
$In_{p,z,t}$ If new capacity is to be installed, otherwise
$Tr_{z,t}$, If electricity is transmitted, otherwise

3.2 Model description

The discounted total cost objective of the power is given by:

$$f_1: \min TotalCost = \sum_t \frac{1}{(1+r)^t}\left[\sum_z \sum_p \widehat{InvCo}_{z,p,t} CaA_{z,p,t} + \sum_z \sum_p \widehat{FixCo}_{z,p,t} CaT_{z,p,t} + \sum_z \sum_p \left(\widehat{VarCo}_{z,p,t} \sum_b EnG_{z,p,b,t}\right) + \sum_z \sum_{(r|r \in fulr)} \widehat{FuCo}_{z,r,t} FuR_{z,r,t}\right] + \sum_t \frac{1}{(1+r)^t}\left[\sum_{(z|z \in inc)} \left(\widehat{TrCo}_{z,t} \sum_b ETr_{z,b,t} + \widehat{InvTr}_{z,t} Trmax_z\, Tr_{z,t}\right)\right] \quad (1)$$

CO_2 emissions objective of the power systems is given by:

$$f_2: \min Emvironmental\ impact = \sum_t \sum_z \left[\sum_{(p|p \in fulp)} \left(\left(\widehat{Em_{z,p}}\right) \sum_b EnG_{z,p,b,t}\right)\right] \quad (2)$$

The model constraints are show below (in all cases the parameter with hat represents a fuzzy value).

3.3 Operational constraints

Energy balance:

$$\sum_p \mathbf{EnG_{z,p,b,t}} + \mathbf{ETr_{z,b,t}} = \mathbf{\widehat{D}_{z,b,t}} \ \forall z, b, t \quad (3)$$

Reserve margin:

$$\sum_p PoG_{z,p,t} \geq (1 + \rho_z)(\widehat{DP}_{z,t}) \forall z, t \quad (4)$$

Availability factor:

$$EnG_{z,p,b,t} \leq A_{z,p} DB_{z,b,t} PoG_{z,p,t} \ \forall z, p, b, t \quad (5)$$

Capacity factor:

$$PoG_{z,p,t} \leq F_{z,p} CaT_{z,p,t} \ \ \forall\, z, p, t \qquad (6)$$

The amount energy flow transmitted limit:

$$ETr_{z,b,t} \leq \widehat{Trmax}_z DB_{z,b,t} \sum_{v \leq t-Tt} Tr_{z,v}, \quad \forall \ z \in inc, b, t \qquad (7)$$

The areas can be connected to the national grid, only once:

$$\sum_t Tr_{z,t} \leq 1, \forall\, z \in inc \qquad (8)$$

3.4 Design constraints

Installed capacity available: $Op_{z,p,t}$ if the existing installed capacity is operational

$$CaT_{z,p,t} = ICa_{z,p}\, Op_{z,p,t} + \sum_{v \leq t-Tp} CaA_{z,p,t} \,\forall\, z, p, t \qquad (9)$$

The maximum and minimum capacity limits:

$$\widehat{Camin}_{z,p} In_{z,p,t} \leq CaA_{z,p,t} \leq \widehat{Camax}_{z,p} In_{z,p,t} \forall\, z, p, t \qquad (10)$$

$\sum_t CaA_{z,p,t} \leq \widehat{Camax}_{z,p}, \forall\, z, p$, limits on available land available are imposing (11)

Limits on renewable energy potentials:

$$\widehat{Rw_{z,r,p}} \ \sum_b EnG_{z,p,b,t} \leq \widehat{Ex_{z,r}}\left(\widehat{PriR}_{\ z,r,t}\right) \,\forall\, z, |(renr, renp) \in l(renr, renp), t \qquad (12)$$

Fuel primary energy consumption:

$$\widehat{Rw_{z,r,p}} \ \sum_b EnG_{z,p,b,t} = \left(PriF_{z,r,p,t}\right) \forall\, z, |(fulr, fulp) \in l(fulr, fulp), t \qquad (13)$$

The total amount of fuel available:

$$PriT_{z,r,t} = \sum_{pl(fulr,fup)} PriF_{z,r,p,t} \ \ \forall\, z, |r \in fulr, t \qquad (14)$$

Useful fuel available:

$$PriT_{z,r,t} \leq \widehat{Ex_{z,r}} \,(\widehat{PriR}_{z,r,t} + \widehat{FuR}_{z,r,t}) \forall\, z, r \in fulr, t \qquad (15)$$

The amount of fuel purchased in the domestic:

$$FuR_{z,r,t} \leq \widehat{FuRmax}_{z,r,t} \forall\, z, r \in fulr, t \qquad (16)$$

