IJEEP
INTERNATIONAL JOURNAL OF ENERGY ECONOMICS AND POLICY

International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2017, 7(4), 38-47.

An Analytic Hierarchy Process Based Approach for Evaluating Renewable Energy Sources

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ABSTRACT

Decision-making in energy planning can be approached as a problem of multicriteria decision analysis in which different types of factors are involved. This task must take into account several aspects due to the increasing complexity of social, technological and economic factors. In this context, this paper uses the analytic hierarchy process (AHP) to prioritize a set of criteria, subcriteria and alternatives as a support for decision-making in the process of energy planning with renewable energies for rural areas in the Caribbean region of Colombia. Based on the participation of experts, 5 criteria, 20 subcriteria and 4 alternatives were defined. Using the AHP, the same group of experts was consulted in order to prioritize all aspects. The results showed that the most relevant criteria were the technical with 24.7%. Next were environmental (21.7%), social (19.6%), economic (17.8%) and risk (16.3%). The best renewable energy alternative was solar with 45.3%.

Keywords: Renewable Energy, Energy Planning, Analytic Hierarchy Process
JEL Classifications: Q20, Q42, D70

1. INTRODUCTION

In recent years, multicriteria decision analysis has been used in a wide variety of fields by decision makers, due to the flexibility of such techniques to find solutions to energy management problems (Diaz et al., 2017). With these tools, a better understanding of decision-making problems is achieved by promoting the role of participants in decision-making, facilitating collective decisions, providing a platform for model perception and allowing for analysis of realistic scenarios.

The number of publications on energy planning problems (Nadimi and Adabi, 2016; Gualtieri, 2016; Muñoz et al., 2014) and multi-criteria scenarios has increased widely in recent years. There are publications in the area of sustainable development (Khalili and Duecker, 2013; Yeh and Xu, 2013; Nnaji et al., 2013), education (Hein et al., 2015; Certa et al., 2015), e-government evaluation (Siskos et al., 2014), e-waste recycling programs (Wibowo and Deng, 2015), and mobility management (Longo et al., 2015). Specifically, in the energy sector, research has been carried out for evaluating energy-saving technologies (Mardani et al., 2016), electric supply planning in rural remote areas (Rojas and Yusta, 2014), rural planning with renewable energies (Mourmouris and Potolias, 2013; Mizanur et al., 2013; Mourmouris et al., 2012), resource management in renewable energy assisted microgrids (Naveed et al., 2017), policies in favor of solar mobility (Popiolek and Thais, 2016) and hydropower megaprojects (Gul, 2014).

One of the multi-criteria techniques preferred by users for energy planning projects is the analytical hierarchical process (AHP). The AHP is a flexible and intuitive method for decision makers, which also calculates the consistency of the judgments of the experts. Several studies demonstrate the relevance of this method in energy planning projects with renewable energies. In Kon et al. (2013), a hybrid model was implemented for efficiently allocating energy R&D resources; in Hernández et al. (2015), a hierarchical methodology for the integral net energy design was developed; and in Ahmad and Tahar (2014) AHP was used to select renewable energy sources.

The potential for renewable energy in rural areas is growing rapidly due to the gradual decline in prices and increased applications in sectors such as agriculture, education, health, lighting, radio, television and drinking water filtration systems (International Renewable Energy Agency, 2015).

In rural areas, generation projects are usually carried out prioritizing the technical-economic criteria in order to maximize the amount of energy produced, as well as the profits, without taking into account the social and environmental aspects that guarantee the participation of local communities. In addition, there are problems with the communities that do not generate the economic resources for the costs of maintenance and replacement of equipment. This shows a need for local knowledge in the communities to perform preventive maintenance and repair of equipment.

For the reasons explained above, projects that promote rural electrification using renewable energies taking into account the communities and their socioeconomic environment, are currently being carried out. In this context, the importance of multi-criteria decision-making tools is emphasized because these techniques allow the integral inclusion of different aspects.

Thus, the purpose of this paper is to use the AHP to prioritize criteria, subcriteria and alternatives for renewable energy supply in rural areas of the Caribbean region of Colombia, presenting the integration of technical, economic, environmental, social and risk criteria as its main novelty, which require a coherent planning to guarantee permanence. The methodology carried out can be used in different Colombian rural areas that have the potential for the implementation of projects with the renewable energies studied in this work (Unidad de Planeación Minero Energética - Energy Mining Planning Unit [UPME], 2015).

2. AHP REVIEW

The AHP is a decision-making tool used to solve problems with multiple criteria. In this method a hierarchy is performed in which the problem to solve is located at the top and at the base are the solution alternatives. At the intermediate levels are the criteria that are the basis of decision-making (Saaty and Vargas, 2012).

One of the characteristics of the AHP is that for the case of a comparison matrix of $n \times n$, $n(n-1)/2$, judgments can be omitted. If the element a_{ij} of the matrix is known, a priori would be known of the element a_{ji}. There is a structured process of successfully applying AHP in decision-making, which can be summarized in the following steps:

Step 1: Problem hierarchy. The goal is located at the top-level; at the second level are the criteria, which can be divided into subcriteria according to the level of detail required. The criteria are defined as a set of attributes that allow the decision maker to set preferences. In the last level are all the alternatives, which are the possible solutions to make the final decision.

Step 2: Set priorities for criteria. A numerical value must be assigned to all criteria according to the preferences of the decision maker. In Saaty (2008) the scale presented in Table 1 was proposed, and its effectiveness has been validated by numerous researchers with a theoretical support related to the best scale to compare homogeneous elements.

