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A Fuzzy Logic Decision Support System for Assessing Sustainable Alternative for Power Generation in Non-Interconnected Areas of Colombia- Case of Study

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To evaluate sustainable alternatives for power generation from a planning perspective, there are still limited tools that consider the specific challenges of these alternatives in isolated communities. Then this work aims to integrate a fuzzy logic decision support system for assessing the most appropriate long planning sustainable alternative for power generation in non-interconnected areas of Colombia. The assessment incorporates 4 factors or criteria: the implementation time (C1), the technological criterion (C2), the environmental criterion (C3), and the social criterion (C4). Those criteria are evaluated trough energy expert's opinion with a Delphi questionnaire. Subsequently, a real case of study concerning San Andrés Island energy-planning problem demonstrates the applicability of the proposed approach. However, the application of the framework is illustrated on a case in non-interconnected areas; the approach is applicable to other energy systems and regions.

1. Introduction

In Colombian, non-interconnected areas (NIA) are located in isolated places; cover almost 66% of the national territory with 16 departments, 91 tows and 2 million people (Castro and Hernández, 2010). In addition, these zones do not have appropriate access routes, lack industrial and commercial development, public services are limited and undeveloped, and the people's basic needs are unsatisfied (Rosso-Cerón et al., 2015).

To supply the lack of electricity in NIA of Colombia have been established solutions with diesel generation, which are not sustainable in the long term (Silva and Nakata, 2009). Therefore, the implementation of renewable energy systems (RES) for power generation in situ has been presented as a solution for the people who do not have this service in developing countries (Zerriff, 2010). Nevertheless, the decision about choosing energetic alternatives for power supply in isolated communities has traditionally been based on technical and economic criteria, leaving behind environmental and social issues which complement the conception of sustainability. In addition, there are very practical barriers such as the availability of data, the measurement of the social dimension of sustainability, and the consensus on the energy planning procedure by several stakeholders.

In this perspective, multicriteria decision-making approach seems to be the most appropriate tool to understand all the different viewpoints involved with the energy planning process by creating a set of relationships between several alternatives trough sustainable criteria (Zeng, et al., 2007). In this sense several studies have been developed (Wimmler, et al., 2015), however most of them consider separated generation units/ technologies and leaving out the mixture of these units to give reliability and security to the system in the long term.

On the other hand, it is relatively difficult for the experts provide exact numerical values for the criteria, since most of the evaluation parameters cannot be given precisely and the evaluation data of each energetic alternative are usually expressed in linguistic terms by the experts. To model this kind of uncertainty in human preferences, fuzzy logic is applied very successfully (Kahraman and Kaya, 2010).

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In a previous work (Rosso-Cerón, et al., 2016), a spatial fuzzy multi-objective mixed integer long-term planning model was developed to meet the expected electricity demand for ten periods (2015-2024) in NIA. The model´s objectives were to minimise the total power system cost and the CO_2 emissions and took into consideration design, operational, and efficiency constraints for archiving a set of 11 alternatives of power generation (Pareto front) between generations units of solar photovoltaic (SolarPV), gasification of residual biomass (BioGen), wind generators (WindGen), small hydro (SmallHydro), grid extension, and the current diesel engines (DiselGen).
Based on the above, in this work a fuzzy logic decision support system is suggested to assess the most appropriate long planning alternative between the 11 alternatives (Pareto front). The proposed assessment incorporates a hierarchy of factors (criteria, sub-criteria and alternatives), where in the first level are 4 criteria (implementation time-C1, technological-C2, environmental-C3, and social-C4) and in the second level are 10 sub- criteria.
These factors are evaluated trough nine-expert's (market, governmental, education and research sectors energy) with a Delphi survey due to it has been widely used for technology foresight studies, when long-term issues have to be assessed, there is no empirical database, or the social arguments may dominate economic or technical considerations. It is point out that Delphi is not intended to produce statistically significant results but it achieves a degree of convergence among the expert's opinion (Joint Research Centre, 2006).
In addition, the experts take into account a miscellany of the factors and interrelationships among them. Then, the qualitative characteristics and numerical scales (linguistic terms) of these factors are represented by fuzzy membership sets. This measures help in decision-making and are treated in a fuzzy inference system (FIS) developed especially for selecting the best alternative.
Finally, a real case concerning to San Andrés Island (North of the country) energy-planning demonstrates the applicability of the proposed support system for choosing the most sustainable option. The results indicate that the best option consists of 92.5% DiselGen (current installed capacity, 57574 kW) and 7.5% WindGen.

