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(2), 111-119.

Implementation of the Hierarchical Analytical Process in the Selection of the Best Source of Renewable Energy in the Colombian Caribbean Region

Christian Manuel Moreno Rocha*, José Ricardo Nuñez Alvarez, Daniel A. Díaz Castillo, Esnaider D. Florian Domíngue, Juan Camilo Barrera Hernandez

Department of Energy, Universidad de la Costa (CUC), Barranquilla, Atlántico, Colombia. *Email: cmoreno7@cuc.edu.co

Received: 10 October 2021 **Accepted:** 05 January 2022 **DOI:** https://doi.org/10.32479/ijeep.12537

ABSTRACT

In this study, the Analytic Hierarchy Process methodology is implemented to provide decision criteria in the selection, planning, and development of electric power generation projects from renewable energy sources in the Caribbean region of Colombia. Six sources of renewable energy; biomass combustion; anaerobic digestion of biomass; biogas landfills; waste incineration; Photovoltaic energy and solar thermal radiation were considered in this study due to their energy potential in rural areas and areas not interconnected to the national electricity system. To determine the order of priority in the development of energy conversion technologies, a questionnaire was developed and sent to a group of experts. Given the need to generate electricity sustainably, the information was analyzed under four main criteria: technical, environmental, social, and economic. Sixteen additional sub-criteria were selected based on a literature review. In general, the economic criterion is the most relevant in the area due to the high investment and operating costs of electricity generation. The social criterion highlights the opportunity to create new jobs, while the environmental criterion highlights the component of substitution of renewable energy, a key aspect in the diversification of the energy matrix, which is part of the country's political agenda. Regarding the technological component, photovoltaic energy seems the most favorable due to its low environmental impact and the considerable reduction in prices experienced by the solar panel market in recent years.

Keywords: Hierarchical Analytical Process AHP, Renewable Energy, Decision Making, Multi-criteria
JEL Classifications: C44, C45, C46

1. INTRODUCTION

One of the greatest challenges facing humanity today lies in obtaining electrical energy that meets quality standard parameters, that is always available, that is easily accessible, and that does not pollute the environment. The accessibility objective is directly linked to the pricing policy that is managed, availability is linked to the quality, safety and continuity of the electricity supply, and acceptability is fundamentally linked to a set of social, economic and environmental objectives. The technological advances that have been presented in the energy sector have been able to respond to each of the aforementioned objectives or factors, and have contributed, to a greater or lesser extent, to satisfy social, economic and environmental demands (Diaz et al., 2021; Ochoa et al., 2019; Ochoa et al., 2019), although there is still much to analyze and investigate. On the other hand, scientific studies have made it possible to know the probable date on which fossil fuels and some minerals may be exhausted, taking into account how the historical evolution has been in terms of their extraction and use (Gaete-Morales et al., 2019), so the study and the use of renewable sources of energy plays a fundamental role in reversing this alarming situation.

The daily use and consumption of electricity is a vital service for the development and evolution of a country, constituting the main input in the vast majority of industrial activities worldwide, which sustain the economy and the generation of jobs. Furthermore, electrical energy is an essential factor to guarantee the quality of life of the inhabitants (Ferretti and Montibeller, 2016). In Colombia, as in other countries in the region, there is great interest in increasing the coverage and electricity supply to the entire territory, guaranteeing the quality of said energy and achieving a diverse energy matrix where the use of renewable sources predominates of energy (Hacatoglu et al., 2015). Government policies can affect the two indicators mentioned and also the sales prices of renewable energy projects. Many policies are applied around the world to support research and development investments, for example, low interest rate investment incentives, tax incentives such as accelerated depreciation opportunities, fee incentives such as Feeding Fees (FIT), certificates negotiable, among others; however, the planning, evaluation and selection of alternative energies for an adequate investment is a complex decision. In the first place, it is very important to consider that in addition to satisfying the projected demand, electric power generation plants must be economically viable and be environmentally and socially sustainable. Taking into account these criteria and others that have been used in recent years (Ghavami, 2019), our research aims to provide a solution that allows selecting the best investment alternative in terms of electricity generation using renewable energy sources, also considering the option of hybrid systems (Nuñez et al., 2020; Zeng et al., 2019).

Companies that invest in renewable energies must choose between different technologies, diverse structures and varied costs and uncertainties, so it is essential to select those that offer the highest profitability for a given level of risk (John et al., 2014); however, making a proper selection among several alternatives is not an easy task. Investment decisions in renewable energy depend mainly on economic, environmental and technical aspects, therefore there is a great need to develop tools that support the decisions of potential investors in renewable energy (Algarín et al., 2017). The objective of this research seeks to develop a mathematical model that allows choosing the best investment alternative in the use of energy sources. That is why the Analytic Hierarchy Process (AHP) decision-making aid method is proposed, which establishes, based on the multi-criteria decision method, the importance weights of both the criteria and the alternatives evaluated (Saaty, 1980). The model has a differentiating factor in terms of other investigations that have been developed due to the implementation of AHP as a solution method to address the best solution taking into account qualitative criteria such as economic and environmental and quantitative criteria such as technical, social, environmental, pathways. access, among others. In the development of the research, energy planning in Colombia in the last 10 years is taken into account, considering changes that may occur in the availability of resources and a limited investment budget. As a result, there is a tool that serves as a guide for government entities or other private companies to access electricity generation projects using renewable energies (Suresh et al., 2020; Mehrjerdi, 2019; Budes et al., 2020). Similar investigations have been initiated in Colombia, with the support of the Ministry of Mines and Energy, aimed at selecting the best power generation alternatives to solve the connectivity problem of Non-Interconnected Zones (NIZ) (Robles-Algarín et al., 2018).