With the scale proposed by Saaty, the decision maker must perform the paired comparison, set priorities, and assign relative weights. A matrix A of paired comparisons must be developed where the terms a_{ij} (w_i/w_j) are the result of the comparison between the elements i and j. The opposite values of the comparisons are placed in the a_{ji} position of A as can be seen in Equation 1.

$$A=\begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ 1/a_{12} & 1 & \dots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \dots & 1 \end{bmatrix} \quad (1)$$

In the case of problems of consistency with the decision maker, a matrix R is generated by performing a perturbation in the matrix A in such a way that: $R^*w = \lambda_{max}{}^*w$; where w is the auto-vector of the comparison matrix and λ_{max} is the dominant auto-value of the same matrix.

Step 3: Verify the consistency of the judgments. Consistency index (CI) is used to measure consistency, which is mathematically defined as $CI = (\lambda_{max}-n)/(n-1)$. To verify the CI values, a comparison is made with the random consistency index (RI). This parameter is defined as an average of the CIs of a large set of matrices with random inputs (Saaty and Vargas, 2012) Table 2.

In addition, Saaty defines the consistency ratio (CR) = CI/RI. If $CR \leq 0.1$, then the results are consistent. When $RC > 0.1$, the data are inconsistent and therefore the decision maker judgments must be reviewed.

Step 4: Define priorities for subcriteria. In the case that subcriteria have been defined in the decision problem, it is necessary to proceed as in step 3. For this purpose, the paired comparisons must be made in order to establish the importance of the subcriteria with respect to the higher level.

Table 1: Pair-WISE comparison

Numerical rating	Definition
1	i is equally important to j
3	i is slightly more important than j
5	i is strongly more important than j
7	i is very strongly more important than j
9	i is extremely more important than j
2,4,6,8	Intermediate
Reciprocals	If activity i has one of the above numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i

Table 2: RI

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

RI: Random consistency index

Step 5: Define priorities for alternatives. In this case also the procedure explained in step 3 is followed, but taking into account that a comparison must be made between alternatives to establish preferences according to the criteria and subcriteria that have been defined.

Finally, the global weight for the criteria, subcriteria and alternatives is obtained from the multiplication of the local weight (w_l) by the global weight of the immediately superior criterion. The sum of the global weights of the alternatives in relation to each criterion is the mechanism to obtain the evaluation of all possible alternatives.

3. POTENTIAL OF RENEWABLE ENERGY SOURCES IN COLOMBIA

Due to its climatic conditions, its location in the tropics and in the Andes Mountains, Colombia is a country with a high potential for the development of renewable energies, mainly for wind, solar, biomass and small hydroelectric power plants (SHPP). However, it must create the necessary conditions to foster its development in order to consolidate itself as a leading country in reducing the carbon footprint with capacity to export clean energy. Currently, 78% of the energy consumed in Colombia comes from fossil fuels; the remaining 22% is obtained with renewable energy. By 2020, 30% penetration of renewables in non-interconnected areas is expected (Consorcio Energético Corpoema, 2010). Below are some statistics on the potential of renewable energies (solar photovoltaic [PV], wind, SHPP, biomass) according to the statistics presented in (UPME, 2015):

The potential of the solar PV energy has been calculated based on the information provided by the meteorological stations installed by the Institute of Environmental Studies (IDEAM). The UPME has, at its disposal, the general community the atlas of solar radiation in Colombia, which was carried out using solar brightness stations and radiometric stations. From this information, the solar potential was calculated for each of the Colombian regions. The values are between a minimum of 1,278 kWh/m^2/year for the Pacific coast and a maximum of 2,190 kWh/m^2/year for La Guajira. On the Caribbean region of Colombia, there is an annual average solar irradiation of 1,825 kWh/m^2/year.

On the other hand, the UMPE and IDEAM made the atlas of energy resources of Colombia as a tool for energy planning. The information available in the atlas was taken from 111 stations installed throughout Colombian territory, in addition to meteorological models. The greatest potential for the country is in La Guajira with values between 1,000 and 1,331 W/m^2. In addition, there are cities where wind speeds are ideal for wind energy. The island of San Andrés, Island of Providencia, Gachaneca, Riohacha, Soledad, Cúcuta, Bucaramanga, Bogotá and Santa Marta have wind speeds varying between 4 and 5 m/s.

Colombia has great potential in regards to biomass, taking into account the amount of agricultural and forestry residue that are generated in the country. It is estimated that in Colombia there is an approximate energy capacity of 12,000 MWh/year from agricultural residual biomass using the oil palm pulp, rice husks, cane bagasse, coffee pulp, among others. For example, in the Department of Magdalena located in the Caribbean region of Colombia, there is potential for residual biomass in the following sectors: Livestock (5,803.13 TJ/year), bovine (5,774.17 TJ/year), oil palm (1,911.53 TJ/year), banana (1,591.58 TJ/year) and coffee (661.5 TJ/year).

The country has a potential of 25,000 MW for SHPP, of which 197 small plants have been built with an installed capacity of around 220 MW. According to the Energy Consortium Corpoema, this hydraulic potential has not been fully exploited. In big installations, only 8.27% have been exploited and in SHPP only 0.67% have been exploited.

4. ESTABLISHING CRITERIA, SUBCRITERIA AND ALTERNATIVES

A bibliographic review of researches related to energy planning problems using multicriteria decision tools was carried out in order to establish the criteria and subcriteria. In this way, a preliminary list of 35 subcriteria was prepared, grouped into 5 categories: Technical, economic, social, environmental and risk.

To establish the final subcriteria, a group of experts in the following categories was consulted:
1. Companies: Firms from the renewable energy sector.
2. Academics: Researchers, university professors.
3. Regulators: Regional administrative entities.

Non-governmental organizations: Environmental protection organizations and community organizations belonging to rural communities.

A survey was developed and answered by 47 of the 55 experts consulted. From the responses obtained, 21 subcriteria were defined (Table 3). The references that were consulted to define the subcriteria are shown in Annex Table 1.

