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Article

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An AHP-GIS Based Approach for Site Suitability Analysis of Solar-wind Projects in Santa Marta, Colombia

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ABSTRACT

This paper presents an analysis to determine the suitable areas for the implementation of solar-wind projects in Santa Marta, Colombia. For this, an approach that integrates the decision-making tool of the Analytical Hierarchical Process (AHP) with Geographic Information Systems (GIS) was used. To identify the selection criteria, the existing literature and the renewable resources available in the study area were considered. Seven sub-criteria were identified (solar irradiation, wind speed, protected areas, armed conflict, indigenous reservations, populated zones and roads), which were weighted with the AHP by 15 experts with experience in projects with renewable energies. After performing a consistency analysis, it was found that 5 experts were consistent, while another 5 were discarded for being highly inconsistent. A consistency correction method was implemented for the remaining 5 experts, in order to have 10 experts for the weighting process. Each sub-criterion represents a map of the study area, which were superimposed in a GIS environment to implement the weighting obtained with the experts. A global map for the implementation of renewable energy projects, considering environmental, social and local infrastructure criteria was obtained. The map was classified into five categories: not suitable, marginally suitable, moderately suitable, highly suitable and optimally areas.

Keywords: Renewable Energy, Analytical Hierarchical Process, Energy Planning, Geographic Information Systems
JEL Classifications: Q20, D70, Q42, D81

1. INTRODUCTION

Traditional energy sources constitute more than 80% of the global energy demand and extreme dependence on oil is largely responsible for climate change (Ali et al., 2019). 90% of the energy consumption is related to carbon dioxide (CO_2) emissions and the concentration of greenhouse gases (GHG) in the atmosphere (IPCC, 2007). The high demands are also closely related to the notable economic, social and industrial growth that different countries have experienced in recent decades, especially developed countries, which are the largest consumers of energy per capita and therefore the largest CO_2 emitters (Gómez-Ramírez et al., 2017). It is expected that developing countries tend to imitate this behavior of industrial progress, and the evidence can be found in the development of most human activities that require the supply of conventional energy. It is estimated that of the total energy consumed worldwide, coal accounts for 28%, oil for 31% and natural gas for 22%. Thus, approximately 2.7 billion people in the global population increasingly depend on these traditional sources of energy.

In this panorama of societies whose economies are based on the exploitation and use of fossil fuels, transport has been distinguished as one of the human needs that has the greatest impact on pollution and that contributes significantly to climate change since it represents 26% of global CO_2 emissions (Chapman, 2007) Regarding the contribution of GHG, the use of vehicles with internal combustion engines, road transport and aviation stand out as critical activities. One of the main causes is that developing countries such as Colombia are experiencing rapid growth in their vehicle fleet, similar to the development of the transport sector in developed countries. Therefore, experts recommend that these activities should be controlled and eventually replaced by cleaner and renewable technologies (Simsek et al., 2017).

The priority of the Colombian institutional scheme is to cover the basic needs of the population, through the supply of electricity to the public lighting, education, health and transportation sectors, due to its contribution to the development of the country (Ñustes and Rivera, 2017). However, there are still a number of technical difficulties in the installed power generation capacity, with areas that have not been integrated into the National Interconnected System (SIN) (Superservicios, 2018; Castro et al., 2019).

The Non-Interconnected Zones (ZNI) are usually small towns isolated from the main urban capitals, difficult to access and abandoned by the central government. In general, these areas do not have decent and quality basic services. Faced with this problem, it is important to diversify the energy generation sector, based on a new clean, sustainable and decentralized energy model, based on solar and wind energy. These systems are characterized by being easy to install, operate and maintain, suitable for supplying an inexhaustible source of electrical energy for areas that do not have this service (Gómez-Ramírez et al., 2017).

The strategic geographical position of Colombia, and especially the district of Santa Marta, facilitates the development of this type of initiative, especially due to the high availability of the solar resource. Regarding the exploitation of the wind as a source of energy, in this part of the national territory there are some technical difficulties related to the orography of the region, a subject that is still being studied by government organizations and other parties interested in developing energy projects. For these reasons, the need arises to evaluate the suitability of hybrid generation systems (solar-wind), as a renewable alternative for the electricity supply in the city of Santa Marta (Krishna and Kumar, 2015). The implementation of a comprehensive analysis of the installation site is a strategic matter, in order to ensure that the renewable energy project can be profitable and with good performance (Al Garni and Awasthi, 2017).