In 1999, the Mining-Energy Planning Unit (UPME) contracted the design of a structural, institutional and financial plan for the supply of electricity to the NIZ of the national territory with the collaboration of the communities and the private sector (Rosso et al., 2017). The study carried out in (Vides-Prado et al., 2018) indicates that in Colombia projects involving NIZ are analyzed taking into account technical feasibility and economic viability, without taking into account other evaluation criteria. However, this traditional scheme is modified by investigations such as those of (Alptekin, 2021; Zhou, 2012; Zhou et al., 2019) where, in addition to technical and economic feasibility, other criteria such as social and natural are considered. In (Robles-Algarín et al., 2018) the methodology of sustainable livelihoods is used for the selection of projects that seek to supply electrical energy to the town of Calamar, Guaviare, Colombia, using renewable energy sources.

The study carried out in (Garces, et al., 2021) shows the evaluation of policies for the electrification of NIZ in southwestern Colombia and in (Cherni et al., 2007) an analytical tool called Sustainable Rural Energy Decision Support System is presented, which aims to that of maximizing the five main criteria that represent a locality (physical, financial, natural, social and human), and whose variations depend mainly on the provision of electrical energy and other complementary productive and social projects.

The Energy Institute of the National University of Colombia, Medellín campus, has developed planning tools and methodologies for the development of rural electrification, studying various objectives and genetic algorithms (Mamaghani et al., 2016; Balbis-Morejón et al., 2021). In the work of (Moghadam and Lombardi, 2019) an economic, technological and environmental optimization model of energy generation projects is developed with the aim of minimizing greenhouse gases, economic energy costs and increasing energy efficiency; the uncertainty treatment was carried out using Monte Carlo simulation (Milanés-Hermosilla et al., 2021). These investigations, both nationally and internationally, help to set an important precedent for future research on energy planning in Colombia and serve as a starting point for our work focused on energy planning in the Colombian Caribbean region (Silvera et al 2021; Zanghelini et al., 2018).

This article is organized in three sections; in the first one, a review of the scientific results on various evaluation methods on the application of renewable energies is presented. In the second section, the method under study is applied, analyzing the selection criteria and sub-criteria. In third place, the discussion of the results obtained and the comparison with those of other researchers is presented, and finally the conclusions of the work are provided.

2. MATERIALS AND METHODS

This research performs an analysis to determine the renewable energy potential to be implemented in the Colombian Caribbean region using the hierarchical analytical process, also known as AHP. In this analysis, it is necessary to evaluate a series of criteria and sub-criteria associated with the different energy alternatives of renewable energies and also the environmental, economic and social problems of the communities that comprise this area. That is why this research aims to propose a hierarchy of use of renewable energy sources taking into account the energy potential of each area in particular.

2.1. Renewable Energy Alternatives

In the study and analysis of the potential of renewable energies in the Colombian Caribbean region, technical, social, environmental and economic criteria are evaluated, as well as a series of sub-criteria associated with them. The alternatives for the use of renewable energies present in the area under study are also taken into account. Figure 1 shows the hierarchical structure of the decision-making problem according to the criteria, sub-criteria and alternatives considered.

On various occasions, the social, economic and environmental problems of the communities become more complex and to find the best solution requires the analysis of many variables, criteria, studies and other aspects that justify obtaining the most viable solution from all points of view. Therefore, it is proposed to use the AHP method due to its advantages to identify problems and propose solutions according to the best response to complex and difficult decisions (Escrivá, 2016; Ashek-Al-Aziz et al., 2020).

2.2. Model Training

Decision-making is a very important mechanism that becomes more complex every day, fundamentally due to the number of variables that are present and the constant transformation of the scenarios in which we work. In this context, multi-criteria methodologies are born as a way to face this type of challenge. The AHP methodology contemplates the construction of a hierarchical structure to define the problem in its entirety and includes the creation of goals, the definition of evaluation criteria and sub-criteria, the identification of alternatives to solve the problem, until a ranking of the best options is obtained. to maximize and facilitate the choice of the best energy source that can be used in a certain area. Among the advantages of the AHP method are that it presents mathematical support, allows to break down and analyze a problem by parts, analyzes quantitative and qualitative criteria and allows verifying the consistency index by making corrections if necessary. The hierarchical analysis process developed by (Saaty, 1980) is based on the conception of a complex problem with multiple criteria that can be solved by classifying the problems posed, for which subjective evaluations are required on the relative importance of each of the criteria and also their preference for each of the decision alternatives. With the result of applying the AHP method, it is possible to generate a ranking with the priorities of each of the decision alternatives (Escrivá, 2016). The AHP method tries to break down a problem and then unite all the solutions of the subproblems into a conclusion and is divided into 4 fundamental stages:

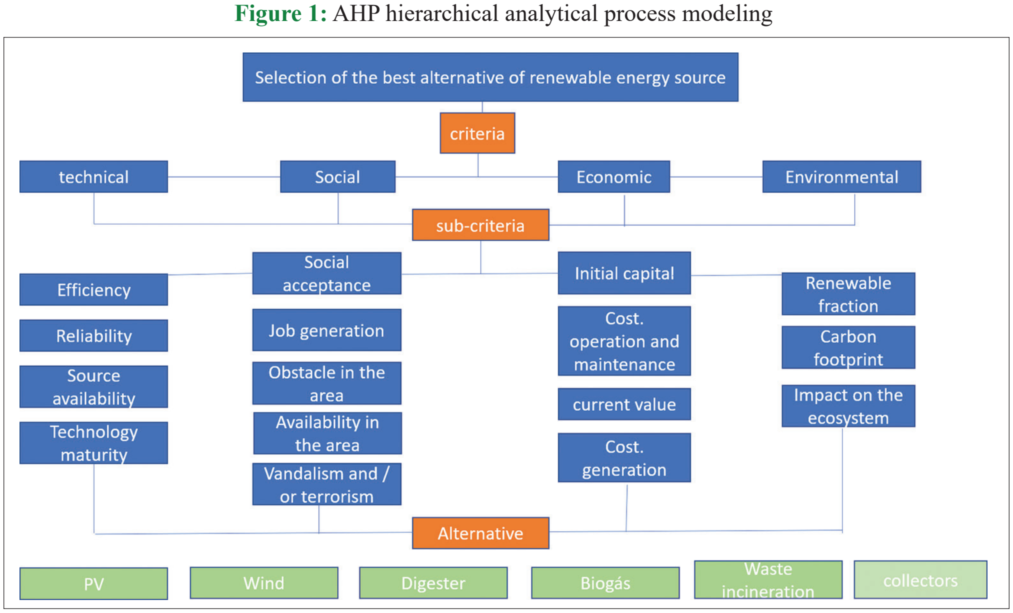
2.2.1. Stage 1. Modeling

In this stage the hierarchical order of the problem is carried out, the objectives, criteria and alternatives to be implemented are defined. The objective of the process is defined according to the criteria of experts. Then the alternatives through which we want to achieve our objective are defined and consequently, the criteria to be evaluated are determined. These criteria must take into account the problem and must identify the attributes that contribute to a good decision. These criteria must be measured and quantified in order to use a comparison scale (Mamaghani et al., 2016). The solution of the problem passes 3 levels, the first level is the fundamental objective that we must achieve to solve the problem, in the second level the criteria would be located according to a descending hierarchical structure of one or more specific objectives, which will allow evaluating the alternatives for each of the criteria. In the third and last level would be the alternatives in the decision-making of (Escrivá, 2016).

2.2.2. Stage 2. Reviews

Knowing the alternatives and defining the criteria, we proceed to order and weight each of the criteria in the selection of alternatives. The objective of this procedure is to measure the importance

Figure 1: AHP hierarchical analytical process modeling



that the decision-maker assigns to each criterion. It is carried out through paired comparisons, that is, each criterion or alternative *i* is compared with each criterion or alternative *j*. An underlying scale with values from 1 to 9 is used to rate the relative preferences of the items (John et al., 2014; Rosso et al., 2017), Table 1.

With this, we proceed to construct the matrix of paired comparisons, it will be a square matrix Anxn = [a*ij*], with $1\leq i, j \leq$ n.

For the construction of the matrix, the following axioms must be taken into account:

Axiom of reciprocity: If *A* is a matrix of paired comparisons, then it is true that if a*ij* = x then a*ji* = 1/x with $1/9 \leq x \leq 9$.

For the Reciprocity property only n (n-1)/2 comparisons are needed:

Axioma of homogeneity: The elements that are compared to each other will be of the same order of magnitude and hierarchy.

Axioma of independence: When the decision-maker makes the comparisons, it is assumed that the criteria do not depend on the properties of the different alternatives.

Axiom of expectations: To make a decision, the hierarchy is assumed to be complete (Algarín et al., 2017; Escrivá, 2016).

Fulfilling the previous axioms, it is possible to determine the Paired comparison matrix, Table 2.

2.2.3. Stage 3. Prioritization and synthesis

After having the paired comparison matrix, the prioritization is calculated. This emphasizes the importance that the decision maker has assigned to each element. The priorities are expressed in the form of vectors. The priorities are expressed in the form of vectors.

Let a matrix A (nxn) be like the one obtained when carrying out the paired comparisons, we call the eigenvalues or proper eigenvectors of A (ʎ1, ʎ2,…, ʎn) to the solutions of the equation: det (A-ʎI) = 0.

The principal eigenvalue of the matrix (ʎmax) is the maximum of the eigenvalues obtained by performing the previous equation, n is the dominant eigenvalue of {A} and {a} the associated eigenvector. The eigenvector associated with the dominant value is the weight vector to be obtained.

When the eigenvector obtained is that of the criteria matrix, we will call it Vc, and it indicates the weight or relative importance that each of the selected criteria has in the assessment of the set of alternatives on which we are going to work. When the eigenvector obtained is that of the alternative matrix for a given criterion, we will call it Vai (column vector), which indicates the weight or relative importance of each of the alternatives for criterion i. As many eigenvectors as criteria will be obtained. One consideration to take into account that affects the final decision will be the consistency of the decisions of the decision-maker when filling in the paired matrices (Vinogradova-Zinkevič et al., 2021). This is because the decision-maker makes a personal judgment, which can lead to a certain inconsistency that will have to be evaluated to see if it is below the limits (Escrivá, 2016).

Table 1: Implementation of the Saaty scale according to the degree of importance (Saaty, 1980)

Value	Definition
1	Equal importance
3	Moderate importance
5	Great importance
7	Very great importance
9	Extreme importance
2, 4, 6 and 8	Intermediate values

Table 2: Paired comparison matrix

	A1	A2	A3
A1	1	a_{12}	a_{13}
A2	a_{21}	1	a_{23}
A3	a_{31}	a_{32}	1

2.2.4. Stage 4. Consistency analysis

This analysis takes into account the subjectivity of the decision maker. When performing the paired matrix comparison procedure, subjectivity is sought to be as real and objective as possible since the different elements of the matrix are successively compared to form another matrix.

There is a procedure to calculate it. If it is acceptable, the decision process can continue, but if it is unacceptable, a new analysis will be necessary because it is likely to modify the judgments about the paired comparisons (Escrivá, 2016). The consistency relationship is calculated using Equation 1 obtaining the normalized matrix A:

$$A\,normalized\left[\frac{a_y}{\sum_{k-1}^{n} a_{kj}}\right] \quad (1)$$

The sum of rows is obtained from Equation 2:

$$\begin{gathered}\frac{a_{11}}{\sum_{n-1}^{n} a_{n1}}+\frac{a_{12}}{\sum_{n-1}^{n} a_{n2}}+\ldots\ldots\ldots\ldots\ldots+\frac{a_{1n}}{\sum_{n-1}^{n} a_{nn}}=b_1\\ \frac{a_{11}}{\sum_{n-1}^{n} a_{n1}}+\frac{a_{12}}{\sum_{n-1}^{n} a_{n2}}+\ldots\ldots\ldots\ldots\ldots+\frac{a_{1n}}{\sum_{n-1}^{n} a_{nn}}=b_2 \\ \frac{a_{11}}{\sum_{n-1}^{n} a_{n1}}+\frac{a_{12}}{\sum_{n-1}^{n} a_{n2}}+\ldots\ldots\ldots\ldots\ldots+\frac{a_{1n}}{\sum_{n-1}^{n} a_{nn}}=b_n\end{gathered} \quad (2)$$