4.1. Technical Criteria

These criteria define the technical relevance of the renewable energy to be implemented, according to the scope established in the following subcriteria:
1. Efficiency: Conversion efficiency of primary energy into electrical energy.
2. Maturity of technology: Stage of development of renewable energy.
3. Spare parts availability: Availability of spare parts for preventive and corrective maintenance activities in small and large faults.
4. Infrastructure: Existence of the physical infrastructure necessary for the implementation of the system.
5. Reliability: Ability of the system to function according to design conditions and to support failures.

4.2. Economic Criteria

The economic criteria allow for incorporation of the benefits and costs incurred in implementing the project, according to the scope established in the following subcriteria:

1. Investment costs: Total cost of equipment and materials.
2. Operation and maintenance costs: Costs for preventive and corrective maintenance.
3. Payback period: Time required to recover the cost of the initial investment.
4. Service life: Time during which the devices of the renewable system can be used according to the specifications of the manufacturers.

4.3. Social Criteria

These criteria take into account the benefits and problems in the communities of the rural areas, according to the renewable system that is implemented in their lands:

1. Acceptability of local residents: Willingness of the community to accept the implementation of the renewable system in their localities.
2. Local job creation: Number of local jobs created for installation, maintenance and repair of the renewable system.
3. Energy for rural health and education: The capacity of the renewable system to supply electricity in schools and health centers in the rural community.
4. Installation on indigenous lands: Acceptance of the indigenous authorities regarding the installation of the renewable system in territories considered sacred.

4.4. Environmental Criteria

The environmental criteria incorporate the impact of the implementation of the project with renewable energies in the environment, according to the scope established in the following subcriteria:

1. Gas emissions: Emissions of greenhouse gases produced by the renewable system to be implemented.
2. Requirement of land and water resources: Land and water resources needed to implement the renewable system.
3. Visual impact: Impact of the renewable system on the existing natural landscape in the rural community.
4. Hazardous waste: Generation of waste that impacts the environment and the community.

4.5. Risk Criteria

With the risk criteria, the objective is to incorporate the risks to which the system is exposed to the occurrence of unforeseen situations but that can significantly affect its functioning:

1. Natural phenomena: Risks to which the renewable system is exposed by the occurrence of natural phenomena such as storms, heavy rains, earthquakes and floods.
2. Armed conflict: Risks related to events specific to the armed conflict in Colombia.
3. Investment risk: The risks to which the investment is exposed because of variations in the market representative rate.
4. Technological obsolescence: Risks of equipment becoming obsolete in the short or medium term. Equipment that stops being manufactured and cannot be replaced in case of failure.

4.6. Alternatives

Based on the statistics presented in UPME (2015) and the participation of the expert group, four types of renewable energy were defined for the decision-making process: Wind power, SHPP, solar PV and biomass.

Table 3: Selected subcriteria

Criteria	Subcriteria
C1. Technical	1. Efficiency
	2. Maturity of technology
	3. Spare parts availability
	4. Infrastructure
	5. Reliability
C2. Economic	1. Investment cost
	2. Operation and maintenance costs
	3. Payback period
	4. Service life
C3. Social	1. Acceptability of local residents
	2. Local job creation
	3. Energy for rural health and education
	4. Installation on indigenous lands
C4. Environmental	1. Gas emissions
	2. Requirement of land and water resources
	3. Visual impact
	4. Hazardous waste
C5. Risk	1. Natural phenomena
	2. Armed conflict
	3. Investment risk
	4. Technological obsolescence

5. PRIORITIZATION

In the process of prioritization of criteria, subcriteria and alternatives, the same group of experts used in the selection process was consulted. A questionnaire was developed following the methodology proposed for the AHP, which was answered by 47 experts.

For each expert, 11 matrices of comparison were elaborated distributed as follows: Criteria, technical subcriteria, economic subcriteria, social subcriteria, environmental subcriteria, renewable energy alternatives with respect to technical, economic, social, environmental and risk criteria. Each expert was assigned the same weight, so a process of aggregation of all the judgments was performed using the geometric mean.

For the case of prioritization of the criteria, after the aggregation process performed with the answers of the 47 experts, the comparison matrix of Table 4 was obtained. The pairwise

Table 4: Pairwise comparison matrix of criteria

Criteria	Technical	Economic	Social	Environmental	Risk
Technical	1	1.958	1.175	0.963	1.316
Economic	0.511	1	1.149	0.938	1.043
Social	0.851	0.870	1	1.098	1.185
Environmental	1.039	1.066	0.911	1	1.572
Risk	0.760	0.959	0.844	0.636	1

Table 5: Normalized pairwise comparison matrix of criteria

Criteria	Technical	Economic	Social	Environmental	Risk
Technical	0.240	0.335	0.231	0.208	0.215
Economic	0.123	0.171	0.226	0.202	0.171
Social	0.205	0.149	0.197	0.237	0.194
Environmental	0.250	0.182	0.179	0.216	0.257
Risk	0.183	0.164	0.166	0.137	0.164

comparison matrices for subcriteria and alternatives are shown in Annex Tables 2-11.

Subsequently, the normalized pairwise comparison matrix of criteria was obtained, as can be seen in Table 5.

From Tables 4 and 5, the priority vector and the CR for the criteria were obtained (Table 6). To obtain the other priorities, the same procedure presented for the criteria was applied. In order to facilitate the calculations, expert choice software was used, which enters the individual judgments of the experts and generates the local and global preferences of all levels of the hierarchical tree (criteria, subcriteria and final selection alternatives).