The development of any energy project requires the study of both technical and environmental criteria, and social and economic aspects, which has a certain degree of difficulty due to the amount of statistical information available from the study area and the human effort necessary to analyze, process, quantify and reclassify each of the criteria previously raised (Oliveros-Cano et al., 2020). Consequently, in order to evaluate all this volume of information and correctly determine the suitable areas, the AHP method was implemented, which is a multi-criteria decision-making tool. AHP is a well-known decision technique in different areas of knowledge that is used to compare alternatives based on sustainability criteria, when multiple factors affect a single objective (Simsek et al., 2017).

The criteria to be considered in the suitability studies are associated with a specific geographic location, therefore it is necessary to have computational tools for modeling the physical space, such as Geographic Information Systems (GIS). GIS are geo-referenced land maps, which have recently become very popular due to their ability to combine apparently different data. These data can be grouped depending on public perceptions and expert opinions (Ali et al., 2019). Furthermore, it is possible to superimpose several layers of information through the application of logical and mathematical operators, in order to evaluate and define the areas suitable for the installation of solar/wind projects.

In previous works we found that for this type of approach the combination of GIS with MCDM techniques is widely recommended, precisely because of the practicality in the methodological application. The MCDM tool most used in energy planning projects is the AHP, which, combined with GIS platforms, have been implemented in many case studies aimed at the selection of suitable sites, in countries such as Turkey, Thailand, Ecuador, Saudi Arabia, England, Tanzania and Morocco (Ali et al., 2019; Marcillo and Fuentes, 2016; Rapal et al., 2017; Tahri et al., 2015). In Colombia, the combination of these tools has been little explored, reporting in the literature the analysis of the suitability of the soil for the construction of public schools in urban areas of the city of Bogotá (Ospina, 2015; Rivera et al., 2017) and another study for the correct location of sanitary landfills (Mejía et al., 2012).

The above context shows the importance of implementing this research, using the city of Santa Marta as a case study. Thus, this paper is structured as follows: section 2 presents the study area, criteria selection and implementation of AHP and GIS. Section 3 presents the results obtained with the criteria selected. Finally, the conclusions and references are presented.

2. MATERIALS AND METHODS

2.1. Study Area

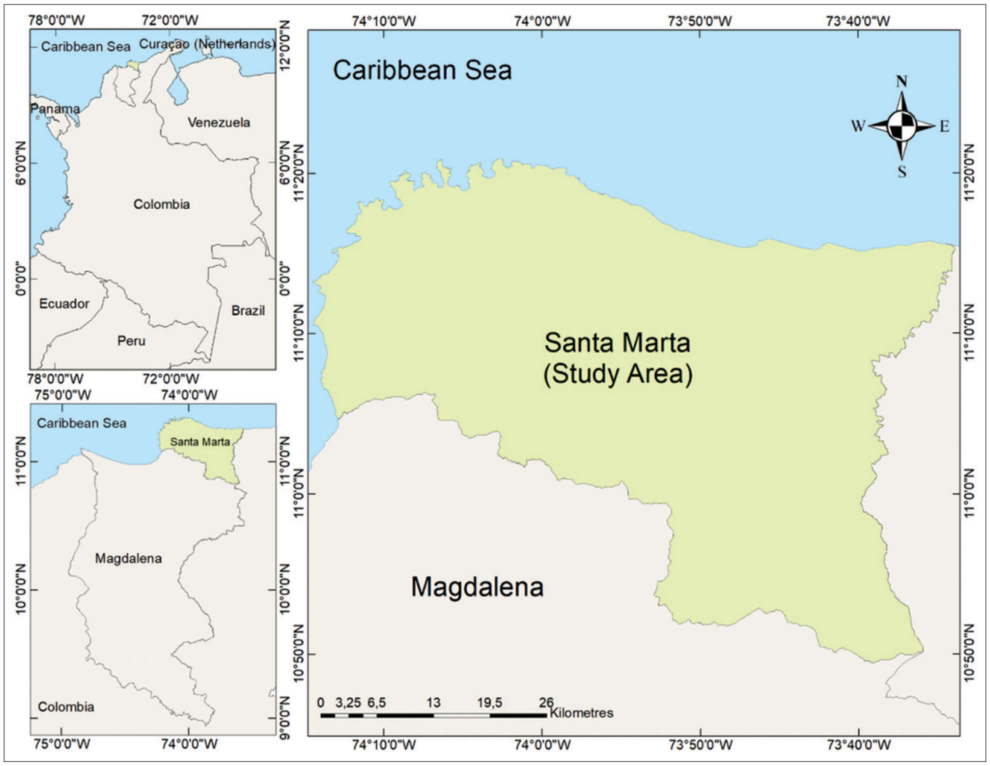
Colombia has a high renewable energy potential in most of its territory. The solar radiation atlas shows that on average the highest intensity occurs in the departments of the Caribbean Region, located in the north of the country. The study area is located in this region, as shown in Figure 1. The geographical delimitation of the study area includes the city of Santa Marta, capital of the Magdalena department, being the oldest existing city in Colombia and the second oldest in South America (Universidad del Norte, 2020).