The priority vector B that is formed is given by Equation 3:

$$\left[\frac{b_1}{n},\frac{b_2}{n},\ldots\ldots\frac{b_n}{n},\right]^T \quad (3)$$

The product of the original matrix A and the priority vector B forms a column C matrix, Equation 4:

$$A*B = C = \left[c_{1,}c_{2\ldots\ldots\ldots,}\,c_n\right]^T \quad (4)$$

Table 3: Comparison between the CI obtained and the random CI

Array size (n)	1	2	3	4	5	6	7	8	9	10
Random consistency	0.0	0.0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

CI: Consistency Index

We proceed to calculate the quotient between the matrix column C and the vector of priorities B, obtaining another column vector D, Equation 5:

$$\frac{C}{B} = D \quad (5)$$

Adding and averaging its elements, the value of the consistency index (CI) is obtained, Equation 6:

$$CI = \frac{\lambda_{max-n}}{n-1} \quad (6)$$

Subsequently, the CI obtained is compared with the random CI in Table 3:

The random consistency (CI) value as a function of the size of the matrix represents the value that the CI should obtain if the numerical judgments with the scale of (Saaty, 1980) had been completely randomly introduced into the comparison matrix.

Therefore, the CI is divided by the random consistency, thus obtaining the Inconsistency Ratio (IR), Equation 7:

$$IR = \frac{CI}{\text{Random consistency}} \quad (7)$$

Finally, a consistent matrix will be considered when the following values stipulated for the size of each matrix are not exceeded, Table 4.

If any matrix exceeds the consistency ratio, the valuations made by the decision-maker are reviewed and modified to reduce this consistency ratio to admissible values (Escrivá, 2016).

Table 4: Consistency limits (Saaty, 1980)

Matrix size (n)	Consistency ratio
3	5%
4	9%
5 or more than 5	10%

Table 5: Classification of sub-criteria according to criteria

Criteria	Sub-criteria
Social (C1)	Social acceptance (C 1.1)
	Generation of work (C 1.2)
	Obstacles in Zones (C 1.3)
	Disponibilidad de zona (C 1.4)
	Vandalism and/or terrorism (C 1.5)
Economical (C2)	Initial Capital (C 2.1)
	Operation and maintenance cost (C 2.2)
	Net present value (C 2.3)
	Electricity generation cost (C 2.4)
Environmental (C3)	Renewable faction (C 3.1)
	Carbon footprint (C 3.2)
	Ecosystem impact (C 3.3)
Technicians (C4)	Efficiency (C 4.1)
	Reliability (C 4.2)
	Source availability (C 4.3)
	Technology maturity (C 4.4)

2.3. Criteria and Sub-criteria Approach

In the selection of criteria and sub-criteria, a set of qualitative criteria was established that are considered as a means of comparison between the different alternatives. These parameters influence multi-criteria decision making for the selection of technologies to be used. The criteria considered in the analysis are based on the study of different articles and/or publications from different databases (John et al., 2014; Robles-Algarín et al., 2018; Jamal et al., 2020; Ruiz et al., 2012). Table 5 shows the classification of the sub-criteria according to the Social (C1), Economic (C2), Environmental (C3) and Technical (C4) criteria.

Once the final list of criteria has been obtained, the interrelationships between the elements are determined in order to make pairwise comparisons. The theoretical definitions of the elements were carefully examined and the literature reviewed to establish precise interrelationships. The initial relationships were decided based on information obtained from the literature. On the other hand, the participation of experts from the energy sector plays a very important role. In our study, and taking into account the multidisciplinary nature of energy investments, a team of experts of 16 people was assembled. The experts have a minimum of 2 years of experience and know about the topics of investments in renewable energy sources. The experts were asked to review the interrelationships obtained from the literature and complete the interrelationship matrix. The set of scales suggested by (Saaty, 1980) was used in the pairwise comparison matrices and the numbers 1 to 9 are used to indicate the relative importance of the items. In the next step, the relative importance indices of the clusters were determined and the items were determined. The set of scales suggested by (Saaty, 1980) was used in the pairwise comparison matrices. The profile of the experts is shown in Table 6.

The objective of this methodology is to be able to analyze the criteria, sub-criteria and alternatives of a hierarchical structure in order to obtain the judgments issued by each of the experts consulted. In the method, the comparison is made in pairs, where it is necessary to generate the evaluation issued by one or more experts; success at this stage will depend on the knowledge and expertise of the group of decision makers. The evaluated criteria are assigned the Satty scale to obtain the weightings of each one of them.

3. RESULTS AND DISCUSSION

According to the opinion and assessment of the experts in each of the decision matrices, and with the help of the AHP methodology, it is possible to establish, as shown in Figure 2, the weighting of the criteria used in the study area, managing to determine that the weighting and ranking of the economic criteria are the most.

To validate the reliability of the results obtained in the weightings and ranking of criteria and sub-criteria, the experts consulted calculate the consistency index and the consistency radius of each of the decision matrices. The paired comparison matrix reflects the importance of one attribute with respect to another, however, it is always necessary to validate the consistency of the judgments provided by the experts to obtain a valid and accurate comparison matrix in their responses. Table 7 shows the decision matrix of some of the experts, where the comparison between the criteria is observed (Hernández et al., 2021).

Table 8 shows the normalization of the decision matrix of some of the experts, which is an important step in determining the consistency index and the consistency radius.