Table 6: CR of criteria

CR		Priority vector	
Λmax	5.063	Technical	0.247
N	5	Environmental	0.217
CI	0.016	Social	0.196
RI	1.11	Economic	0.179
CR	0.01419	Risk	0.163

CR: Consistency ratio, CI: Consistency index, RI: Random consistency index

Table 7: Local priorities for alternatives

Alternatives	Local priority	CR (%)
Alternatives/technical criteria	Solar PV: 47.0%	0.316
	Wind: 21.9%	
	Biomass: 16.0%	
	SHPP: 15.1%	
Alternatives/economic criteria	Solar PV: 50.9%	0.977
	Wind: 21.6%	
	SHPP: 15.3%	
	Biomass: 12.3%	
Alternatives/social criteria	Solar PV: 44.7%	1
	Wind: 22.4%	
	SHPP: 16.8%	
	Biomass: 16.1%	
Alternatives/environmental criteria	Solar PV: 46.0%	0.319
	Wind: 25.7%	
	Biomass: 16.1%	
	SHPP: 12.1%	
Alternatives/risk criteria	Solar PV: 38.6%	0.960
	Wind: 27.2%	
	SHPP: 17.7%	
	Biomass: 16.4%	

CR: Consistency ratio, SHPP: Small hydroelectric power plants, PV: Photovoltaic

6. RESULTS AND DISCUSSION

After processing the matrices of importance for the criteria, subcriteria and alternatives, as a result of the process of aggregation of the individual judgments of the 47 experts, reasons of consistency between 0.238% and 1.419% were obtained. The individual CRs that were calculated for all the experts ranged from 0.298% to 10%.

6.1. Results of Local Priorities for Criteria and Subcriteria

Using Expert Choice, graphic representations of the priority vectors for all levels of the hierarchy established with the AHP were obtained. According to experts, the two most important technical subcriteria include efficiency (30.1%) and spare parts availability (21.8%). Figure 1a for the economic subcriteria (Figure 1b), the first two places of relevance were assigned to the investment cost (33.9%) and the payback period (25.7%).

In the case of social subcriteria Figure 2a, the highest priority was for acceptability of local residents (32.4%), followed by energy for rural health and education (26.6%). For the environmental subcriteria, Figure 2b, the first two places of relevance were for requirement of land and water resources (36.8%) and gas emissions (30.3%).

The two risk sub-criteria that obtained the most relevance were the risks of natural phenomena (33.8%) and the risks of technological obsolescence (23.6%) (Figure 3a). In the case of the criteria, Figure 3b, it can be observed that the technical criteria with a 24.7% have a greater influence for the decision-making according to the experts. However, there is no greater difference with respect to environmental criteria (21.7%) and social criteria (19.6%). The criteria that have the lowest priority are the economic criteria (17.8%) followed by the risk criteria (16.3%).

The results obtained for the prioritization of criteria and subcriteria can be compared with different researches in energy planning problems:

In Hernández et al. (2015) used 3 technical subcriteria for the integral net energy design of small-scale hybrid renewable energy systems. As in this paper, the technical sub-criterion with greater relevance was the efficiency with a high percentage of acceptability of 75.14%. Second was the infrastructure with 17.82%, followed by the maturity of the technology with 7.04%. Similarly, in the case of economic subcriteria, the highest priority was in the same direction as in the present study, which was obtained by the total cost of the project (42.86%).

On the other hand, in Rojas and Yusta (2014), three social subcriteria were used in their research work for electric supply planning in rural remote areas. In contrast to this work, the first two places of global relevance were for the human development index (10.23%) and the social acceptance of energy (8.87%).

In the research carried out in Ahmad and Tahar (2014) for the selection of renewable energy sources for sustainable development, 3 environmental subcriteria were used, which obtained percentages of relevance different from the results obtained in this work. The greatest relevance was for the emission of CO_2 with an overall percentage of 9.30%, followed by the impact on the environment with 3.80% and land requirements with 1.50%.

Table 8: Global priorities for criteria and subcriteria

Subcriteria	Global (%)
Requirement of land and water resources	8.0
Efficiency	7.4
Gas emissions	6.6
Acceptability of local residents	6.3
Investment cost	6.0
Natural phenomena	5.5
Spare parts availability	5.4
Energy for rural health and education	5.2
Local job creation	4.7
Payback period	4.6
Reliability	4.3
Maturity of technology	4.0
Service life	3.9
Hazardous waste	3.8
Armed conflict	3.8
Technological obsolescence	3.8
Infrastructure	3.6
Operation and maintenance costs	3.3
Installation on indigenous lands	3.3
Visual impact	3.3
Investment risk	3.2

In the case of the criteria, the results obtained are in line with the work done in Rojas and Yusta (2014), where four of the criteria established in the present study were used - economic, environmental, social and technical - for supply planning electricity in rural areas. As in this research, the highest percentage was assigned to the technical criteria with a 30.14%. However, there are differences regarding the other priorities obtained: Social criteria (26.65%), environmental criteria (22.48%) and economic criteria (20.72%).

6.2. Results of Local Priorities for Alternatives

The 5 renewable energy alternatives (wind, SHPP, solar PV and biomass) were compared through a hierarchy of 3 levels, with respect to each of the 5 established criteria (technical, economic, social, environmental and risk). Using expert choice, graphic representations of priority vectors were obtained. Table 7 summarizes the results obtained for the local priorities of the alternatives with respect to the 5 types of criteria studied. According to experts, the first two places of relevance were for solar PV and wind energy. The third and fourth preference was alternated between biomass and SHPP.