3.5 Budget constraint

$$\sum_t \frac{\mathbf{1}}{\mathbf{(1+r)^t}} \left(\sum_{\mathbf{p}} \widehat{\mathbf{InvCo}}_{\mathbf{z,p,t}} \mathbf{CaA_{z,p,t}}\right) \leq \widehat{\mathbf{BugCo}}_{\mathbf{z}} \forall\, \mathbf{z} \qquad (17)$$

3.6 Framework to Solve FMOMILP

A fuzzy epsilon constraint framework is proposed for finding the Pareto solution. The problem is

Min $f_i(x) = \widehat{D}_i x, \quad i = 1, \ldots, k$ (18)

Subject to.: $x \leq \hat{b}$ and $x \geq 0$ (19)

Where $\widehat{D}_i = \left(\widehat{D}_1, \ldots, \widehat{D}_k\right)^t$ is the vector of coefficients of the ith objective function, $A = \left[\hat{a}_{ij}\right]_{k \times n}$ is a technological matrix, $\hat{b} = (\hat{b}_1, \ldots, \hat{b}_k)^t$ is the vector of available resources, all vague and represented by their corresponding distributions possibility $x = (x_1, \ldots, x_n)^t$ is the vector of the decision variables. The proposed solution is:

In the first phase, the ambiguity of the parameters in the problem is represented by a triangular possibility distribution of fuzzy number $\widehat{D}$, defined geometrically by a triplet (Dl, Dm, Dh), which are the low, the most likely (middle) and the high values, respectively. On the other hand, the vagueness of the parameters is resolved given a minimum acceptable possibility level. Expressing D in terms of β:

$$D_\beta = \left[D^l_\beta, D^m_\beta, D^h_\beta\right] = \left[\left(D^m - D^l\right)\beta + D^l,\ D^m_\beta,\ D^h - \left(D^h - D^m\right)\beta\right], \beta \in [0, 1] \qquad (20)$$

Fuzzy parameters in the objectives are transformed into crisp values using the equation proposed by Jiménez et al. (2007):

$$\widehat{D} = \frac{D^l_\beta + 2D^m_\beta + D^h_\beta}{4} \qquad (21)$$

This method has been computationally efficient for solving fuzzy linear problems since it preserves the linearity of the model; does not increase the number of objective functions; and can be applied to different membership functions (Damghani et al., 2014).

Fuzzy parameters in the constraints are transformed into crisp values following Lai and Hwang (1992):

<u>With imprecise right-hand sides of constraints (soft constraints).</u> The weighted average method is used for converting the parameters into its equivalent crisp number. In the practice, the suitable values for these weights as well as β are usually determined subjectively by the experience and knowledge of the decision maker. Based on the concept of the most likely values proposed by Lai and Hwang (1992) and considering several relevant works (Wang and Liang 2005, Liang 2006), the equivalent soft constraints are considered as:

$$x \leq \hat{c} = \left\{x \leq 1/6c^l_\beta + 4/6c^m_\beta + 1/6c^h_\beta\right. \qquad (22)$$

<u>With imprecise parameters both in the left-hand side and right-hand side</u> Fuzzy ranking concept involves replacing each imprecise constraint with three equivalent auxiliary inequality constraints (Lai and Hwang, 1992):

$$\widehat{A}x \leq \widehat{b} = \begin{cases} A_{\beta}^{h}x \leq b_{\beta}^{h} \\ A_{\beta}^{m}x \leq b_{\beta}^{m} \\ A_{\beta}^{l}x \leq b_{\beta}^{l} \end{cases} \quad (23)$$

Determine the positive ideal solution PIS and negative ideal solution NIS by solving each objective function in the initial model. For values of f_2 bounded by $[PIS_2, NIS_2]$, the range of the objective function f_2, i.e., range2 is:

$$range_2 = NIS_2 - PIS_2 \quad (24)$$

Then, divide it into N equal intervals by $N + 1$ points, namely equidistant grid points. ε_2 in the problem is determined by these grid points and the following equation:

$$\varepsilon_2^n = NIS_2 - \frac{range_2}{N} * n, \; n = 1,2,..,N \quad (25)$$

4. CPLEX was applied to solve the FMOMILP in this work by using software GAMS.Results and Analysis

Following the procedure steps explained in Section 3, the following results are obtained.

The distribution of the no dominated points on the tradeoff curve is shown in Figure 2. Vertical ordinate and horizontal abscissa represent the value of the first and second objective functions, respectively. It is observed that the points are diverse and well distributed over the Pareto front.