The district of Santa Marta is a small tourist city located in the north of Colombia between the Sea and the Sierra Nevada, with geographic coordinates of 11°14'50" north latitude and 74°12'50" west latitude, and a total area of 2,393.35 km^2. The altitude of this municipal head is 6 meters above sea level (masl), with a maximum elevation of 5775 masl at the highest peak in the Sierra Nevada, known as Cristóbal Colón, considered the highest point in the entire country. Generally, the district of Santa Marta is characterized by having a warm and dry climate, with a temperature range between 23°C and 32°C, an average annual rainfall of 362 mm and a relative humidity of 77% (Alcaldía Distrital de Santa Marta, 2020).

2.2. Literature Review for the Identification of Variables for Decision Making

For the identification process of variables for decision making, the existing literature and the availability of renewable energy

Figure 1: Geographic delimitation of the study area



resources in the study area were considered. As shown in Table 1, solar irradiation and wind speed are the most essential natural resources in suitability studies for the implementation of solar-wind systems. In the same way, Table 1 shows other factors that can affect the development of the renewable energy project, which were used as criteria for decision-making.

The environmental criteria allow addressing information about environmental resources in the study area. Generally, this criterion is considered the most important for decision-makers, in order to select the most suitable among the alternatives (Simsek et al., 2017). Orography is also a very important decision criterion when the construction of a power substation with renewable energies is required. The economic criteria allow the incorporation of the costs and benefits obtained with the implementation of the system. With this criterion, the viability of the project and the generation of significant growth in the quality of life of the population are evaluated, through the creation of a local economy, health centers, education and employment opportunities.

Local infrastructure helps decision-makers to size the energy project, in order to identify the resources available for implementation, such as access to roads for the transport of personnel and equipment, or the area needed for solar-wind farms. The last criterion is the social impact, which can be categorized as an exclusion criterion. This means that the sub-criteria related to social impact function as indicators of agreement. A positive indicator consists of generating a good social impact and benefiting a vulnerable population. A negative indicator is due to the negative perception that renewable energy projects generate for society, such as electrical noise from wind turbines or accidents that birds and other animals could have with this type of technology.

2.3. Selection and Description of Criteria

The criteria and sub-criteria for this suitability study were selected after an extensive bibliographic review of research related to the determination of suitable areas for the implementation of hybrid systems. As a result of this activity, 3 criteria and 7 sub-criteria were chosen, which were later evaluated by experts. It should be noted that the selected criteria and sub-criteria are justified by the relationship with the characteristics of the study area. This way, criteria such as average temperature, maximum temperature and minimum temperature were discarded. Although it is true that these variables affect the performance of solar modules, in the city of Santa Marta the climate is generally warm, therefore, the temperature does not change abruptly.

2.3.1. Environmental criteria

2.3.1.1. Solar irradiation

Direct solar irradiation is considered the best source of energy, a resource that the city of Santa Marta has due to its excellent geographical location. This information was corroborated by the government entities responsible for monitoring solar irradiation. Until 2018, Colombia had 149 irradiation sensors owned by IDEAM (Institute of Hydrology, Meteorology and Environmental Studies) and more than 91 sensors from other entities (IDEAM, 2018).

2.3.1.2. Wind speed

Considering that the city of Santa Marta is also located in front of a territorial sea, the wind resource was used as a decision criterion. The information confirming the availability of this resource was obtained from the global wind speed atlases of various international private entities, which spatially analyze

Table 1: Literature review of suitable criteria for the development of solar-wind energy projects