2. Fuzzy logic decision support system

In this section is described a decision making approach that involves the stages of the decision support system proposed, Figure 1.

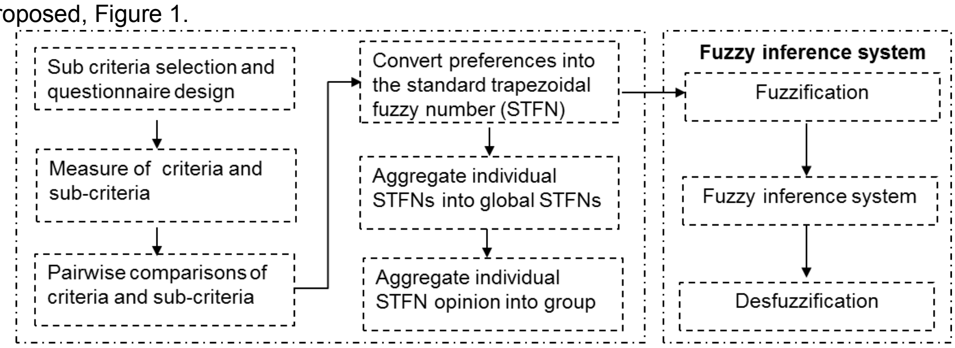

Figure 1: Fuzzy logic decision support system

2.1 Sub criteria selection and questionnaire design

The sub-criteria related to sustainable energy planning were selected from (Wimmler, et al., 2015, Parodi, 2013 and Wang, et al. 2009). These sub-criteria and the measuring scale are described below:
Efficiency: measures the amount of useful energy that can be obtained from a primary energy source, as always losses occur in the process of converting one form of energy to another, % of efficiency is always<100%.
(1) Unacceptable: efficiency <65% significant losses, very low competitiveness.
(2) Regular: 65% <efficiency <75%, acceptable if the process is improved, low competitiveness.
(3) Acceptable: 75% <efficiency <85% slight losses and competitiveness.
(4) Good: 85% <efficiency <95% values world-class energy efficiency and good competitiveness.
(5) Excellence Efficiency> 95% values world-class energy efficiency and excellent competitiveness.
Maturity measures the stage of development of the proposed technology. Technology has reached maturity when it has been used for such a time that their initial failures and technical, operational and commercial problems are overcome or reduced significantly: (1) Alternative obsolete; (2) Alternative tested only in the laboratory; (3) Alternative technically and operationally tested in a pilot plant; (4) Alternative tested under development; and (5) Alternative that has reached maturity.

Reliability: reflects whether the power supply is facing some kind of interruptions. The presence of such interruptions affects the stability of the power grid: (1) Unpredictable and not continuous operation; (2) Predictable, but not continuous operation; and (3) Predictable and continuous operation.
Access routes: refers to road connectivity with the level of accessibility that is based on the quality of existing roads and which determines the road coverage.
(1) No access or very complicated.
(2) Difficult access: pathways that despite not being paved, allow the movement of vehicles.
(3) Average access: Fluvial or maritime access due to the lack of road.
(4) Normal access: secondary road that allow mobility although they are not as fast like main roads.
(5) Good access: Main roads that allow entry and exit of vehicles and connection with other smaller roads.
Implementation time: measures the time that has planned the implementation of the alternative from government policies: (1) Short term (1-4 years); (2) Medium term (4-7 years); and (3) Long-term (7-10 years).
Pollutant residues: measures these categories: I. Emissions to the atmosphere, mainly due to the combustion process (NOx, CO, SO_2 and particulate matter). II. Liquid wastes, associated with by-products for the treatment of fumes or process water. III. Solid waste generated during the lifecycle of the actions.
(1) High level: all each category is relevant.
(2) High level: at least two of the categories are relevant.
(3) Average level: at least one category is relevant.
(4) Low level: all categories are negligible or zero.
Land required: represents the use of land directly affects the environment and landscape, as these lands could have been used for other community benefits.(1) Land requirements are high and there is a significant alteration of the landscape that limit socio-economic growth of the area; (2) Land requirements are high and there is a significant alteration of the landscape but have no effect on future socio-economic growth of the area; (3) Land requirements and alteration of the landscape are average; (4) Land requirements and alteration of the landscape are low; and (5) No land requirements or alteration of the landscape. .
Habitat impact: represents the rate of intervention of technology in the natural environment, causing impact on the following aspects (I) flora, (II) wildlife, (III) the noise level, and (IV) visual pollution: (1) Very high intensity on all the aspects; (2) High intensity on three of the aspects; (3) Medium intensity on two of the aspects; (4) Low intensity on one of the aspects; and (5) Zero impact or very low intensity.
Job creation: measures the number of direct and indirect jobs created during the life cycle of the power plant. Direct jobs are those established during construction, operation and maintenance of the plant; and indirect jobs are all created above or below the supply chain. (1) Very low employment, only in the installation process; (2) Low level of employment, only during maintenance; (3) Medium level of employment during installation, O&M (operation and maintenance); (4) High level of employment during installation, but average during O&M, (5) Very high level of employment, during installation, O&M.
Social acceptance: measures the acceptance level of the power device by local community, socio-political and market actors, which opinion is important for the implementation of the project: (1) Low acceptance; (2) Medium acceptance; and (3) High acceptance.
With this information, a Delphi questionnaire was designed to provide useful information for assessing generation units in two rounds. The first round was used to obtain an initial list of generation units with better prospects of viability from expert judgment. In the second round, the alternatives and the answers were validated for avoiding contradictions and achieving convergence in the opinions.
The experts were selected from a previous project database from the area of renewable energy and they were required to provide via e-mail their judgments based on their knowledge and expertise for each factor.