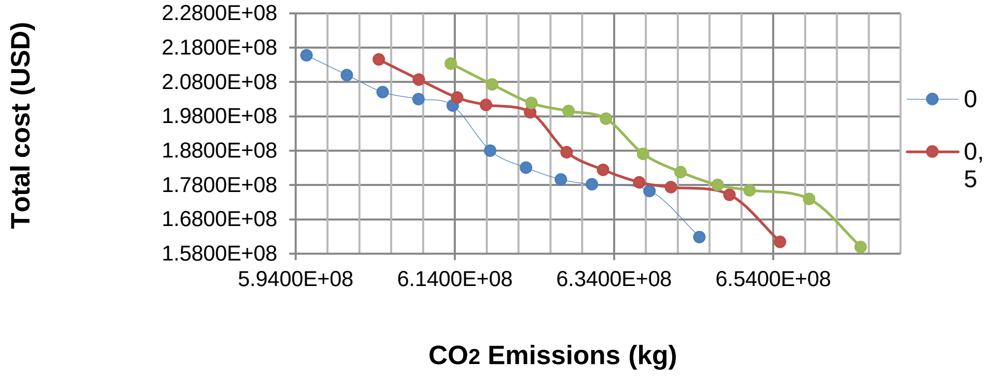

Figure 2. Distribution of no dominated points of the problem for three acceptable possibility levels β

In the fuzzy probabilistic ε-constraint method eleven different solutions (alternatives) are obtained. The results show that the solutions vary for different ranges of epsilon and acceptable possibility levels β. The trend shows high total costs and a low CO_2 emission when acceptable possibility levels β tends to zero.

The following figures show the new capabilities to be installed by technology in each area, when acceptable possibility levels β is 0.5 (most likely). The first alternative (A1) favours continue operating residual biomass gasification in the case of La Macarena (LM) and adding diesel plants in the case of San Andres (SA). With A1 results are obtained minimums costs and maximum environmental impacts.

On the other hand, for the case of San Andres, the A11 favours the implementation of solar PV and wind generators. In the case of La Macarena alternative favours the implementation of small hydro, solar PV, and the transmission. With A11 results are obtained maximums costs and minimum environmental impacts.

Finally, it is worth emphasizing that for all betas, similar trends are reached and with exception of fuel technologies, the construction of technologies is selected to medium term.

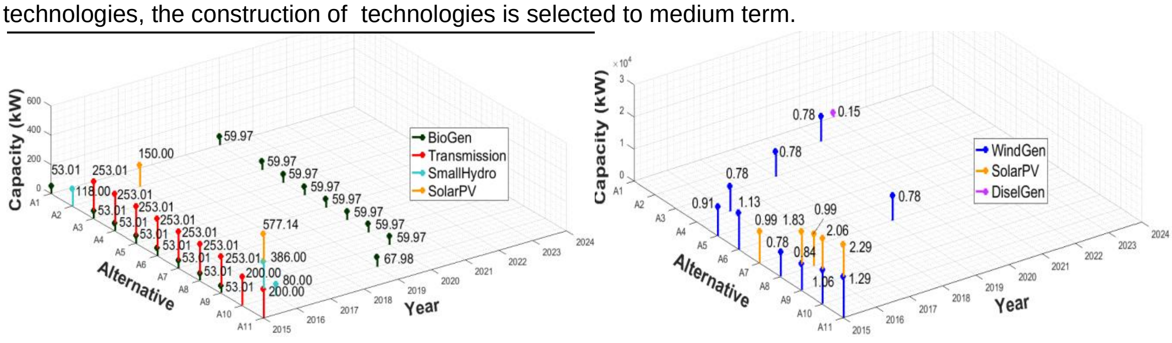

Figure 3. New capacity alternative throughout the planning horizon in LA and SA for β=0.5Conclusions

The proposed multiobjective model intended to minimize two competing objective functions. Then, we proposed an efficient framework based on a hybrid ε-constraint-fuzzy method to solve the multiobjective FMOMILP. The results of computational experiment show that the ε-constraint method can efficiently solve the multiobjective optimization problem within a reasonable time (12.4 s) and find an efficient Pareto front for several acceptable possibility levels β of parameters. The framework is illustrated on two case studies of non-interconnected areas of Colombia, the result indicate that in the case of San Andres Island the environmental objective favours the use of solar PV and wind systems, while economic objective favours to continue using diesel plants. On the other hand, in the case of La Macarena, the environmental objective favours the use of small hydro, solar PV, and the transmission, while economic favours biomass plants. In future work we are trying other fuzzy multi-criteria method in order to choose the best alternative from the Pareto front. Then it will be taken into account national decision maker’s opinion.

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