Table 6: Categorization of the group of experts

Expert number	Occupation	Academic training	Years of experiences
1	Professor	Magister	2
2	Professor	Magister	2
3	Professor	Magister	2
4	Professor	Magister	2
5	Professor	Magister	4
6	Professor	Magister	4
7	Professor	Magister	4
8	Lawyer	Magister	4
9	Lawyer	Magister	6
10	Field engineer	Magister	6
11	Field engineer	Magister	6
12	Administrative	Magister	6
13	Administrative	Magister	8
14	Administrative	Magister	8
15	Professor	Doctor	More than 10
16	Professor	Doctor	More than 10

Table 7: Comparison matrix between criteria

	Economic	Social	Environmental	Technicians
Economic	1	3	7	5
Social	1/3	1	1/7	1/3
Environmental	0.14	7	1	9
Technicians	1/5	3	1/9	1
Sum	1.68	14.00	8.25	15.33

Table 8: Matrix of normalized values

	Economic	Social	Environmental	Technicians
Economic	0.60	0.21	0.85	0.33
Social	0.20	0.07	0.02	0.02
Environmental	0.09	0.50	0.12	0.59
Technicians	0.12	0.21	0.01	0.07
Sum	1.00	1.00	1.00	1.00

Table 9: Determination of the consistency index and consistency radius

ʎ max	Consistency index	Consistency radius
4.1005	0.0335	0.0338

Table 9 shows the consistency index and the consistency radius of the obtained values, it is noted that the consistency radius is <0.1, allowing us to determine the validity and precision of the values reflected in the matrix.

1. Influential with 38%, followed by the environmental criteria with 34%, and finally, the technical and social criteria with 15% and 13% respectively. One aspect to take into account is the high percentage that environmental criteria have in recent years, this is due to the fact that today there is greater concern for the conservation of natural resources and the efficient exploitation of these.

It was also possible to evaluate and classify each of the sub-criteria associated with the evaluated criteria. The results shown in Figure 3 reflect the behavior of the economic sub-criteria where it is evidenced that the one with the highest weighting is due to costs, operation and maintenance with 38%, followed by the sub-criterion of cost of electricity generation with 28% and then the sub-criteria of initial capital and net present value with 22% and 11% respectively.

Within the social criteria and bearing in mind the area where the research was carried out, the predominant sub-criterion was the generation of work, because in these areas the lack of a job opportunity, the almost or null presence of a state or its representative, conditions the lifestyle of each individual and family, that is why this sub-criterion acquires great value within the social criteria, as reflected in the weighting and ranking in Figure 4.

For the environmental and technical criteria, results were obtained where it is reflected that the renewable fraction sub-criterion with 49% and the efficiency sub-criterion with 43% lead the weighting and ranking of the results shown in Figures 5 and 6. It should be noted how the The group of experts takes into account the efficiency and implementation values of the renewable fraction within the project to be executed.

Figure 2: Criteria weighting by AHP%

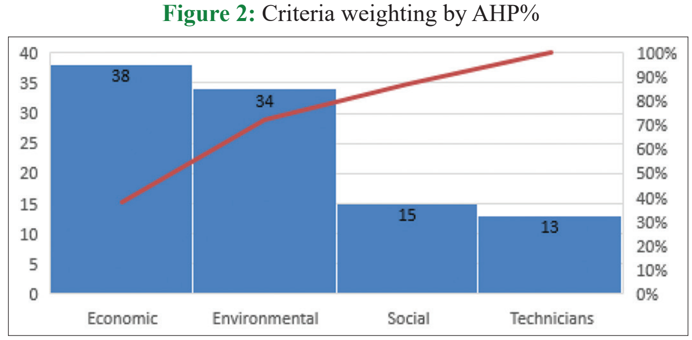


Figure 3: The weighting of economic criteria by AHP%

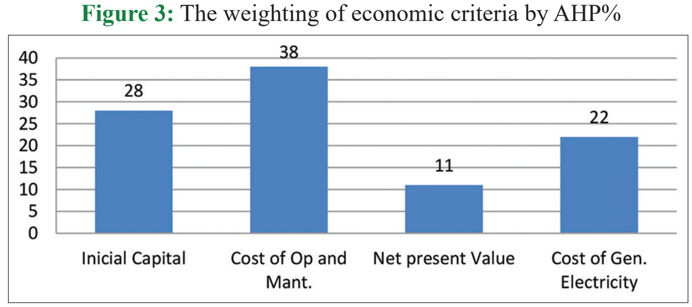


Figure 7 shows the overall percentage weighting of each of the sub-criteria. It should be noted that for the group of experts consulted, the sub-criteria of removable fraction and work generation are the most important because it is a project where the efficient use of different sources of renewable energy is implemented. According to the International Renewable Energy Agency, reaching the Paris Agreement requires doubling the share of renewable energies in electricity generation to 57% worldwide by 2030. To achieve this requirement it is necessary to increase investments annually in renewable energy from 330 billion dollars today to 750 billion dollars, with the consequent boost to job creation and growth linked to the green economy of the International Energy Agency (IEA).

