International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2022, 12(5), 79-87.

Decision-Making Support Framework for Electricity Supply in Non-Interconnected Rural Areas Based on FAHP

Christian Moreno[1], Adalberto Ospino-Castro[1]*, Carlos Robles-Algarín[2]*

[1]Universidad de la Costa, Barranquilla, Colombia, [2]Universidad del Magdalena, Santa Marta, Colombia.
*Email: croblesa@unimagdalena.edu.co

Received: 15 February 2022 **Accepted:** 23 July 2022 **DOI:** https://doi.org/10.32479/ijeep.12913

ABSTRACT

The implementation of electrification programs in non-interconnected rural areas in Colombia is a challenge for the country in order to reduce the social gap in these regions. This task is responsibility of the mining and energy planning unit, which has as challenges the implementation of renewable energy projects that allow diversifying the national energy matrix. For this reason, this paper proposes a support framework for multicriteria decision-making in the electricity supply of non-interconnected rural areas for the Colombian Caribbean Region. The multicriteria method of the fuzzy analytical hierarchical process was used, which allows the incorporation of a fuzzy triangular scale to improve the imprecision in the judgments made by experts. A hierarchical structure with 6 renewable energy alternatives, 4 criteria and 16 sub-criteria was designed, which allowed the implementation of a paired comparison survey that was answered by 10 experts from the region. The results obtained show the relevance of all alternatives, which is evidenced by a percentage difference of less than 5% between all the options. The best alternative was solar PV (20.27%). Regarding the criteria, the most relevant were economic (39.6%) and environmental (30.8%). The most relevant sub-criterion was the renewable fraction, related to the possible reuse of equipment (20.2%).

Keywords: Decision-Making, Fuzzy Analytical Hierarchical Process, Renewable Energy, Energy Planning
JEL Classifications: Q20, Q42, D70, D81

1. INTRODUCTION

Electric power is a vital service for the development and evolution of a country, becoming an essential element for most industrial activities worldwide and to guarantee people's quality of life. In a developing country like Colombia, there is great interest in increasing the coverage and supply of energy in a sustainable way, a context in which renewable energies play a fundamental role in diversifying the country's energy matrix (Pérez et al., 2019).

Renewable energies can be implemented in rural environments, non-interconnected areas and even urban environments where there is no electrical service, or it is of poor quality. The objective of these renewable technologies is to reduce energy consumption originating from conventional sources that have a negative impact on the environment. In Colombia, according to studies performed by the mining and energy planning unit (UPME), in a large part of rural areas, especially in the Caribbean Region, there is the potential to implement solutions for the supply of energy in the fields of biomass, photovoltaic, wind and small hydro-power (UPME, 2020; Castro, 2010; Muñoz et al., 2014).

The Caribbean Region is located in the northern part of Colombia (9.5355°N, 74.2179°W), and is mainly composed of continental plains. This region has large rural areas distributed in the departments of Atlántico, Bolívar, Magdalena, César, Córdoba, Sucre and Guajira, in which a great potential for the implementation of renewable energy projects stands out, but there are also many problems for access to a quality energy service that helps cover the basic needs of rural populations (UPME, 2015). In this scenario, rural energization projects become relevant, which, through proper planning, allow solving energy access problems.

The energy planning process to energize non-interconnected rural areas must consider the social and environmental relevance of the projects, as well as the implementation of policies aimed at obtaining local knowledge about renewable energies (Robles-Algarín et al., 2018). Rural areas, being generally remote communities, require the existence of local knowledge that is trained to perform preventive maintenance, updating and repair of equipment. Logically, the economic and technical aspects of the different viable energy alternatives for the area under study must also be considered.

However, the planning, evaluation and selection of energy alternatives for an appropriate investment is a complex decision, since it involves many dimensions that are difficult to address without a structured plan (Alizadeh et al., 2020; Ospino-Castro et al., 2017). Decision-making is a process inherent to human nature, which becomes complex when it is necessary to consider more criteria in the decision process. In this context, methods for multi-criteria decision making become important, since these methods allow different dimensions to be integrated into a decision problem (Kandakoglu et al., 2019; Nuriyev, 2021).

Considering the above context, this paper presents a support framework as a tool for energy planning in non-interconnected rural areas of the Colombian Caribbean Region. For this, the multicriteria decision tool of the fuzzy analytical hierarchical process (FAHP) was used, which results in a hierarchical structure composed of criteria, sub-criteria and energization alternatives for the area under study. The use of the FAHP is presented as a novelty in this type of work applied to the Caribbean region, since it allows the use of multiple criteria and the incorporation of a fuzzy triangular scale to mitigate the subjectivity of expert judgments (Vinogradova-Zinkevič et al., 2021).

In the literature, there are publications that show the importance of multicriteria tools in solving energy planning problems. Awad and Jung (2022) implemented the AHP for urban energy planning in Dubai, where environmental and economic criteria were the most important for decision-making. Jusakulvijit et al. (2021) used the Delphi-AHP technique to prioritize a set of criteria in the second-generation bioethanol development process. Günen (2021) established a support framework based on GIS-AHP for the installation of solar farms in Turkey, obtaining as a result the suitable areas for the implementation of PV projects. In general, there are numerous studies that make use of these multi-criteria tools in the field of renewable energies in order to prioritize criteria and solution alternatives for electrification projects that are sustainable over time, where we can mention those performed by Seker and Kahraman (2021); Ossei-Bremang and Kemausuor (2021); Saraswat and Digalwar (2021); Ulewicz et al. (2021) and Algarín et al. (2017).