Criteria	Sub-criteria	Reference
1. Environmental	Solar irradiation	(Aly et al., 2017; Anwarzai and Nagasaka, 2017)
	Wind speed	(Jahangiri et al., 2016; Höfer et al., 2016)
	Wind direction	(Marcillo and Fuentes, 2016)
	Power density	(Rapal et al., 2017; Jahangiri et al., 2016)
	Average temperature	(Al Garni and Awasthi, 2017; Tahri et al., 2015)
	Land use	(Höfer et al., 2016; Robles-Algarín et al., 2018)
	Distance to rivers or lakes	(Aly et al., 2017; Algarín et al., 2017)
	Forests	(Ali et al., 2019; Janke, 2010)
	Natural parks	(Höfer et al., 2016; Aly et al., 2017)
	Natural disasters	(Rapal et al., 2017; Robles-Algarín et al., 2018)
2. Orography	Slope	(Anwarzai and Nagasaka, 2017; Höfer et al., 2016)
	Orientation	(Tahri et al., 2015)
	Elevation	(Ali et al., 2019)
	High mountains	(Janke, 2010)
3. Economic	Population	(Uyan, 2013; Rapal et al., 2017)
	Quality of life	(Algarín et al., 2017)
	Power transmission lines.	(Janke, 2010; Höfer et al., 2016)
	Energy service costs	(Rapal et al., 2017)
4. Local Infrastructure	Urban areas	(Ali et al., 2019; Al Garni and Awasthi, 2017; Aly et al., 2017)
	Rural areas	(Anwarzai and Nagasaka, 2017)
	Area for energy farms	(Höfer et al., 2016; Rapal et al., 2017)
	Main roads	(Al Garni and Awasthi, 2017; Anwarzai and Nagasaka, 2017)
	Airports	(Ali et al., 2019)
	Power substation	(Rapal et al., 2017)
	Historical center	(Höfer et al., 2016)
5. Social Impact	Archaeological sites	(Sánchez-Lozano et al., 2013)
	Paleontological sites	(Sánchez-Lozano et al., 2013)
	Animal shelter	(Janke, 2010; Baseer et al., 2017)
	Armed conflict	(Robles-Algarín et al., 2018)
	Indigenous communities	(Janke, 2010; Algarín et al., 2017)

meteorological numerical modeling data to illustrate the average wind speeds at 10 m above sea level for several years.

2.3.1.3. Protected areas

This criterion responds to the need to safeguard protected areas and social actors that are linked to the national natural parks of Colombia, such as the Sierra Nevada de Santa Marta.

2.3.2. Social criteria

2.3.2.1. Armed conflict

Due to the social situation of the country, acts of vandalism or adverse events caused by the armed conflict may occur, which affects the proper development of projects with renewable energy.

2.3.2.2. Indigenous reservations

This criterion is established because in a large part of the territory of the Sierra Nevada de Santa Marta there are indigenous settlements. These territories, considered sacred by these communities, are legally recognized and documented with inalienable, collective or community property title. In Colombia, indigenous reservations are socio-political legal institutions of colonial origin (Agencia de Tierras, 2020).

2.3.3. Local infrastructure criteria

2.3.3.1. Populated zones

This is considered a difficult decision criterion, because the city of Santa Marta has a political-administrative division governed by three localities. The municipal seat is where most of the commercial, tourist and hotel activities are concentrated. On the other hand, there are the districts and villages classified as dispersed rural areas, but which also have their own trade and tourism zones. For this reason, some research covers this criterion from an economic perspective, however, in this work it will be understood as existing local infrastructure. This way, the evaluation of this criterion provides information about the accessibility to the energy service, considering it as a favorable factor for people in urban or rural areas who need the service.

2.3.3.2. Roads

Proximity to major roads allows the project developer to have an idea about construction and transportation costs for maintenance and operational purposes. It is considered that this criterion also works as a favorable factor, since the proximity between towns and roads in good condition benefits the community.

2.4. Analytic Hierarchy Process (AHP)

The AHP developed by Saaty is a multi-criteria decision tool, which prioritizes alternative solutions by introducing a hierarchical decision-making structure capable of involving multiple objectives (Al Garni and Awasthi, 2017). This hierarchic structure links objectives, criteria, sub-criteria and alternatives, to obtain the importance weights of the decision criteria and the relative performance measures of the alternatives in terms of each individual decision criterion, for which a paired comparison is used (Tahri et al., 2015).

To determine the weights, the criteria are arranged in a square matrix. The rows and columns in the matrix are defined by the number of criteria, which facilitates the pairwise comparison process. If the comparisons are not consistent, then a mechanism must be provided to improve consistency. For this reason, before applying the AHP method it is necessary to represent the problem in an interdependence structure, where the objective is at the highest level of the hierarchy, the criteria and sub-criteria in the middle levels and the alternatives in the bottom of the hierarchical structure. The opinions of the experts are considered for the comparison by pairs, which allows choosing the best alternative and prioritizing criteria (Abu Taha and Daim, 2013).