Figure 4: The weighting of social criteria by AHP%

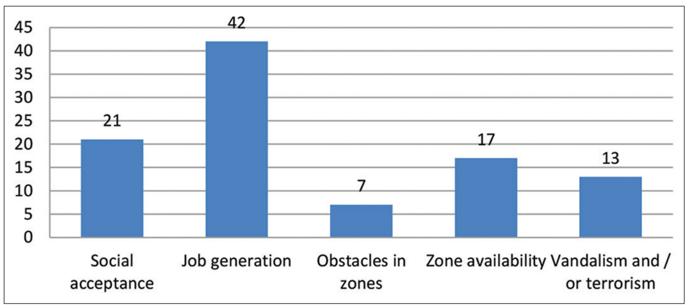


Figure 5: The weighting of technical criteria by AHP%

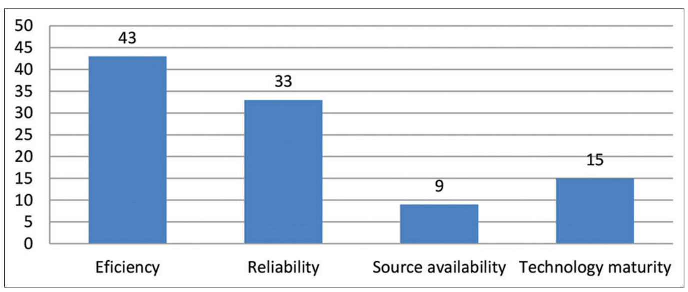
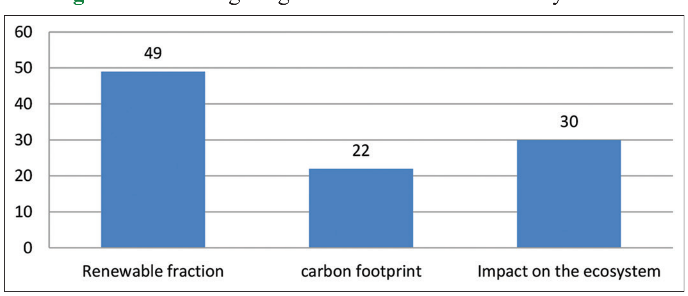


Figure 6: The weighting of environmental criteria by AHP%



The level of importation of each of the criteria varied according to the renewable energy sources that are present in the area, Figure 8. According to the experts, the economic criterion was the most important in the use of wind energy, while for the solar collectors the most important criterion was social. These results demonstrate the variability in the degree of importance of the criteria for each of the renewable energy sources.

Table 10 shows the percentage obtained in each of the four criteria analyzed (C1, C2, C3 and C4). In addition, the Table reflects the values of the local and global weights of each sub-criterion, and finally, the percentage of each one of them compared to the alternatives of renewable energy sources. It is necessary to mention that the union of these figures forms what is called the decision matrix.

The growth of renewable energies worldwide is on the rise according to the data provided annually by the IEA. According to IEA forecasts, the share of renewable energies in world electricity supply will go from 26% in 2018 to 44% in 2040 and will contribute 2/3 of the increase in electricity demand in that period, mainly to through the use of wind and photovoltaic technologies. According to the IEA, global electricity demand will increase by 70% in 2040, which will allow an increase in the share of final energy use from 18% to 24%, mainly in emerging regions such as India, China, Africa, Middle East and East and Southeast Asia (Khan et al., 2021).

The development and use of clean energy is essential to reverse the serious situation of the environment and mitigate the effects of climate change. For example, 2019 was the second warmest year on record, behind 2016. The average temperature recorded over the past 5 years has been about 1.2 °C higher than pre-industrial, according to the Copernicus climate change service. In addition, approximately 860 million people in the world did not have access to electricity in 2018, which requires a great additional effort in the deployment of clean energy to achieve universal access to electricity by 2030.

The poor decision to choose a renewable energy that has the resources available in an application area leads to great losses of time and money. The methodology described in this research would then help to make better decisions that could converge in public policies aimed at taking advantage of the energy resources available in a given area. The methodology selected in this study was AHP, which provides the hierarchical analysis process. By applying the methodology in the Colombian Caribbean region,

Table 10: Hierarchy associated with criterion

Weight	C1 (15%)					C2 (38%)				C3 (34%)			C4 (12%)			
	C1.1	C1.2	C1.3	C1.4	C1.5	C2.1	C2.2	C2.3	C2.4	C3.1	C3.2	C3.3	C4.1	C4.2	C4.3	C4.4
L %	21%	42%	7%	17%	13%	28%	38%	11%	22%	49%	22%	30%	43%	33%	9%	15%
G %	0.03	0.06	0.01	0.03	0.02	0.11	0.14	0.04	0.08	0.17	0.07	0.10	0.06	0.04	0.01	0.02
A1	0.33	0.22	0.26	0.31	0.28	0.35	0.05	0.07	0.05	0.16	0.08	0.24	0.38	0.39	0.31	0.32
A2	0.27	0.20	0.16	0.12	0.23	0.29	0.06	0.18	0.15	0.20	0.09	0.19	0.10	0.19	0.20	0.21
A3	0.09	0.14	0.11	0.14	0.14	0.09	0.11	0.30	0.27	0.14	0.30	0.15	0.20	0.18	0.12	0.11
A4	0.10	0.13	0.11	0.14	0.11	0.07	0.20	0.21	0.25	0.15	0.24	0.18	0.17	0.10	0.11	0.11
A5	0.08	0.13	0.10	0.08	0.08	0.03	0.35	0.08	0.18	0.24	0.11	0.08	0.06	0.04	0.08	0.08
A6	0.13	0.19	0.26	0.22	0.17	0.17	0.22	0.15	0.10	0.11	0.18	0.15	0.10	0.09	0.18	0.17