This paper is organized into three sections. The FAHP method is first presented, for which a comparison is made with the standard AHP method. Next, the materials and methods are presented, where the selection criteria and alternatives are detailed, as well as the methodology implemented in the investigation. Finally, the main results obtained and the conclusions are shown.

2. AHP AND FAHP

The AHP is a method for decision-making, proposed by Saaty in 1980, used to solve selection problems with multiple criteria. The main characteristic of this method is that a hierarchical structure is proposed, in which the problem to be solved is located at the top and at the bottom are the solution alternatives. In the intermediate stages, the hierarchical criteria that are the basis for decision-making are established.

To implement the AHP it is necessary to construct a set of pairwise comparison matrices in which each element in a higher level is used to compare the elements in the immediately lower level. These comparisons are made through preference relations (for the alternatives) and importance relations (for the criteria), which are evaluated through a numerical scale with integer values between 1 and 9.

The advantages of the AHP method can be summarized as follows:
1. Includes a mathematical support
2. Allows breaking down complex problems to analyze them by parts using paired comparisons
3. Allows the use of quantitative and qualitative criteria
4. Includes the participation of experts with different interests to reach a consensus.

However, the method also has some disadvantages reported by the researchers, among which the existence of a fixed measurement scale that can affect the judgment given by the respondent stands out (Canco et al., 2021).

In this context, the FAHP method arises, which is a variant of the AHP originally proposed by Saaty. In the FAHP method, the traditional numerical scale is replaced by a fuzzy triangular scale, which improves the imprecision in the judgments made by the experts in the decision-making process. With the application of fuzzy logic, the imprecision and subjectivity of human judgments are improved, since this technique can represent imprecise data. With the FAHP, a range of values is implemented that allows incorporating the uncertainty of the decision maker, using fuzzy triangular numbers according to the scale shown in Table 1 (Vinogradova-Zinkevič et al., 2021; Papaioannou et al., 2015).

Table 1: AHP and FAHP scales

AHP scale	Importance scale	FAHP scale	FAHP reciprocal scale
1	Equally important	(1,1,1)	(1,1,1)
2	Intermediate 1	(1,2,3)	(1/3,1/2,1)
3	Moderately more important	(2,3,4)	(1/4,1/3,1/2)
4	Intermediate 2	(3,4,5)	(1/5,1/4,1/3)
5	Strongly more important	(4,5,6)	(1/6,1/5,1/4)
6	Intermediate 3	(5,6,7)	(1/7,1/6,1/5)
7	Very strongly more important	(6,7,8)	(1/8,1/7,1/6)
8	Intermediate 4	(7,8,9)	(1/9,1/8,1/7)
9	Absolutely more important	(9,9,9)	(1/9,1/9,1/9)

The stages to implement the FAHP can be summarized as follows (Parra-Calderon et al., 2019):

a. Make paired comparisons between the criteria, sub-criteria and alternatives, using the scales shown in Table 1 for the FAHP. With this, a fuzzy comparison matrix is obtained (Eq. 1). Each element of this matrix is a triangular fuzzy number resulting from the comparison between pairs.

$$\tilde{D}^K = \begin{bmatrix} \tilde{d}_{11}^k & \tilde{d}_{12}^k & \dots & \tilde{d}_{1n}^k \\ \tilde{d}_{21}^k & \tilde{d}_{22}^k & \dots & \tilde{d}_{2n}^k \\ \dots & \dots & \dots & \dots \\ \tilde{d}_{n1}^k & \tilde{d}_{n2}^k & \dots & \tilde{d}_{nn}^k \end{bmatrix} \quad (1)$$

b. When several experts are consulted in the process of paired comparisons, as is the case in this study, the judgments are averaged using Eq. 2, where k represents the number of experts consulted. Thus, a new fuzzy matrix is obtained that incorporates the judgments of all the experts consulted (Eq. 3).

$$\tilde{d}_{ij} = \sqrt[k]{\tilde{d}_{ij}^1 \times \tilde{d}_{ij}^2 \times \dots \times \tilde{d}_{ij}^k} \quad (2)$$

$$\tilde{D} = \begin{bmatrix} \tilde{d}_{11} & \cdots & \tilde{d}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{d}_{n1} & \cdots & \tilde{d}_{nn} \end{bmatrix} \quad (3)$$

c. Calculate the fuzzy comparison values, for which the geometric mean is used (Eq. 4). With this, a new matrix of consolidated fuzzy values is obtained.

$$\tilde{r}_i = \left(\prod_{j=1}^{n} \tilde{d}_{ij} \right)^{1/n} \quad (4)$$

d. The next step is to calculate the relative fuzzy weights, multiplying their respective fuzzy comparison value by the inverse of the total obtained (Eq. 5).

$$\tilde{w}_i = \tilde{r}_i \times (\tilde{r}_1 + \tilde{r}_2 + \dots + \tilde{r}_n)^{-1} = (lw_i, mw_i, uw_i) \quad (5)$$

e. Subsequently, the priority vector is calculated, which represents the normalized values for the terms of each of the relative weights. The average of each fuzzy weight is calculated using Eq. 6, and then is normalized using Eq. 7.