This decision-making tool has been widely applied in solving various decision problems, some related to energy planning and load capacity in renewable energy facilities (Ali et al., 2019; Yalcin, 2008). The AHP method allows the combination of qualitative and quantitative inputs, offering an approximate approach to solving very complex decision problems. Therefore, an important stage in the development of this work is the implementation of the hierarchical structure to prioritize criteria and sub-criteria, in energy planning with renewable energy sources in the populated zones of the city of Santa Marta, Colombia. The hierarchical structure with the criteria and sub-criteria defined in section 2.3 is presented in Figure 2.

The AHP method is based on a theoretical foundation that allows structuring the information of n alternatives ($A_1, A_2, \cdots, A_n$), with n weights ($W_1, W_2, \cdots, W_n$). The decision maker does not know the value of the weights, but is able to make a pairwise comparison between the different alternatives and make judgments that are represented by an n × n matrix (Sánchez-Lozano et al., 2013). See equation (1).

$$A = \begin{matrix} A_1 \\ A_2 \\ \bullet \\ \bullet \\ A_n \end{matrix} \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \bullet & \bullet & \cdots & \bullet \\ \bullet & \bullet & \cdots & \bullet \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \quad (1)$$

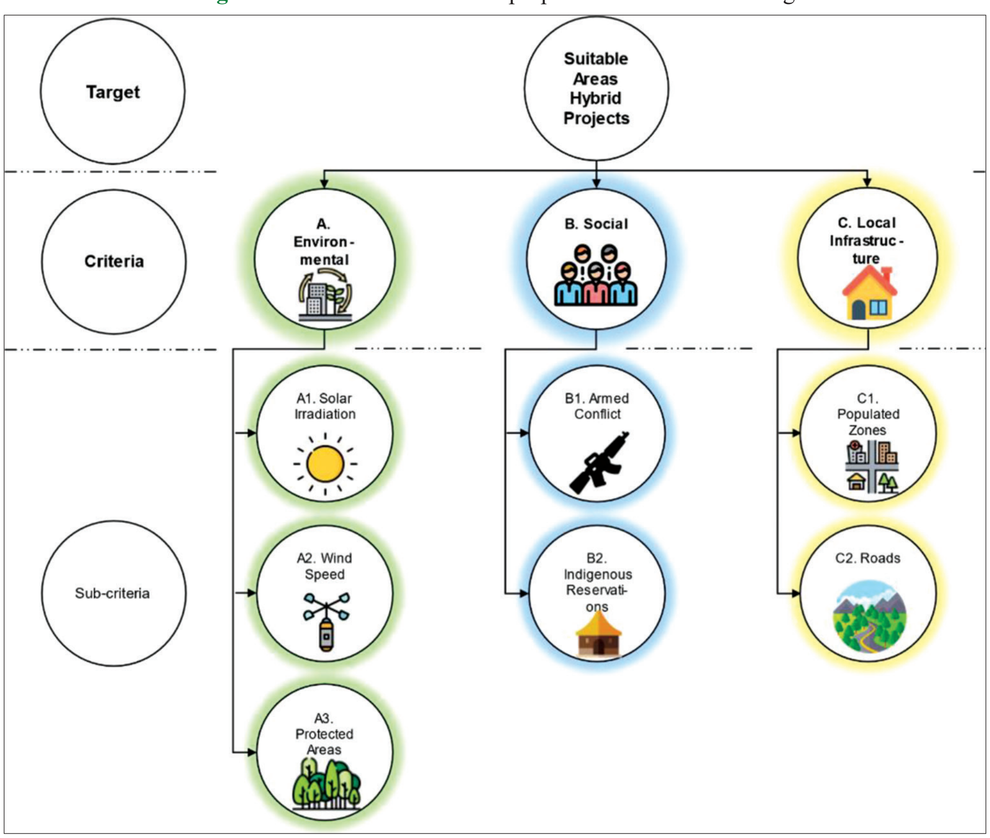
The AHP methodology begins with the values assigned by the experts for all the a_{ij}, which are in a range from 1 to 9 with their respective reciprocal values. Table 2 describes the definition of each of these values. The usefulness of this scale was proposed by Saaty in 2008 and its effectiveness has been validated by numerous research reports, classifying it as the best scale to compare homogeneous elements. With this scale, the decision maker performs the pairwise comparison of the criteria and sub-criteria, establishes priorities and assigns the relative weights (Algarín et al., 2017).

To obtain the level of consistency of the experts, initially the Consistency Ratio (CR) is calculated (Ali et al., 2019), for this, a disturbance matrix R is generated, in such a way that $R \times w = \lambda_{max} \times w$, where w is the automatic vector of the comparison matrix and λ_{max} is the automatic vector of the same matrix. Initially, the Consistency Index (CI) is calculated using equation (2).