Figure 7: Global sub-criteria %

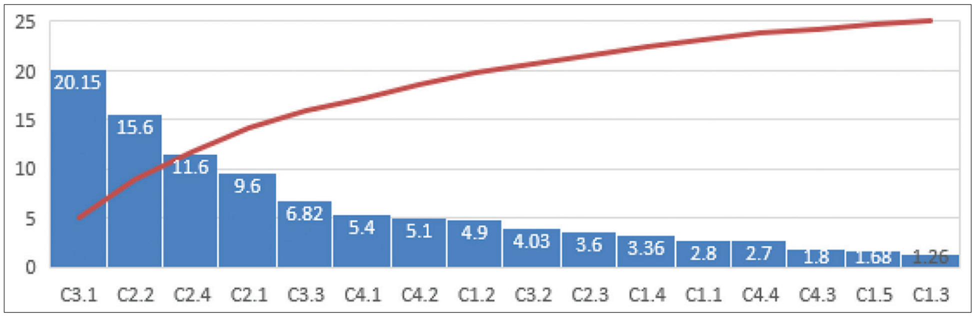


Figure 8: Comparison of alternatives and each criterion

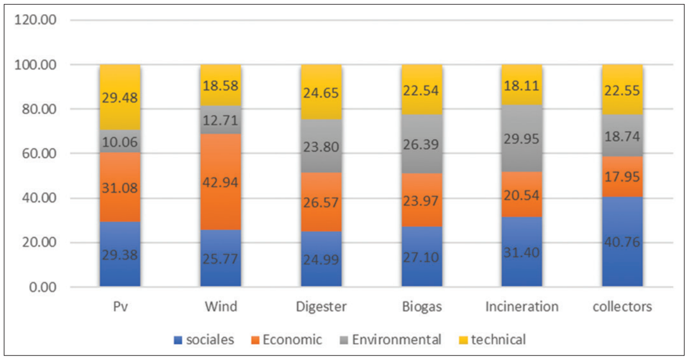
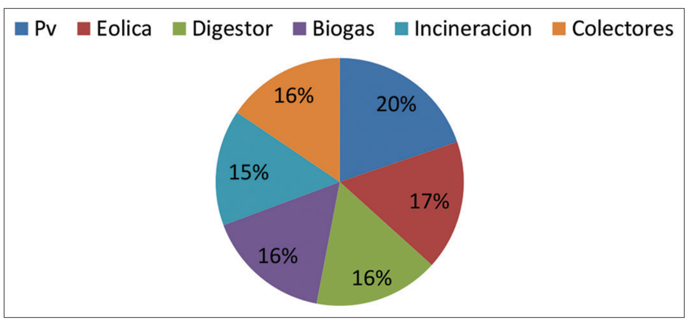


Figure 9: Weighting of renewable energies by AHP



the result is that the most feasible renewable energy source to use is photovoltaic solar, with a rating of 20%, followed by wind energy with 16.88%. In the third step is the energy from Biogas with 16.24%, followed by the energy produced by Digester with 16.12%, in fifth place we have the energy obtained by solar collectors with 15.46% and in sixth place is the energy obtained by Waste Incineration with 15.10%, Figure 9. It should be noted that the variation between the selection of one source of renewable energy and another is very small, in the order of thousandths, which shows how complex the process of selection. The result obtained in this research corroborates the results obtained by other researchers and serves as a reference for the Colombian government and decision makers to improve the quality of life of the inhabitants of the area under study.

4. CONCLUSION

The application of the proposed AHP method allowed the participation of a group of experts for the weighting and ranking of the 4 criteria and the 16 sub-criteria used, which can be generalized in energy planning projects in rural and non-interconnected areas of Colombia using renewable energy sources.

The calculation of the consistency index and consistency radius made it possible to measure the level of relevance and reliability of each of the decision matrices by the experts.

The selected sub-criteria allowed the comprehensive evaluation of energy planning projects taking into account technical, economic, social and environmental criteria, as well as each of the 16 sub-criteria that were used in the Colombian Caribbean region.

In addition, it is concluded that the environmental criterion, as well as the sub-criteria assigned to it in energy planning, have increased their percentage value, which shows a greater concern for the conservation and proper use of each of the energy sources that are currently used. they use.

The proposed methodology allowed the consolidation of 4 criteria and 16 sub-criteria that, in the opinion of the experts, are relevant for energy planning projects in rural areas and not Colombian interconnected networks, especially in the Colombian Caribbean region.

REFERENCES

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

Alptekin, S.E. (2021), A fuzzy decision support system for digital camera selection based on user preferences. Expert Systems With Applications, 39(3), 3037-3047.

Ashek-Al-Aziz, M., Mahmud, S., Islam, M.A., Mahmud, J.A., Hasib, K.M. (2020), A comparative study of AHP and fuzzy AHP method for inconsistent data. International Journal of Sciences: Basic and Applied Research, 54(4), 16-37.

Balbis-Morejón, M., Cabello-Eras, J. J., Rey-Hernández, J.M., Rey-Martínez, F.J. (2021), Global air conditioning performance indicator (ACPI) for buildings, in tropical climate. Building and Environment, 203, 108071.

Budes, F.A.B., Ochoa, G.V., Obregon, L.G., Arango-Manrique, A., Álvarez, J.R.N. (2020), Energy, economic, and environmental evaluation of a proposed solar-wind power on-grid system using HOMER Pro®: A case study in Colombia. Energies, 13(7), 1662.

Cherni, J.A., Dyner, I., Henao, F., Jaramillo, P., Smith, R., Font, R.O. (2007), Energy supply for sustainable rural livelihoods. A multi-criteria decision-support system. Energy Policy, 35(3), 1493-1504.

Díaz, S., Moreno, C., Berdugo, K., Silva, J., Caicedo, J., Ruiz, J., Gordon, J. (2021), Electric power losses in distribution networks. Turkish Journal of Computer and Mathematics Education, 12(12), 581-591.

Escrivá, L. (2016), Aplicación del Proceso Analítico Jerárquico (AHP) al Dimensionamiento de Sistemas Renovables. Thesis, Technical School of Industrial Engineering, Universidad Politécnica de Valencia, Spain. p84.

Ferretti, V., Montibeller, G. (2016), Key challenges and meta-choices in designing and applying multi-criteria spatial decision support systems. Decision Support Systems, 84, 41-52.

Gaete-Morales, C., Gallego-Schmid, A., Stamford, L., Azapagic, A. (2019), Life cycle environmental impacts of electricity from fossil fuels in Chile over a ten-year period. Journal of Cleaner Production, 232, 1499-1512.

Garces, E., Tomei, J., Franco, C.J., Dyner, I. (2021), Lessons from last mile electrification in Colombia: Examining the policy framework and outcomes for sustainability. Energy Research and Social Science, 79, 102156.