$$M_i = \frac{(lw_i + mw_i + uw_i)}{3} \quad (6)$$

$$N_i = \frac{M_i}{\sum_{i=1}^{n} M_i} \quad (7)$$

f. Calculate the Consistency Ratio (RC). This has the purpose of measuring the degree of consistency for each expert. An expert is considered to be consistent when the value of RC≤0.1. To find RC the fuzzy matrices must be converted to real numbers. A fuzzy triangular number (l, m, u), is converted into a real number with Eq. 8, which is known as the defuzzification process.

$$M_{real} = \frac{(4m + l + u)}{6} \quad (8)$$

With the matrix of real numbers and the priority vectors, the RC calculation is performed with the same procedure established for the traditional AHP (Eq. 9). Random consistency index (RI) values are defined in Algarín et al. (2017).

$$CI = \frac{\lambda_{max} - 1}{n - 1}, \; CR = \frac{CI}{RI} \quad (9)$$

3. MATERIALS AND METHODS

The purpose of this study is to weigh and prioritize the criteria, sub-criteria and alternatives to be taken into account for energy planning projects with an emphasis on rural areas of the Colombian Caribbean Region. This way, a descriptive investigation was performed with a field design that allowed the assessment of experts to weigh and prioritize the criteria and sub-criteria, and select the best alternative. The FAHP has been proposed as a method for weighting and ranking, in order to ensure accuracy and mitigate the degree of subjectivity of the judgments issued by the experts.

3.1. Renewable Energy Alternatives

For the selection of the different alternatives proposed in this research, the potential to implement renewable energies in the area under study, the experience of the authors and the bibliographic review of scientific articles related to energy planning decision-making were considered (UPME, 2020; Muñoz et al., 2014; Jusakulvijit et al., 2021). Six renewable technologies were identified that can be used in the selected rural area and the surrounding non-interconnected areas: Solar PV (A1), Wind (A2), Biogas Digester (A3), Landfill Biogas (A4), Waste Incineration (A5) and Solar Collectors (A6).

- Solar PV (A1): this alternative considers the generation of energy from solar radiation using PV modules
- Wind (A2): this alternative contemplates the generation of electrical energy from the wind resources available in the area, with the use of wind turbines
- Biogas Digester (A3): this alternative considers the use of biodigesters or hermetic containers with a biogas collection and storage system for its use as electric energy. In this process occurs the phenomenon of decomposition by anaerobic microorganisms that produce biogas. Thus, this option contemplates generation from local waste produced directly in rural areas
- Landfill Biogas (A4): this alternative is based on the combustion of gases generated by the decomposition of trash to produce electricity. The biogas is a combustible gas that is obtained as a result of the degassing of the landfill. Therefore, this option contemplates the generation of energy from large trash landfill near the rural areas under study
- Waste Incineration (A5): consists of the generation of energy from the incineration of waste such as metals, glass and

organic matter, which allows the generation of steam to drive electricity generation turbines
- Solar Collectors (A6): this alternative considers the generation of solar thermal energy by taking advantage of the sun's rays with solar collectors, in this way usable heat is generated for cooking, hot water production and the generation of electrical energy from mechanical energy.

3.2. Criteria and Sub-criteria

For the selection of criteria and sub-criteria, the same aspects used in the selection of alternatives were considered, based on the bibliographic review and experience of the authors (Ulewicz et al., 2021; Robles-Algarín et al., 2018; Awad and Jung, 2022; Algarín et al., 2017). Thus, 4 criteria and 16 sub-criteria were defined, which allowed the implementation of paired comparisons with the FAHP. Next, all the criteria are detailed individually and each associated sub-criterion.

Criteria: Social (C1), Economic (C2), Environmental (C3) and Technical (C4).

Social sub-criteria: Social Acceptance (C1.1), Employment Generation (C1.2), Territory Availability (C1.3), Resources Availability (C1.4), Vandalism (C1.5).

Economic sub-criteria: Initial Capital (C2.1), Operation and Maintenance Costs (C2.2), Net Present Value (C2.3), Cost of Electricity Generation (C2.4).

Environmental sub-criteria: Renewable Fraction (C3.1), Carbon Footprint (C3.2), Ecosystem Impact (C3.3).

Technical sub-criteria: Efficiency (C4.1), Reliability (C4.2), Source Availability (C4.3), Technology Maturity (C4.4)
- Social Acceptance (C1.1): This sub-criterion is important when evaluating technologies, since it considers the degree of acceptability that the population has with the installation of renewable technologies
- Employment Generation (C1.2): Implementing a renewable energy generation project requires the intervention of a varied workforce. The intervention of this workforce is essential to complete the phases of the project, from planning, execution and finally to operation. This criterion considers the generation of employment for local personnel in the area under study
- Territory Availability (C1.3): The extraction of energy from some renewable resource is not an easy task, many technologies require large land for their implementation. This criterion considers the availability of suitable land for the implementation of projects and possible obstacles
- Resources Availability (C1.4): It must be understood that each region is a totally independent geographical area. Therefore, this criterion considers the need to have suitable areas for the implementation of the renewable energy alternatives considered
- Vandalism (C1.5): This factor is decisive on many occasions when developing a civil project in our national territory. The presence of illegal armed groups must be studied and the impact that this may have on the implementation of the project in the area
- Initial Capital (C2.1): The initial investment includes the cost of the equipment and machinery necessary to start the project
- Operation and Maintenance Costs (C2.2): This sub-criterion includes the costs for the operation and maintenance of the equipment and machinery used in the energy project
- Net Present Value (C2.3): This is a financial indicator used to determine the viability of a project. After measuring the flows of future income and expenses and discounting the initial investment, the feasibility of the project is determined
- Cost of Electricity Generation (C2.4): In any energy project, the cost of the kW generated is very important. This data will determine the valuation of the project in the future, any variable that increases the cost of generation must be mitigated
- Renewable Fraction (C3.1): It refers to the amount of energy, equipment or products that once used can be reused in some other activity
- Carbon Footprint (C3.2): It is defined as the totality of greenhouse gases emitted by the renewable energy source
- Ecosystem Impact (C3.3): Refers to any change or alteration in the environment, due to human intervention. This impact on the ecosystem can be positive or negative, the negative represents a break in the ecological balance, causing serious damage to the environment, and the health of people and living beings. The positive impact implies the conservation and maintenance of the ecological balance of the area
- Efficiency (C4.1): Efficiency is defined as the useful energy that a system can extract from its energy source
- Reliability (C4.2): It is an important sub-criterion in the implementation of any energy project, and contemplates a continuous service with the best possible performance over time
- Source Availability (C4.3): To produce electricity it is necessary to have a primary source, which will depend on the natural resources available in the study area. The availability of a primary source defines whether or not a resource can be fully exploited to transform it into energy
- Technology Maturity (C4.4): It is vital to have a mature technology that ensures better performance in order to obtain great technical, economic and environmental benefits.