Table 2: Saaty scale for the pairwise comparison process

Numerical value	Description
1	*i* is of equal importance 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 values
Reciprocals	If activity *i* is assigned any of the above numbers when compared to activity *j*, then *j* has the reciprocal value compared to *i*

Figure 2: Hierarchical structure proposed for decision making



$$CI = \left(\frac{\lambda_{max} - n}{n - 1} \right) \quad (2)$$

Equation (2) allows determining CR by dividing CI with the Random Consistency Index (RI).

$$CR = \frac{CI}{RI} \quad (3)$$

The values of RI are obtained from a standard matrix with random inputs, developed by Saaty for different values of n (Table 3).

If the CR≤ 0.1, then the data are consistent. If CR> 0.1 the data are considered inconsistent and the expert judgments should be reviewed. For this work, after performing the criteria prioritization process with the AHP method, the weights obtained will be used in a GIS environment in order to obtain the definitive evaluation of all possible alternatives.

2.4.1. Prioritization process and consistency analysis

For the prioritization process with the AHP method, a total of 15 experts from academic, technical and business sectors were consulted, who have experience in energy planning projects with renewable energies in Colombia. The judgments of the experts were analyzed using the Expert Choice software, in order to calculate the consistency ratio and subsequently obtain the weights for the criteria and sub-criteria of the hierarchical structure.

For this work it was considered that an expert is consistent with a 0 ≤ CR ≤ 0.1 (Saaty, 2003). For the experts with 0.1 < CR ≤ 0.3, a consistency correction method was applied. Experts with a CR> 0.3 were discarded (Table 4). In the process of improving the consistency of the matrices, the aim is to preserve the greatest amount of information provided by the experts in the consultation instruments. Additionally, the variation of any parameter will result from the study of each of the available matrices, that is, it is not allowed to apply random changes that considerably affect the judgment provided by the expert.

2.4.2. Method for consistency correction

Addressing a problem from a multi-criteria perspective with mathematical support and different methods to verify the validity of the judgments made by a group of experts, have made multi-criteria methods widely accepted tools in different areas of knowledge. However, despite the structuring and decomposition of complex problems offered by methods such as AHP (Saaty, 1990), the way in which the final result depends on the subjectivity of the experts has been questioned, downplaying the mathematical objectivity that the method proposes. The AHP allows inconsistencies because when making judgments, experts show a certain degree of difficulty to cardinally assess a set of options accurately, even though there is a pre-established assessment scale (Saaty, 2003).

To have a consistent paired comparison matrix, the properties of transitivity and proportionality must be met. If the matrix of expert judgment is consistent, it means that there is a logical order of preferences, otherwise the matrix is considered to be inconsistent (Xu and Xiong, 2017). This situation is detailed in equation (4).

$$\begin{cases} a_{ij}, & x_i \text{ dominates } x_j \\ 1/a_{ji}, & x_j \text{ dominates } x_i \\ 1, & \text{There is no dominance relationship between } x_i \text{ and } x_j \end{cases} \quad (4)$$

Likewise, transitivity takes mathematically the form of equation (5) (Bagla et al., 2013):

$$(a\ R\ b) \wedge (b\ R\ c) \Rightarrow (a\ R\ c)\ \forall\ a,b,c \in A \quad (5)$$

New methods for improving the inconsistency in paired comparison matrices are proposed in (Bozóki and Rapcsák, 2008; Benítez et al., 2012; Gastes and Gaul, 2013). The objective of some of these methods can be summarized in the following alternatives: (1) explore the origin of the inconsistency in the matrix, (2) compare the inconsistent matrices with reference matrices, (3) perform an algebraic relationship with the values of the matrix, and (4) establish the statistical deviation from a reference value.

In Bozóki and Rapcsák (2008), a method that compares the consistency ratio (CR) proposed by Saaty and the inconsistency index proposed by Koczkodaj (CM) is presented, finding equivalent properties that allow improving consistency. In the case of this work, the procedure for reciprocal 3 × 3 matrices is presented, since the maximum number of sub-criteria addressed for decision-making is 3 (Equation 6).

$$\begin{pmatrix} 1 & a & b \\ 1/a & 1 & c \\ 1/b & 1/c & 1 \end{pmatrix}, a,b,c \in R^+ \quad (6)$$

For the matrices implemented in the AHP, (a, b, c) denote the judgments or paired comparisons made by the experts consulted. To maintain the consistency of the matrix, the expression b = ac must be satisfied. If this condition is not met, equation (7) is implemented to improve the consistency of the matrix (Bozóki and Rapcsák, 2008).

$$0.38\left(\frac{b}{a}\right) \leq c \leq 2.63\left(\frac{b}{a}\right) \quad (7)$$

For example, given the 3x3 matrix of equation (8), which is inconsistent with a CR of 0.23.