Ghavami, S.M. (2019), Multi-criteria spatial decision support system for identifying strategic roads in disaster situations. International Journal of Critical Infrastructure Protection, 24, 23-36.

Hacatoglu, K., Dincer, I., Rosen, M.A. (2015), Sustainability assessment of a hybrid energy system with hydrogen-based storage. International Journal of Hydrogen Energy, 40(3), 1559-1568.

Hernández, J.C.B., Moreno, C., Ospino-Castro, A., Robles-Algarin, C.A., Tobón-Perez, J. (2021), A hybrid energy solution for the sustainable electricity supply of an irrigation system in a rural area of Zona Bananera, Colombia. International Journal of Energy Economics and Policy, 11(4), 521-528.

Jamal, T., Urmee, T., Shafiullah, G.M. (2020), Planning of off-grid power supply systems in remote areas using multi-criteria decision analysis. Energy, 201, 117580.

John, A., Yang, Z., Riahi, R., Wang, J. (2014), Application of a collaborative modelling and strategic fuzzy decision support system for selecting appropriate resilience strategies for seaport operations. Journal of Traffic and Transportation Engineering, 1(3), 159-179.

Khan, I., Hou, F., Zakari, A., Tawiah, V.K. (2021), The dynamic links among energy transitions, energy consumption, and sustainable economic growth: A novel framework for IEA countries. Energy, 222, 119935.

Mamaghani, A.H., Avella, S., Najafi, B., Shirazi, A., Rinaldi, F. (2016), Techno-economic feasibility of photovoltaic, wind, diesel and hybrid electrification systems for off-grid rural electrification in Colombia. Renewable Energy, 97, 293-305.

Mehrjerdi, H. (2020), Modeling, integration, and optimal selection of the turbine technology in the hybrid wind-photovoltaic renewable energy system design. Energy Conversion and Management, 205, 112350.

Milanés-Hermosilla, D., Codorniú, R.T., López-Baracaldo, R., Sagaró-Zamora, R., Delisle-Rodriguez, D., Villarejo-Mayor, J.J., Núñez-Álvarez, J.R. (2021), Monte carlo dropout for uncertainty estimation and motor imagery classification. Sensors, 21(21), 7241.

Moghadam, S.T., Lombardi, P. (2019), An interactive multi-criteria spatial decision support system for energy retrofitting of building stocks using communtiy VIZ to support urban energy planning. Building Environment, 163, 106233.

Nuñez, J.R., Mestre, J., Cabello, J.J., Dominguez, H., Fong, J., Peña, L., Benítez, I. and De Oliveira, D. (2020), Design of a fuzzy controller for a hybrid generation system. IOP Conference Series: Materials Science and Engineering, 844, 012017.

Ochoa, G.V., Alvarez, J.N., Acevedo, C. (2019), Research evolution on renewable energies resources from 2007 to 2017: A comparative study on solar, geothermal, wind and biomass energy. International Journal of Energy Economics and Policy, 9(6), 242-253.

Ochoa, G.V., Alvarez, J.N., Chamorro, M.V. (2019), Data set on wind speed, wind direction and wind probability distributions in Puerto Bolivar Colombia. Data in Brief, 27, 104753.

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

Rosso, A.M., Kafarov, V., Latorre-Bayona, G. (2017), A fuzzy logic decision support system for assessing sustainable alternative for power generation in non interconnected areas of Colombia case of study. Chemical Engineering Transactions, 57, 421-426.

Ruiz, M.C., Romero, E., Pérez, M.A., Fernández, I. (2012), Development and application of a multi-criteria spatial decision support system for planning sustainable industrial areas in Northern Spain. Automation in Construction, 22, 320-333.

Saaty, T.L. (1980), The Analytic Hierarchy Process. New York: McGraw-Hill; 1980.

Silvera, O.C., Chamorro, M.V., Ochoa, G.V. (2021), Wind and solar resource assessment and prediction using Artificial Neural Network and semi-empirical model: Case study of the Colombian Caribbean Region. Heliyon, 7(9), e07959.

Suresh, V., Muralidhar, M., Kiranmayi, R. (2020), Modelling and optimization of an off-grid hybrid renewable energy system for electrification in a rural areas. Energy Reports, 6, 594-604.

Tavana, M., Arteaga, F.J.S., Mohammadi, S., Alimohammadi, M. (2017), A fuzzy multi-criteria spatial decision support system for solar farm location planning. Energy Strategy Reviews, 18, 93-105.

Vides-Prado, A., Camargo, E.O., Vides-Prado, C., Orozco, I.H., Chenlo, F., Candelo, J.E., Sarmiento, A.B. (2018), Techno-economic feasibility analysis of photovoltaic systems in remote areas for indigenous communities in the Colombian Guajira. Renewable and Sustainable Energy Reviews, 82(3), 4245-4255.

Vinogradova-Zinkevič, I., Podvezko, V., Zavadskas, E.K. (2021), Comparative assessment of the stability of ahp and fahp methods. Symmetry (Basel), 13(3), 13030479.

Zanghelini, G.M., Cherubini, E., Soares, S.R. (2018), How multi-criteria decision analysis (MCDA) is aiding life cycle assessment (LCA) in results interpretation. Journal of Cleaner Production, 172, 609-622.

Zeng, Y., Guo, W., Wang, H., Zhang, F. (2019), A two-stage evaluation and optimization method for renewable energy development based on data envelopment analysis. Applied Energy, 262, 114363

Zhou, J., Wu, Y., Wu, C., Deng, Z., Xu, C., Hu, Y. (2019), A hybrid fuzzy multi-criteria decision-making approach for performance analysis and evaluation of park-level integrated energy system. Energy Conversion and Management, 201, 112134.

Zhou, X. (2012), Fuzzy Analytical Network Process Implementation with Matlab. In: MATLAB A Fundamental Tool for Scientific Computing and Engineering Applications. Vol. 3. London: InTech. p132-160.