3.3. Hierarchical Structure

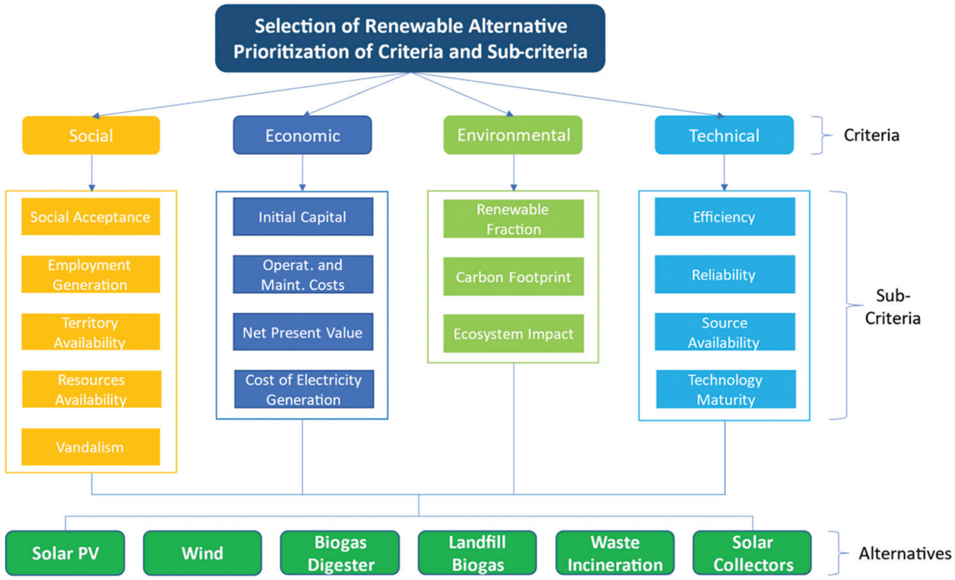
With the 6 alternatives, 4 criteria and 16 sub-criteria, the hierarchical structure for decision-making with the FAHP method was defined. Figure 1 shows each of the levels of the implemented structure.

3.4. Expert Judgments

The objective of this methodology is to analyze the criteria, sub-criteria and alternatives of a hierarchical structure, with the purpose of obtaining the judgments issued by each of the experts consulted, applying the FAHP.

For a successful decision-making process, it is necessary to have a group of experts on the subject to be evaluated. For this reason, in this research, 10 experts linked to at least one of the following areas in the Colombian Caribbean Region were consulted:

Figure 1: Hierarchical structure for decision making



(1) Employees of the renewable energy sector, (2) Research university professors with experience in energy planning projects, (3) Public or private employees with functions associated with the rational use of resources and energy planning projects, (4) Non-governmental organizations that protect the environment and (5) Organizations belonging to rural communities.

The experts were consulted via email with a form designed in the free version of the QuestionPro online program. A form with questions organized in a bipolar matrix was implemented, in which the expert selects the preferred relationship between two factors, using the fuzzy scale presented in Table 1.

Figure 2 shows an example of a matrix question implemented for the case of the six renewable energy sources considered in this study. This comparison was made considering the Initial Capital sub-criterion (C2.1). The expert could only check one box for each row of the matrix, in order to make the pairwise comparison. Depending on the box checked by the expert, the selected preference ratio is coded using the FAHP scale or FAHP reciprocal scale.

The information collected from the experts allows the construction of the paired comparison matrices with the fuzzy scale. Table 2 shows an example of the matrix implemented for the 4 criteria according to the responses of one (1) expert. With this information, the aggregation process is subsequently performed with all the experts consulted, and the FAHP is implemented according to the stages described in section 2.

4. RESULTS

The FAHP method, in addition to allowing the selection of the best renewable energy alternative, also provides an important contribution regarding the relative importance of the criteria and sub-criteria, which indicates the most relevant aspects to consider in the decision-making process, according the concepts of experts from different fields involved in energy planning projects.