For this matrix, $a = 1/7$ and $b=3$, therefore, implementing equation (7), the rank that c must have is obtained, in order to improve the consistency of the matrix M1. Equation (8).

Table 3: Values of the random consistency index for different matrix sizes

n	1	2	3	4	5	6	7	8	9	10	11	12
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48

$$7.98 \leq c \leq 55.23 \quad (8)$$

Therefore, choosing a value of $c = 8$ (which is defined on the Saaty scale), the matrix M1 is obtained again, which improved the consistency to CR = 0.1.

2.5. Geographic Information Systems (GIS)

According to the National Center for Geographic Information and Analysis (NCGIA), a Geographic Information System can be defined as a systematized computational tool, designed to capture, query, analyze, model, store, present and edit data, develop maps and in a general way manipulate spatial information useful in solving problems related to planning and administration that require the georeferencing of information. There are two ways to work with GIS, by raster data or vector data. Raster models are represented by a grid of rectangles, all of the same size. Each element is called a pixel or cell, and has information and geographic location. In a vector model, the GIS features are expressed as vectors and retain the geometric properties of the figure. The elements of the vector also have information associated with the database and geometrically the most used elements are points, lines and polygons (Tahri et al., 2015).

In energy studies, GIS play a very important role in the geographic exploration of localities, to facilitate the installation and development of electrical power generation systems. In more complex suitability studies, GIS tools are integrated with multicriteria decision-making methods. The successful combination of GIS with decision techniques is a perfectly complementary resource because it allows the decision maker to perform the analysis, management, storage and visualization of all geospatial information (Sánchez-Lozano et al., 2013). By combining these two tools, a new digital map associated with a database is obtained, where each point on the map has its respective geographic coordinate. The final map should contain all the characteristics and attributes related to the input files.

In Figure 3 the structure of the GIS model for this research is presented, which was structured from the hierarchical structure defined in section 2.4. Table 5 shows the geographic information related to this model.

The data of the sub-criteria represented geographically by each thematic layer with its corresponding spatial information can be seen in Figure 4. These 7 maps that belong to the district of Santa Marta (study area) will be superimposed in a GIS environment to apply the assessment of the weights obtained in the AHP process.

Table 4: Ranges established to determine the consistency of the experts

Consistency ratio	Decision
0≤CR≤0.1	Include these experts in the prioritization process.
0.1<CR≤0.3	Implement mathematical correction to improve the consistency of the experts, and include the results in the prioritization process
CR>0.3	Discard these experts from the prioritization process

The layers of geographic information, available as sub-criteria of the AHP, represent different variables of interest, from geographic locations, extensions of land, areas of interest, civil works or environmental variables. Although these criteria make up the input data layers of the GIS, by representing different parameters and values, it is necessary to achieve a representation that allows comparing and operating the different layers to obtain results for each criterion of interest.

A general scale is proposed for the treatment of the geographic information layers, which numerically indicates the level of suitability to establish the optimal areas for the development of solar-wind projects in communities with known characteristics in the environmental, infrastructure and accessibility fields. The scale between 1 and 5 determines whether a certain area has suitable characteristics for the development of the project, as follows:

1. Not suitable
2. Marginally suitable
3. Moderately suitable
4. Highly suitable
5. Optimally suitable

The importance of this scale is that it allows different characteristics to be implemented in a geographic information environment, even when different types of information are processed Table 6.

3. RESULTS

3.1. Results Obtained with the AHP

The judgments of the experts were collected and analyzed using the Expert Choice software, with which the weights for each criterion