6.3. Results of Global Priorities for Criteria and Subcriteria

Table 8 shows the subcriteria ordered according to their global priority. The 3 subcriteria with the highest global priority were: Requirement of land and water resources (8%), efficiency (7.4%)

Figure 1: (a and b) Priority vectors for technical and economic subcriteria

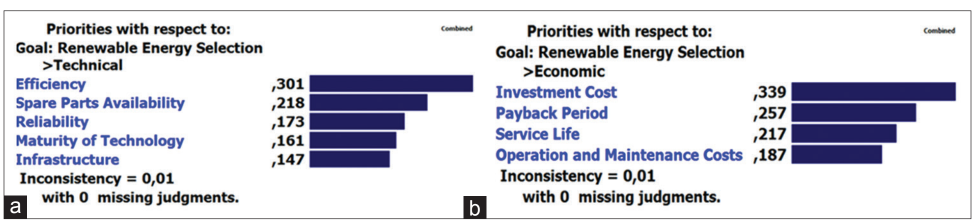


Figure 2: (a and b) Priority vectors for social and environmental subcriteria

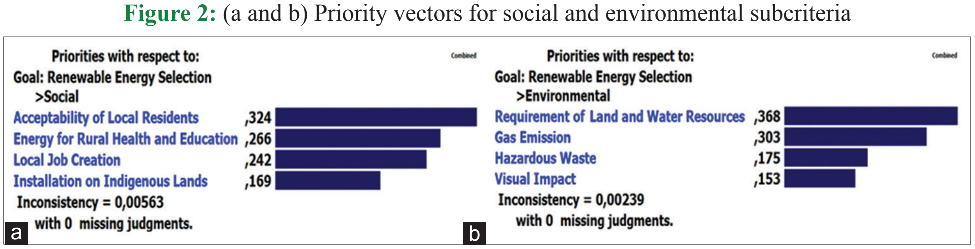


Figure 3: (a and b) Priority vectors for risk subcriteria and for criteria

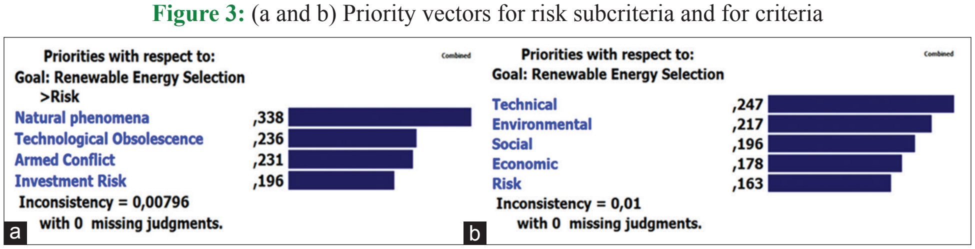
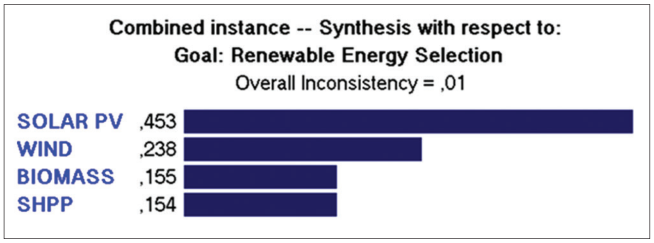


Figure 4: Global priorities for alternatives



and gas emissions (6.6%). In the three last places of preference are the installation on indigenous lands (3.3%), visual impact (3.3%) and investment risk (3.2%).

6.4. Results of Global Priorities for Alternatives

Figure 4 shows the overall priorities for the four types of renewable energy. Solar energy in the opinion of experts is the best option to implement in rural areas of the Caribbean region of Colombia with 45.3%. Second is wind energy with 23.8%. In the last two places with very similar percentages are the biomass with 15.5% and the SHPP with 15.4%.

These results are consistent with the statistics compiled by the UPME regarding the solar potential of the Colombian Atlantic Coast, which indicate that the potential in this region of the country is 73% compared to the global reference of 2,500 kWh/m2/year. In addition, the monthly variations in Colombian territory, with respect to the global measure, are minimal compared to other regions of the world, which reduces the size of energy storage systems.

The results obtained can be compared with the research carried out in Ahmad and Tahar (2014), for the selection of renewable energy sources for sustainable development. As in the present work, the same types of renewable energies were used: Solar, wind, hydroelectric and biomass. The highest priority was for solar energy (35.8%). On the other hand, in Demirtas (2013), research was carried out to evaluate renewable energies in sustainable energy planning, in which, unlike this research, the highest priority given by experts was for wind energy (29.8%), followed by biomass (19.8%), geothermal (18.4%), solar (17.5%) and hydroelectric power (14.5%).

7. CONCLUSIONS

It was possible to establish a multicriteria hierarchy for the selection of renewable energies in the electric supply of the rural areas of the Caribbean region of Colombia. It was demonstrated the flexibility and simplicity of the AHP as a useful tool to prioritize criteria, subcriteria and alternatives, in order to offer assistance to the decision maker.

The importance of expert choice software was verified to facilitate the processing of expert judgments, as well as the calculation of CRs for matrices obtained from paired comparisons. Five criteria were established: Technical, economic, social, environmental and risk; as well as a total of 21 subcriteria. After the process of aggregation of the individual judgments for all matrices combined, a CR ≤10% accepted in the methodology proposed by Saaty for the AHP was obtained. Taking into account that the experts gave their opinions with the verbal scale proposed by Saaty, the geometric mean was obtained by transforming each verbal judgment to its numerical equivalent, using the fundamental scale of Saaty.

The technical and environmental criteria were the most relevant for multicriteria decision-making. In the case of subcriteria, the highest global priority was for the environmental subcriteria of requirement of land and water resources. Four renewable energy options were defined: Wind, SHPP, solar PV and biomass. Five matrices combined were implemented as a result of the comparisons of pairs of the four renewable energy alternatives with respect to the technical, economic, social, environmental and risk criteria. The CR obtained for each of the 5 matrices was lower than the 10% proposed for the AHP.