2.2 Measure of criteria and sub-criteria

The criteria and sub-criteria were assessed using linguistic terms according to a particular scale associate with each of them. In the case of implantation time, the number of years for installing a new capacity was considered from eleven alternatives of the Pareto front. These values, in years, were normalized between 0 and 1 (1 year = 0.9, 2 years = 0.2, etc.).

2.3 Pair-wise comparisons of criteria and sub-criteria

Due to the fact that the approach requires the importance of each factor; the experts were required to compare every factor pair-wise in their corresponding section (criteria or sub-criteria). A 1–9 scale (Saaty, 1990) was employed to classify the pair-wise comparison and obtain the corresponding weight a: $a_1 + a_2 + . . . + a_k = 1$.

2.4 Convert preferences into the STFNs

Linguistic terms preferences were standardized into a scale from 0 to 10 represented by a STFN. A STFN can be denoted by a 4-tuple (a_1, a_2, a_3, a_4) where a1 ≤ a2 ≤ a3 ≤ a4 or like a triangular fuzzy number when $a_2 = a_3$. With this information data matrix (SC_{ik}) for the Delphi method was constructed by using the approach of Zeng, et al., (2007), where rows and columns are the value given by the expert i for sub-criteria k.

2.5 Aggregate individual STFNs into global STFNs

It was used an operator to aggregate the individual sub criteria made by individual expert into a global STFNs for each criterion (social, environmental, and technological). According to the hierarchy factors, the global value by the expert i for generation unit n can be represented as:

$C_{in} = \frac{\sum_k^K a_k SC_{ik}}{10}$, where k is the number of sub criteria and *a* is its corresponding weight (1)

2.6 Aggregate individual STFN opinion into group

It was used an operator of Hsu and Chen, (1996) to add individual preferences made by individual expert into a group preference of each criterion. The degree of agreement between the experts was determined by the intersection of fuzzy numbers and it denotes the consistent area between experts as follows:

$$S(C_{in}, C_{jn}) = \frac{\int_x \min(\{\mu_{Cin}, \mu_{Cjn}\})dx}{\int_x \max(\{\mu_{Cin}, \mu_{Cjn}\})dx} \quad (2)$$

Where the degree of agreement between the expert $S_{ij} = S(C_{in}, C_{jn})$, are the elements of an agreement matrix and the diagonal elements are the unity. If two experts have the same estimates, that is, if $C_{in}=C_{jn}$, then S (C_{in}, C_{jn}) = 1. In other words, the two expert's estimates are consistent, and then the agreement degree between them is 1. If two experts have different estimates, then the agreement degree is 1.
Due to the fact that the main target of this methodology is to assess the alternatives understood as a combination of generation units, a global index for alternative p is proposed:

$$C_p = \sum_n^N f_{np} C_n \quad (3)$$

Where f_{np} is the portion of energy generated from the generation unit n in the p-th alternative.