Table 2: Comparison matrix between criteria

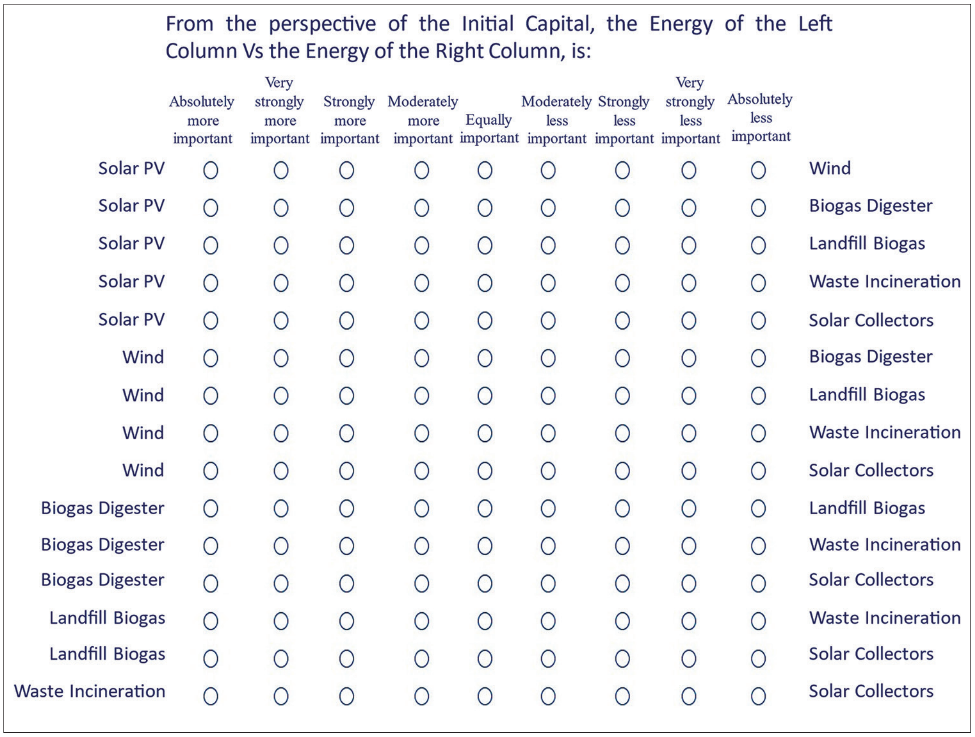
	Economic	Social	Environmental	Technical
Economic	1,1,1	2,3,4	2,3,4	1,1,1
Social	1/4,1/3,1/2	1,1,1	1/4,1/3,1/2	2,3,4
Environmental	1/4,1/3,1/2	2,3,4	1,1,1	1,1,1
Technical	1,1,1	1/4,1/3,1/2	1,1,1	1,1,1

It is important to mention that for all the paired comparison matrices we obtained a consistency ratio (RC) of <10%, which indicates that the experts consulted were consistent. This was achieved thanks to a work of awareness and explanation of the method to each of the experts, prior to the application of the survey. In this sense, it was not necessary to implement any consistency correction method in the data obtained.

The first important result obtained is shown in Figure 3, with the prioritization of the criteria. It can be seen that, according to the experts consulted, economic (39.6%) and environmental (30.8%) criteria are the most relevant for decision-making in energy planning in the Colombian Caribbean Region. The technical and social criteria are also relevant for the experts, although with a lower percentage value than the previous ones. These results demonstrate the importance in the selection of the criteria to be evaluated for decision-making, since the 4 criteria, some to a lesser extent, were considered relevant by the experts.

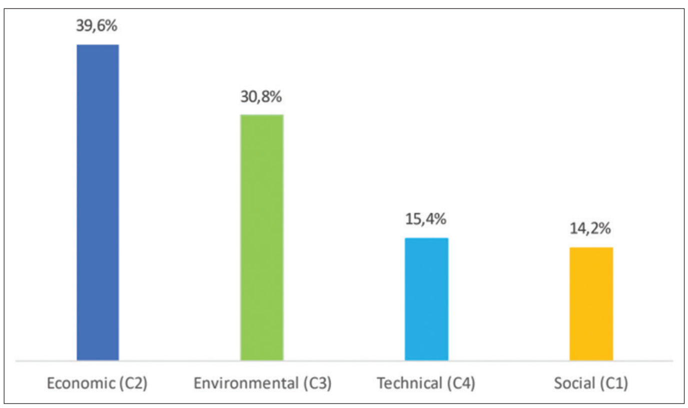
In relation to economic criteria, it is interesting that most experts consider operation and maintenance costs as the most relevant within this category, with 38.7%. Similarly, the cost of electricity generation (29.2%) and the initial capital (23.5%) resulted in a high percentage, which indicates their importance in the selection process (Figure 4a). Regarding the environmental criteria, the most relevant sub-criterion is the renewable fraction, with a great different from the other two criteria, which shows the importance that experts give to the possibility of using the equipment and materials in other types of complementary activity for the region. The assessment of the possible impact on the ecosystem of the

Figure 2: Example of bipolar matrix implemented in the survey of experts


From the perspective of the Initial Capital, the Energy of the Left Column Vs the Energy of the Right Column, is:

	Absolutely more important	Very strongly more important	Strongly more important	Moderately more important	Equally important	Moderately less important	Strongly less important	Very strongly less important	Absolutely less important	
Solar PV	○	○	○	○	○	○	○	○	○	Wind
Solar PV	○	○	○	○	○	○	○	○	○	Biogas Digester
Solar PV	○	○	○	○	○	○	○	○	○	Landfill Biogas
Solar PV	○	○	○	○	○	○	○	○	○	Waste Incineration
Solar PV	○	○	○	○	○	○	○	○	○	Solar Collectors
Wind	○	○	○	○	○	○	○	○	○	Biogas Digester
Wind	○	○	○	○	○	○	○	○	○	Landfill Biogas
Wind	○	○	○	○	○	○	○	○	○	Waste Incineration
Wind	○	○	○	○	○	○	○	○	○	Solar Collectors
Biogas Digester	○	○	○	○	○	○	○	○	○	Landfill Biogas
Biogas Digester	○	○	○	○	○	○	○	○	○	Waste Incineration
Biogas Digester	○	○	○	○	○	○	○	○	○	Solar Collectors
Landfill Biogas	○	○	○	○	○	○	○	○	○	Waste Incineration
Landfill Biogas	○	○	○	○	○	○	○	○	○	Solar Collectors
Waste Incineration	○	○	○	○	○	○	○	○	○	Solar Collectors

Figure 3: Criteria prioritization results



intervened area is also highlighted as an important aspect with 22.3%, due to the impact that this type of project can cause on the landscape (Figure 4b).

From the perspective of the technical criteria, the experts value the efficiency (36.2%) and reliability (33.7%) of the renewable system as the most relevant sub-criteria. To a lesser extent, the maturity of the technology (18.5%) and the availability of the renewable source in the study area (11.6%) are also considered important (Figure 5a). Finally, in the case of social criteria, the sub-criteria of local employment generation (34.8%), availability of resources with areas suitable for projects (24%) and acceptance by the community (20.5%) stand out (Figure 5b).

The FAHP method allows global prioritization of all the sub-criteria, making it possible to analyze the most relevant aspects to be considered in decision-making in a general way, by combining all the aspects according to their degree of relevance. These results are shown in Table 3, where it is observed that the renewable fraction environmental sub-criterion obtained the greatest relative weight (20.2%). In the following places, three economic sub-criteria stand out consecutively, which shows the importance that experts awarded this aspect.

In relation to the renewable energy alternatives in this study, the FAHP method allows selecting the most appropriate, and also ranking them globally according to the preferences obtained from the experts. To achieve the above, intermediate results are obtained with the prioritization of the alternatives according to the sub-criteria under study, which are derived from the social, economic, environmental and technical criteria.

Table 4 shows the prioritization obtained from the 6 alternatives with respect to the 5 social sub-criteria. It is shown that solar PV energy (A1) obtained the highest score in all the sub-criteria evaluated. In the case of wind energy (A2), it obtained second place with the highest score in the sub-criteria of social acceptance 26.4% (C1.1), employment generation 21.1% (C1.2) and vandalism (C1.5), while in the sub-criteria availability of territory (C1.3) and availability of resources (C1.4) it was displaced to the third place of preference by the alternative of solar collectors (A6). This situation reflects that, depending on the social sub-criterion to be evaluated, some alternatives vary their position in the partial ranking presented in Table 4.

When all the alternatives were compared with respect to the economic sub-criteria (Table 5), changes were noted with respect to the results shown in Table 4. In this case, it can be seen that solar PV energy (A1) only occupies the first place with respect to the initial capital (C2.1), since the waste incineration alternative (A5) has the highest percentage with respect to the operation and maintenance

Figure 4: Results of sub-criteria prioritization: (a) economic, (b) environmental

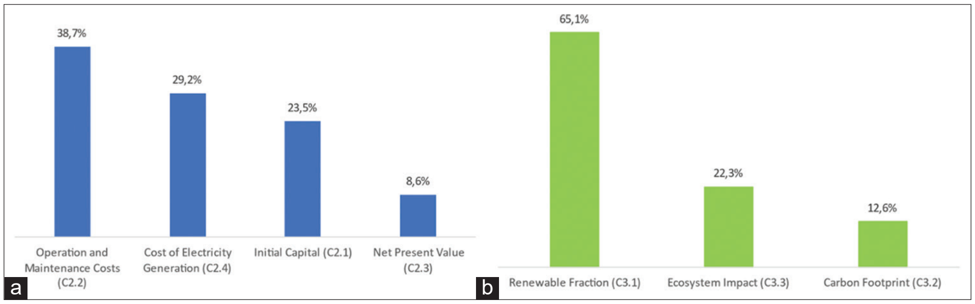


Figure 5: Results of sub-criteria prioritization: (a) technical, (b) social

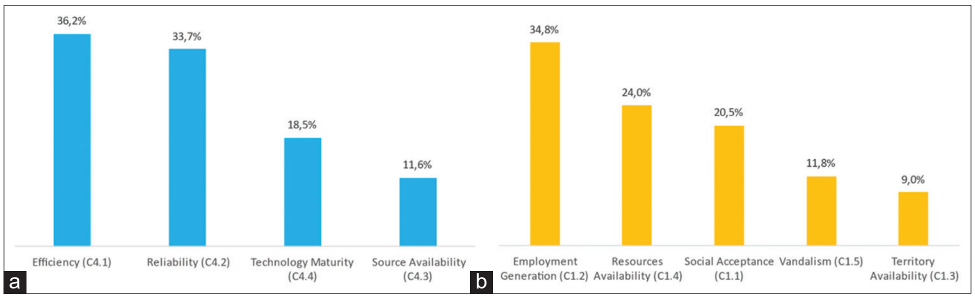


Table 3: Global weights of the sub-criteria

Sub-criteria	Global Weight (%)
Renewable fraction (C3.1)	20.2
Operation and maintenance costs (C2.2)	15.6
Cost of electricity generation (C2.4)	11.6
Initial capital (C2.1)	9.6
Ecosystem impact (C3.3)	6.8
Efficiency (C4.1)	5.4
Reliability (C4.2)	5.1
Employment generation (C1.2)	4.9
Carbon footprint (C3.2)	4.0
Net present value (C2.3)	3.6
Resources availability (C1.4)	3.4
Social acceptance (C1.1)	2.8
Technology maturity (C4.4)	2.7
Source availability (C4.3)	1.8
Vandalism (C1.5)	1.7
Territory availability (C1.3)	1.3