For all the evaluated alternatives, the highest pertinence was for solar energy. Second was for wind power. These results demonstrated the importance that experts gave to these types of renewable energy for energy planning in rural areas of the Caribbean region of Colombia.

REFERENCES

Abdullah, L., Najib, L. (2014), Sustainable energy planning decision using the intuitionistic fuzzy analytic hierarchy process: Choosing energy technology in Malaysia. International Journal of Sustainable Energy, 35(4), 360-377.

Ahmad, S., Tahar, R. (2014), Selection of renewable energy sources for sustainable development of electricity generation system using analytic hierarchy process: A case of Malaysia. Renewable Energy, 63, 458-466.

Amer, M., Daim, T. (2011), Selection of renewable energy technologies for a developing county: A case of Pakistan. Energy for Sustainable Development, 15(4), 420-435.

Aragonés, P., Chaparro, F., Pastor, J., Pla, A. (2014), An AHP (analytic hierarchy process), ANP (analytic network process)-based multi-criteria decision approach for the selection of solar-thermal power plant investment projects. Energy, 66, 222-238.

Baris, K., Kucukali, S. (2012), Availability of renewable energy sources in Turkey: Current situation, potential, government policies and the EU perspective. Energy Policy, 42, 377-391.

Certa, A., Enea, M., Hopps, F. (2015), A multi-criteria approach for the group assessment of an academic course: A case study. Studies in Educational Evaluation, 44, 16-22.

Consorcio Energético Corpoema. (2010), Formulación de un Plan de Desarrollo para las Fuentes no Convencionales de Energía en Colombia. Vol. 2. Bogotá, Colombia: Diagnóstico de las FNCE en Colombia. p6-25.

Daim, T., Yates, D., Peng, Y., Jimenez, B. (2009), Technology assessment for clean energy technologies: The case of the Pacific Northwest. Technology in Society, 31(3), 232-243.

Demirtas, O. (2013), Evaluating the best renewable energy technology for sustainable energy planning. International Journal of Energy Economics and Policy, 3, 23-33.

Diaz, L., González, A., Romero, C. (2017), Measuring systems sustainability with multi-criteria methods: A critical review. European Journal of Operational Research, 258, 607-616.

Gualtieri, G. (2016), An integrated wind resource assessment tool for wind farm planning: System's upgrades and applications. International