2.7 Fuzzy Inference System

The FIS provides an effective tool to deal with imprecise and vague information associated with energy systems (Kahraman and Kaya, 2010). The first step in the FIS is to establish a base knowledge given by an expert in the problem at question. Thus, it is necessary to define the shape and range of the labels of all variables in vague terms. The design process of the FIS system consisted of three steps:
Fuzzification: three global indexes were converted into trapezoidal fuzzy sets, Figure 3. These values are fuzzy membership levels of input values to different fuzzy sets in which the universe of discourse is divided into different input variables to the system.

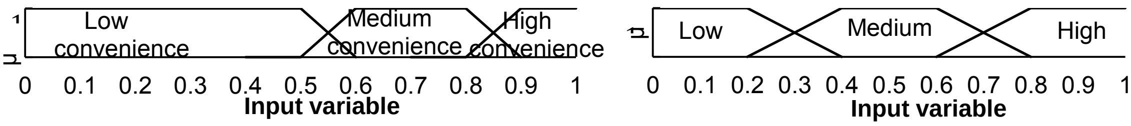

Figure 3: Membership function of the input variable C1 and the input variables C2*, C3*, C4*, respectively.*

Fuzzy inference: according to the different levels of membership from the fuzzification, they were processed to generate a fuzzy output. The task of the inference system is to take the membership levels supported on the rule base to generate the output of the fuzzy system.
The relations between input variables (C1*, C2*, C3*, C4*) and output (Out*) are presented in a form of if-then rules. Rule base are the way for the fuzzy system to keep the linguistic knowledge that solves the problem for which it has been designed. In this work, the l-th rule has three parts in the premise: Rule^l: If C1* is μ^l_{C1*} and C2* is μ^l_{C2*} and C3* is μ^l_{C3*} and C4* is μ^l_{C4*} then Out* is μ^l_{Out*}. Where μ^l_{C1*}, μ^l_{C2*}, μ^l_{C3*}, and μ^l_{Out*} denotes the membership functions of C1*, C2*, C3*, C4*, and Out*, respectively; R^l, l= 1, 2… L, is the l-th rule in the rule base. In this way, each of the four input variables was assigned with one of the three membership labels (Low, Medium and High) from the consensus of experts. The four parts in the premise were connected with "and" and the firing strength μ_R^l of fuzzy Rule R^l were obtained by using fuzzy intersection (minimum) operation. Therefore, there were a total of 81 rules for each possible combination of labels.

-Defuzzification: as the output of the FIS is a fuzzy set, defuzzification was used to convert the fuzzy result into a matching numerical value that could adequately represent Out*. The Centre-average method was employed for defuzzification:

$$\mathrm{Out} = \frac{\sum_{q=1}^{Q} Y_q \mu_{Out^*}(y_q)}{\sum_{q=1}^{Q} \mu_{Out^*}(y_q)},\ q=1,2,\ldots,Q \qquad (4)$$

Where y_q denotes the centre of the i-th fuzzy term set of Out*, and μOut (y_q) denotes the membership function of the q-th fuzzy term set of Out*. The output variable was written with four levels of membership (level of sustainability), as is illustrated in Figure 4.
Finally, the fuzzy logic toolbox from Matlab (version 7.10.0) was applied to solve this problem.

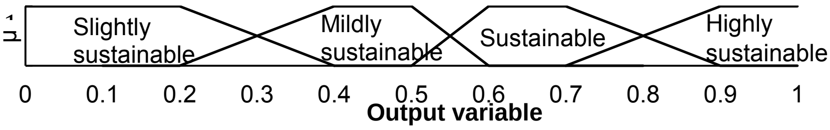

Figure 4: Membership function of the Output variable

3. Results and analysis of the application case

The standardized expert's opinion for the first level in the hierarchy is presented in Table 1. However, it was not possible to indicate a trend about the best generation unit with the separate experts' opinion, thus the aggregate expert's opinion was obtained by Eq. (2) and is presented in Table 2. According to the findings, the SolarPV was selected as the most suitable alternative with respect to the environmental level due to low emissions and pollutant residues, but the lowest score in the sub-criteria of efficiency and reliability. With respect to the technological criterion the most suitable alternative is the DiselGen as a result of the high levels of reliable and maturity, and finally for the social criterion the best alternative is the WindGen with high social acceptance.