Table 4: Alternatives/social sub-criteria

Alternatives	C1.1 (%)	C1.2 (%)	C1.3 (%)	C1.4 (%)	C1.5 (%)
Solar PV (A1)	34.1	27.7	27.4	31.6	26.0
Wind (A2)	26.4	21.1	17.0	11.9	19.2
Biogas digester (A3)	9.6	14.0	11.2	11.0	13.0
Landfill biogas (A4)	9.8	12.0	11.2	10.9	13.8
Waste incineration (A5)	7.6	9.7	9.1	11.0	10.4
Solar collectors (A6)	12.4	15.6	24.0	23.5	17.6

C1.1: Social acceptance, C1.2: Employment generation, C1.3: Territory availability, C1.4: Resources availability, C1.5: Vandalism (C1.5)

Table 5: Alternatives/economic sub-criteria

Alternatives	C2.1 (%)	C2.2 (%)	C2.3 (%)	C2.4 (%)
Solar PV (A1)	26.6	5.5	6.0	4.7
Wind (A2)	24.7	6.1	15.2	12.9
Biogas digester (A3)	11.0	11.2	31.6	28.3
Landfill biogas (A4)	14.6	20.4	20.1	27.4
Waste incineration (A5)	4.5	34.9	8.6	17.2
Solar collectors (A6)	18.6	21.9	18.6	9.4

C2.1: Initial capital, C2.2: Operation and maintenance costs, C2.3: Net present value, C2.4: Cost of electricity generation

Table 6: Alternatives/enviromental sub-criteria

Alternatives	C3.1 (%)	C3.2 (%)	C3.3 (%)
Solar PV (A1)	34.1	17.3	6.4
Wind (A2)	26.4	26.3	7.4
Biogas digester (A3)	9.6	13.5	31.0
Landfill biogas (A4)	9.8	13.5	25.6
Waste incineration (A5)	7.6	18.6	11.0
Solar collectors (A6)	12.4	10.9	18.6

C3.1: Renewable fraction, C3.2: Carbon footprint, C3.3: Ecosystem impact

Table 7: Alternatives/technical sub-criteria

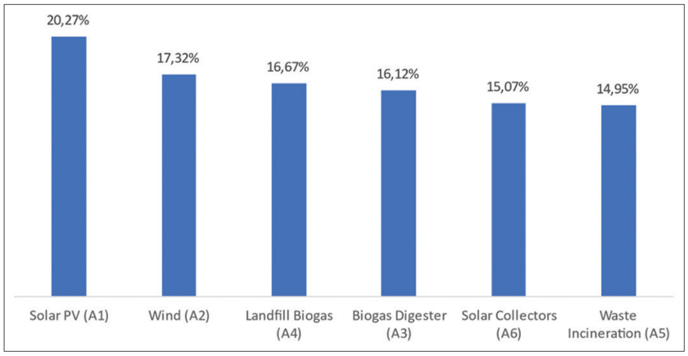
Alternatives	C4.1 (%)	C4.2 (%)	C4.3 (%)	C4.4 (%)
Solar PV (A1)	34.1	42.9	45.3	32.4
Wind (A2)	26.4	9.9	18.0	13.8
Biogas digester (A3)	9.6	18.0	14.5	13.5
Landfill biogas (A4)	9.8	14.3	9.3	13.8
Waste incineration (A5)	7.6	5.4	4.1	6.5
Solar collectors (A6)	12.4	9.5	8.9	20.1

C4.1: Efficiency, C4.2: Reliability, C4.3: Source availability, C4.4: Technology maturity

costs sub-criterion (C2.2). The biogas digester alternative obtained the highest percentages regarding the net present value (C2.3) and electricity generation costs (C2.4) sub-criteria.

From the environmental (Table 6) and technical (Table 7) approaches, the results are variable in the prioritization percentages obtained by the alternatives. For example, from the perspective of the impact on the ecosystem, the alternative with the highest value is the biogas digester 31% (A3). From the comparison of alternatives from the technical aspects, as happened

Figure 6: Global results for the prioritization of alternatives



with the social criteria, the PV solar energy alternative (A1) obtained the highest percentage for the 4 technical sub-criteria considered in the work.

The results presented in Tables 4-7 allowed an aggregation process to be performed to obtain a final global result regarding the ranking of the 6 renewable energies considered for energy projects in the Colombian Caribbean Region. Figure 6 shows the results obtained, where PV solar energy is presented as the best alternative to implement in the region, obtaining a percentage of 20.27%. It is noteworthy that the remaining 5 energies obtained percentages between 14.95% and 17.32%, with a percentage difference between them that does not exceed 3%, showing that all the alternatives are important for the energization processes in the area. This situation also reflects the good selection of renewable energy alternatives in the research, since all were well-valued by the experts.

5. CONCLUSIONS

After completing this investigation, we can conclude that multicriteria decision analysis is a powerful methodology that generates support frameworks for decision-making that require evaluating different alternatives according to individual criteria. We were able to verify that the FAHP is a multicriteria technique that complements the traditional AHP method, since it uses fuzzy logic for the paired comparison process with the aim of mitigating subjectivity in expert judgments.