Journal of Renewable Energy Research, 6, 1464-1475.
Guerrero, G., Sánchez, J., García, M., Lamata, M., Verdegay, J. (2016), Decision-making for risk management in sustainable renewable energy facilities: A case study in the Dominican republic. Sustainability, 8(5), 1-21.
Gul, E. (2014), Qualitative assessment of energy initiative: Case study from Liberia. International Journal of Energy Economics and Policy, 4(3), 360-372.
Gülçin, B., Sezin, G. (2014), A new GDM based AHP framework with linguistic interval fuzzy preference relations for renewable energy planning. Journal of Intelligent and Fuzzy Systems, 27, 3181-3195.
Hein, N., Kroenke, A., Rodrigues, M. (2015), Professor assessment using multi-criteria decision analysis. Procedia Computer Science, 55, 539-548.
Hernández, D., Urdaneta, A., de Oliveira, P. (2015), A hierarchical methodology for the integral net energy design of small-scale hybrid renewable energy systems. Renewable and Sustainable Energy Reviews, 52, 100-110.
International Renewable Energy Agency. (2015), Renewables 2015: Global Status Report. Abu Dhabi: United Arab Emirates. p23-54.
Kahraman, C., Kaya, İ., Cebi, S. (2009), A comparative analysis for multiattribute selection among renewable energy alternatives using fuzzy axiomatic design and fuzzy analytic hierarchy process. Energy, 34(10), 1603-1616.
Kang, H., Hung, M., Pearn, W., Lee, A., Kang, M. (2011), An integrated multi-criteria decision making model for evaluating wind farm performance. Energies, 4, 2002-2026.
Kaya, T., Kahraman, C. (2010), Multicriteria renewable energy planning using an integrated fuzzy VIKOR and AHP methodology: The case of Istanbul. Energy, 35(6), 2517-2527.
Khalili, N., Duecker, S. (2013), Application of multi-criteria decision analysis in design of sustainable environmental management system framework. Journal of Cleaner Production, 47, 188-198.
Kon, S., Mogi, G., Hui, K. (2013), A fuzzy analytic hierarchy process (AHP)/data envelopment analysis (DEA) hybrid model for efficiently allocating energy R and D resources: In the case of energy technologies against high oil prices. Renewable and Sustainable Energy Reviews, 21, 347-355.
Kumar, A., Deng, Y., He, X., Kumar, P. (2016), A multi criteria decision based rural electrification system. IECON 2016-42nd Annual Conference of the IEEE Industrial Electronics Society. p4025-4030.
Longo, G., Medeossi, G., Padoano, E. (2015), Multi-criteria analysis to support mobility management at a university campus. Transportation Research Procedia, 5, 175-185.
Luthra, S., Kumar, S., Kharb, R. (2015), Sustainable assessment in energy planning and management in Indian perspective. Renewable and Sustainable Energy Reviews, 47, 58-73.
Ma, X., Zeng, B., Zhang, Y., Li, Y., Liu, Z. (2015), Comprehensive evaluation of renewable energy for power projects based on CA-DEA model. 5th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT). p1848-1853.
Mardani, A., Kazimieras, E., Streimikiene, D., Jusoh, A., Nor, K., Khoshnoudi, M. (2016), Using fuzzy multiple criteria decision making approaches for evaluating energy saving technologies and solutions in five star hotels: A new hierarchical framework. Energy, 117, 131-148.
Mizanur, M., Paatero, J., Lahdelma, R. (2013), Evaluation of choices for sustainable rural electrification in developing countries: A multicriteria approach. Energy Policy, 59, 589-599.
Mourmouris, J., Potolias, C. (2013), A multi-criteria methodology for energy planning and developing renewable energy sources at a regional level: A case study Thassos, Greece. Energy Policy, 52, 522-530.
Mourmouris, J., Potolias, C., Fantidis, J. (2012), Evaluation of renewable energy sources exploitation at remote regions, using computing model and multi-criteria analysis: A case-study in Samothrace, Greece. International Journal of Renewable Energy Research, 2, 307-316.
Muñoz, Y., Guerrero, J., Ospino, A. (2014), Evaluation of a hybrid system of renewable electricity generation for a remote area of Colombia using homer software. TECCIENCIA, 9, 45-54.
Nadimi, A., Adabi, F. (2016), Optimized planning for hybrid microgrid in grid connected mode. International Journal of Renewable Energy Research, 6, 494-503.
Naveed, M., Irfan, M., Naeem, M., Iqbal, M., Waseem, M., Haneef, M. (2017), Multicriteria decision making for resource management in renewable energy assisted microgrids. Renewable and Sustainable Energy Reviews, 71, 323-341.
Nnaji, C., Chukwu, J., Moses, N. (2013), Electricity supply, fossil fuel consumption, Co2 emissions and economic growth: Implications and policy options for sustainable development in Nigeria. International Journal of Energy Economics and Policy, 3(3), 262-271.
Pisani, C., Villacci, D. (2011), A novel AHP framework for decision making in power systems sustainable development. 21st International Conference on Electricity Distribution. p1-6.
Popiolek, N., Thais, F. (2016), Multi-criteria analysis of innovation policies in favour of solar mobility in France by 2030. Energy Policy, 97, 202-219.
Rojas, J., Yusta, J. (2014), Methodologies, technologies and applications for electric supply planning in rural remote areas. Energy for Sustainable Development, 20, 66-76.
Rojas, J., Yusta, J. (2015), Application of multicriteria decision methods for electric supply planning in rural and remote areas. Renewable and Sustainable Energy Reviews, 52, 557-571.
Rosso, M., Bottero, M., Pomarico, S., La Ferlita, S., Comino, E. (2014), Integrating multicriteria evaluation and stakeholders analysis for assessing hydropower projects. Energy Policy, 67, 870-881.
Saaty, T. (2008), Decision making with the analytic hierarchy process. Services Sciences, 1(1), 83-98.
Saaty, T., Vargas, L. (2012), Models, Methods, Concepts and Applications of the Analytic Hierarchy Process. 2nd ed. Berlin: Springer.
Samal, R.K., Kansal, M.L. (2015), Sustainable Development Contribution Assessment of Renewable Energy Projects using AHP and Compromise Programming Techniques, 2015 International Conference on Energy, Power and Environment: Towards Sustainable Growth (ICEPE). p1-6.
Shabbar, S., Janajreh, I., Ghenai, C. (2014), Sustainability index approach as a selection criteria for energy storage system of an intermittent renewable energy source. Applied Energy, 136, 909-920.
Shen, Y., Lin, G., Li, K., Yuan, B. (2010), An assessment of exploiting renewable energy sources with concerns of policy and technology. Energy Policy, 38(8), 4604-4616.
Siskos, E., Askounis, D., Psarras, J. (2014), Multicriteria decision support for global e-government evaluation. Omega, 46, 51-63.
Tasri, A., Susilawati, A. (2014), Selection among renewable energy alternatives based on a fuzzy analytic hierarchy process in Indonesia. Sustainable Energy Technologies and Assessments, 7, 34-44.
Theodorou, S., Florides, G., Tassou, S. (2010), The use of multiple criteria decision making methodologies for the promotion of RES through funding schemes in Cyprus. A Review, Energy Policy, 38(12), 7783-7792.
Unidad de Planeación Minero Energética-UPME. (2015), Integración de las Energías Renovables no Convencionales en Colombia. Bogotá, Colombia: Cundinamarca. p24-77.
Wibowo, S., Deng, H. (2015), Multi-criteria group decision making for evaluating the performance of e-waste recycling programs under uncertainty. Waste Management, 40, 127-135.

Yeh, C., Xu, Y. (2013), Sustainable planning of e-waste recycling activities using fuzzy multicriteria decision making. Journal of Cleaner Production, 52, 194-204.

Zanuttigh, B., Angelelli, E., Kortenhaus, A., Koca, K., Krontira, Y., Koundouri, P. (2016), A methodology for multi-criteria design of multi-use offshore platforms for marine renewable energy harvesting. Renewable Energy, 85, 1271-1289.

Zhang, J., Lu, K., Liu, G. (2014), Multi-criteria decision making methods for enterprise energy planning under the constraint of carbon emissions. Advanced Materials Research, 962, 1690-1696.

Zhang, Y., Xu, Q., Sun, M. (2012), Perspectives for utilization of multicriteria decision methods AHP/ANP to create a national energy strategy in terms of sustainable development. Advanced Materials Research, 616, 1585-1590.