Table 1: Standardized expert's opinion (E) per criteria and generation unit

Generation Unit	Criteria	E1	E2	E3	E4	E5	E6	E7	E8	E9
SolarPV	C2*	0.49	0.58	0.58	0.69	0.61	0.71	0.58	0.49	0.58
	C3*	0.81	0.75	0.74	0.71	0.87	0.94	0.71	0.81	0.68
	C4*	0.38	0.55	0.58	0.38	0.51	0.35	0.51	0.58	0.48
WindGen	C2*	0.54	0.66	0.82	0.76	0.65	0.64	0.74	0.54	0.82
	C3*	0.81	0.75	0.68	0.68	0.68	0.84	0.58	0.90	0.65
	C4*	0.75	0.75	0.88	0.75	0.88	0.75	0.64	0.63	0.76
DiselGen	C2*	0.75	0.75	0.68	0.79	0.91	0.86	0.91	0.86	0.91
	C3*	0.38	0.55	0.58	0.38	0.51	0.35	0.51	0.58	0.48
	C4*	0.62	0.75	0.87	0.87	0.75	0.63	0.63	0.49	0.49

Table 2: Aggregate expert's opinion per generation unit

Generation Unit/Criteria	C2*	C3*	C4*
SolarPV	0.59	0.76	0.67
WindGen	0.68	0.73	0.75
DiselGen	0.82	0.48	0.67

The input data for the fuzzy inference system are shown in the Table 3. Despite the minimal difference between the input values of the alternatives, e.g. C1* and C2*, the FIS led to obtain the ranking (or level of sustainability) of the eleven alternatives (A) from Rosso-Ceron et al., (2016) as:A5>A7>A10>A9>A8>A11>A4>A6>A3>A2>A1.

Table 3: Aggregate opinion per alternative

Criteria	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11
C1*	0.300	0.500	0.900	0.900	0.854	0.900	0.850	0.873	0.868	0.854	0.853
C2*	0.820	0.818	0.817	0.815	0.813	0.809	0.810	0.805	0.803	0.799	0.797
C3*	0.480	0.483	0.486	0.489	0.493	0.497	0.499	0.503	0.506	0.510	0.513
C4*	0.670	0.671	0.672	0.673	0.674	0.673	0.676	0.675	0.676	0.674	0.675

A5 was selected the most suitable alternative as it is the mixture of energy to give reliability, security and sustainability to the system in San Andres, Figure 3. A5 is equivalent to installing 9063 kW of WindGen that would begin to operate from 2017. This amount represents approximately 4% of the San Andres energy matrix which would depend on 96% of the diesel. These results are in agreement with the plans of the electric company of San Andres that in the future wiil set up wind plants without the disintalation of the current disel plants due to economic aspects and limits of land.

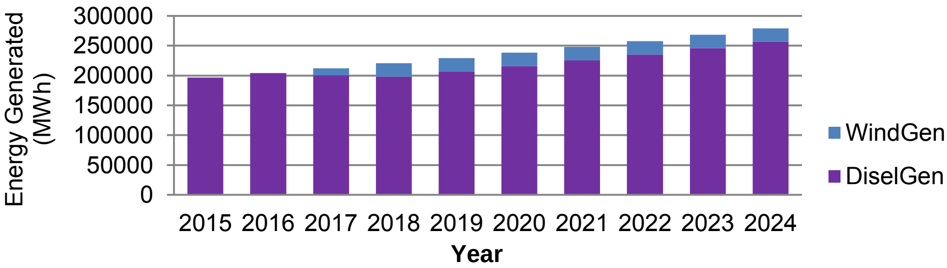

Figure 3: Energy generated with A7 throughout the planning horizon

4. Conclusions

A multi-criteria assessment method based of fuzzy logic was implemented to obtain the best alternative from the Pareto front of Rosso-Cerón, et al., (2016) and illustrate the complexity of decision making in the energy sector, where there are multiple sustainability criteria and different preferences for each. Although the above, the proposed approach is an efficient tool for facilitating the decision about choosing an appropriate alternative for energy generation. A real case of study concerning to San Andrés energy-planning problem demonstrated the applicability of the proposed approach. The assessment of the sustainable alternatives (mixture of energy systems) was based on following criteria: implementation time, environment, social and technological, including also the determination of weight factors. The results indicate that the best option is the generation with a mixture of 96% diesel generators and 4% wind turbines.

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