In this context, it was transcendental to familiarize the experts with the FAHP method before answering the questions, which made it possible to obtain judgments with consistency ratios of <10%. The use of the questionnaire with bipolar matrices was also important since this facilitated the understanding of the methodology by the experts, for the subsequent implementation of FAHP.

The implementation of FAHP allowed prioritizing 6 renewable alternatives, 4 criteria and 16 sub-criteria to be considered in the energy planning processes of non-interconnected rural areas for the Colombian Caribbean Region. This way, a support framework for decision-making was obtained, considering economic, environmental, technical and social criteria, which, like the solution alternatives, were selected based on the particularities of the region under study.

REFERENCES

Algarín, C., Llanos, A., Castro, A. (2017), An analytic hierarchy process based approach for evaluating renewable energy sources. International Journal of Energy Economics and Policy, 7(4), 38-47.

Alizadeh, R., Soltanisehat, L., Lund, P., Zamanisabzi, H. (2020), Improving renewable energy policy planning and decision-making through a hybrid MCDM method. Energy Policy, 137, 111174.

Awad, J., Jung, C. (2022), Extracting the planning elements for sustainable urban regeneration in Dubai with AHP (Analytic hierarchy process). Sustainable Cities and Society, 76, 103496.

Canco, I., Kruja, D., Iancu, T. (2021), Ahp, a reliable method for quality decision making: A case study in business. Sustainability, 13(24), 13932.

Castro, A.J. (2010), Análisis del potencial energético solar en la región Caribe para el diseño de un sistema fotovoltaico. Inge CUC, 6(1), 95-102.

Günen, M. (2021), A comprehensive framework based on GIS-AHP for the installation of solar PV farms in Kahramanmaraş, Turkey. Renewable Energy, 178, 212-225.

Jusakulvijit, P., Bezama, A., Thrän, D. (2021), Criteria prioritization for the sustainable development of second-generation bioethanol in Thailand using the Delphi-AHP technique. Energy, Sustainability and Society, 11(1), 37.

Kandakoglu, A., Frini, A., Amor, S.B. (2019), Multicriteria decision making for sustainable development: A systematic review. Journal of Multi-Criteria Decision Analysis, 26(5-6), 202-251.

Muñoz, Y., Zafra, D., Acevedo, V., Ospino, A. (2014), Analysis of energy production with different photovoltaic technologies in the Colombian geography. International Congress of Mechanical Engineering and Agricultural Sciences, 59, 1-9.

Nuriyev, M. (2021), An integrated approach for renewable energy resource and plant location selection. International Journal of Energy Economics and Policy, 11(3), 64-72.

Ospino-Castro, A., Peña-Gallardo, R., Hernández-Rodríguez, A., Segundo-Ramírez, J., Muñoz-Maldonado, Y. (2017), Echno-Economic Evaluation of a Grid-Connected Hybrid PV-Wind Power Generation System in San Luis Potosi, Mexico. IEEE International Autumn Meeting on Power, Electronics and Computing (ROPEC). Ixtapa, Mexico: IEEE, pp. 1-6.

Ossei-Bremang, R., Kemausuor, F. (2021), A decision support system for the selection of sustainable biomass resources for bioenergy production. Environment Systems and Decisions, 41(3), 437-454.

Papaioannou, G., Vasiliades, L., Loukas, A. (2015), Multi-criteria analysis framework for potential flood prone areas mapping. Water Resources Management, 29(2), 399-418.

Parra-Calderón, C., Osorio-Gómez, J., Escandón-López, J. (2019), Metodología multicriterio para la selección de proveedores bajo consideraciones de riesgo. Scientia Et Technica, 24(2), 232-239.

Pérez, J., Vargas, C., Riaño, D. (2019), Colombia towards an electricity generation matrix using renewable energies. Renewable Energy and Power Quality Journal, 17, 224-228.

Robles-Algarín, C., Taborda-Giraldo, J. and Ospino-Castro, A. (2018). A procedure for criteria selection in the energy planning of Colombian rural areas. Informacion Tecnologica, 29(3), 71-80.

Saraswat, S., Digalwar, A. (2021), Evaluation of energy alternatives for sustainable development of energy sector in India: An integrated Shannon's entropy fuzzy multi-criteria decision approach. Renewable Energy, 171, 58-74.

Seker, S., Kahraman, C. (2021), Socio-economic evaluation model for sustainable solar PV panels using a novel integrated MCDM methodology: A case in Turkey. Socio-Economic Planning Sciences, 77, 100998.

Ulewicz, R., Siwiec, D., Pacana, A., Tutak, M., Brodny, J. (2021), Multi-criteria method for the selection of renewable energy sources in the polish industrial sector. Energies, 14(9), 2386.

UPME. (2015), Integración De Las Energías Renovables no Convencionales En Colombia. Colombia, UPME. Available from: https://www1.upme.gov.co/demandaenergetica/integracion_energias_renovanles_web.pdf

UPME. (2020). Plan Energético Nacional 2020-2050. Available from: https://www1.upme.gov.co/demandayeficiencia/documents/pen_2020_2050/plan_energetico_nacional_2020_2050.pdf

Vinogradova-Zinkevič, I., Podvezko, V., Zavadskas, E. (2021), Comparative assessment of the stability of ahp and fahp methods. Symmetry, 13(3), 479.