ANNEX

Annex Table 1: References used for subcriteria

S.n	Publication	Technical					Economic				Social				Environmental				Risk			
		1	2	3	4	5	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1	Abdullah and Najib (2014)	x					x	x			x	x		x	x							
2	Kumar et al. (2016)	x	x			x	x	x		x	x	x	x			x		x				
3	Samal and Kansal (2015)				x							x			x	x						
4	Demirtas (2013)	x	x			x	x	x	x	x	x	x			x					x		
5	Ma et al. (2015)					x		x	x			x			x	x						
6	Guerrero et al. (2016)							x	x										x			
7	Rojas and Yusta (2015)	x				x	x	x			x	x			x	x						
8	Luthra et al. (2015)	x							x		x		x	x	x	x		x			x	
9	Gülçin and Sezin (2014)	x					x	x	x		x	x			x	x	x			x	x	
10	Zhang et al. (2014)	x						x							x							
11	Mourmouris and Potolias (2013)	x		x		x	x	x	x	x	x	x	x		x	x	x					x
12	Mizanur et al. (2013)						x	x		x	x	x			x	x	x					
13	Mourmouris et al. (2012)	x		x		x	x	x			x	x			x	x	x					
14	Hernández et al. (2015)		x	x			x	x			x				x		x					
15	Ahmad and Tahar (2014)	x	x					x		x	x	x			x	x						
16	Tasri and Susilawati (2014)				x		x				x					x		x				x
17	Daim et al. (2009)			x		x	x															
18	Theodorou et al. (2010)	x	x				x				x											
19	Amer and Daim (2011)	x	x		x	x	x				x	x	x		x	x					x	
20	Kahraman et al. (2009)		x			x		x								x						
21	Zanuttigh et al. (2016)	x	x			x		x			x										x	
22	Shen et al. (2010)		x				x								x	x		x				
23	Baris and Kucukali (2012)	x				x	x				x	x			x		x				x	
24	Shabbar et al. (2014)	x				x	x			x												
25	Rosso et al. (2014)	x					x	x	x			x		x						x		
26	Zhang et al. (2012)				x										x			x		x		
27	Kang et al. (2011)							x		x				x				x	x			x
28	Aragonés et al. (2014)			x	x		x	x											x		x	
29	Kaya and Kahraman (2010)	x	x			x	x	x	x	x	x	x			x	x	x	x				
30	Pisani and Villacci (2011)		x				x				x				x		x		x			
31	Gul (2014)			x				x			x	x				x			x			

Annex Table 2: Pairwise comparison matrix of technical subcriteria

Technical	Efficiency	Maturity of technology	Spare parts availability	Infrastructure	Reliability
Efficiency	1	2.177	1.710	1.878	1.288
Maturity of technology	0.459	1	0.753	1.251	0.966
Spare parts availability	0.585	1.328	1	1.777	1.333
Infrastructure	0.532	0.800	0.563	1	1.056
Reliability	0.776	1.035	0.750	0.947	1

Annex Table 3: Pairwise comparison matrix of economic subcriteria

Economic	Investment cost	Operation and maintenance costs	Payback period	Service life
Investment cost	1	2.283	1.294	1.246
Operation and nce costs	0.438	1	0.741	1.066
Payback period	0.773	1.350	1	1.225
Service life	0.803	0.938	0.816	1

Annex Table 4: Pairwise comparison matrix of social subcriteria

Social	Acceptability of local residents	Local job creation	Energy for rural health and education	Installation on indigenous lands
Acceptability of local residents	1	1.587	1.141	1.711
Local job creation	0.630	1	0.991	1.546
Energy for rural health	0.877	1.009	1	1.613
Installation on indigenous lands	0.584	0.647	0.620	1

Annex Table 5: Pairwise comparison matrix of environmental subcriteria

Environmental	Gas emissions	Requirement of land and water resources	Visual impact	Hazardous waste
Gas emissions	1	0.919	1.838	1.670
Requirement of land and water resources	1.088	1	2.559	2.206
Visual impact	0.544	0.391	1	0.859
Hazardous waste	0.599	0.453	1.164	1

Annex Table 6: Pairwise comparison matrix of risk subcriteria

Risk	Natural phenomena	Armed conflict	Investment risk	Technological obsolescence
Natural phenomena	1	1.513	1.951	1.225
Armed conflict	0.661	1	1.267	0.955
Investment risk	0.513	0.789	1	1.009
Technological obsolescence	0.816	1.047	0.991	1

Annex Table 7: Pairwise comparison matrix of the alternatives with respect to the technical criteria

Alternatives/technical	Solar	Wind power	Biomass	SHPP
Solar	1	2.185	3.229	2.760
Wind power	0.458	1	1.355	1.494
Biomass	0.310	0.738	1	1.164
SHPP	0.362	0.669	0.859	1

SHPP: Small hydroelectric power plants

Annex Table 8: Pairwise comparison matrix of the alternatives with respect to the economic criteria

Alternatives/ economic	Solar	Wind power	Biomass	SHPP
Solar	1	2.880	4.059	2.749
Wind power	0.347	1	1.862	1.620
Biomass	0.246	0.537	1	0.859
SHPP	0.364	0.617	1.164	1

SHPP: Small hydroelectric power plants

Annex Table 9: Pairwise comparison matrix of the alternatives with respect to the social criteria

Alternatives/ social	Solar	Wind power	Biomass	SHPP
Solar	1	2.526	2.591	2.214
Wind power	0.396	1	1.627	1.426
Biomass	0.386	0.615	1	1.070
SHPP	0.452	0.701	0.934	1

SHPP: Small hydroelectric power plants

Annex Table 10: Pairwise comparison matrix of the alternatives with respect to the environmental criteria

Alternatives/ environmentala	Solar	Wind power	Biomass	SHPP
Solar	1	2.009	2.600	3.713
Wind power	0.498	1	1.770	2.152
Biomass	0.385	0.565	1	1.351
SHPP	0.269	0.465	0.740	1

SHPP: Small hydroelectric power plants

Annex Table 11: Pairwise comparison matrix of the alternatives with respect to the risk criteria

Alternatives/ risk	Solar	Wind power	Biomass	SHPP
Solar	1	1.770	2.132	1.894
Wind power	0.565	1	1.800	1.748
Biomass	0.469	0.556	1	0.927
SHPP	0.528	0.572	1.079	1

SHPP: Small hydroelectric power plants