Figure 3: Geographical modeling of the selected criteria and sub-criteria

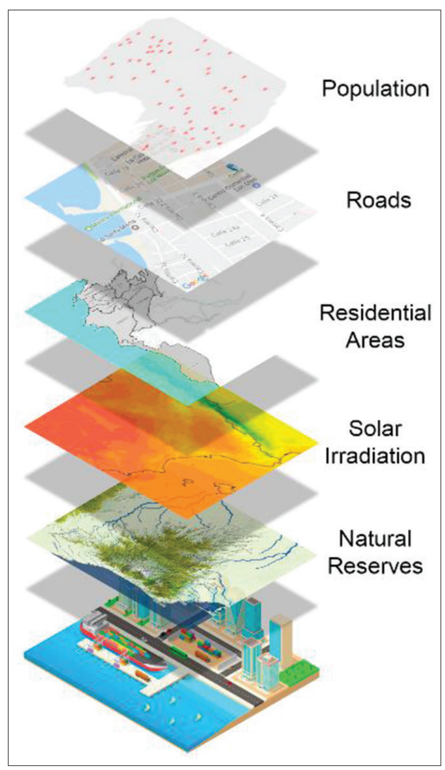
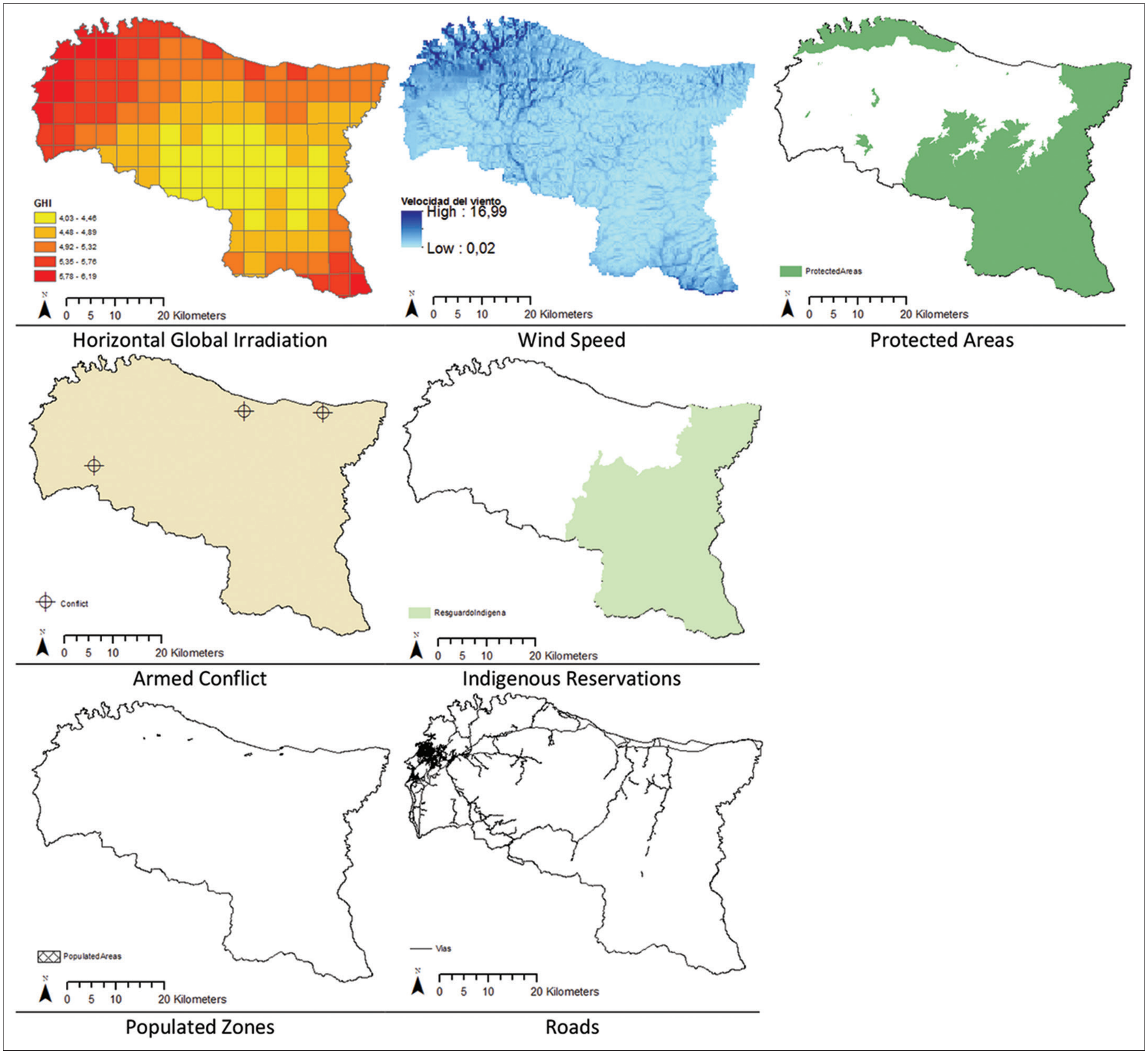


Table 5: Source of the maps to be processed in a GIS environment

Data layer	Spatial resolution	Data source	Update date
SantaMartaDTCH	1:500000	Open Data (ESRI Colombia)	May 29, 2019
GHI (Global horizontal irradiance)	1:150000	National Renewable Energy Laboratory (NREL)	2019
Wind 10 m	1:150000	RE Explorer	2020
Protected areas	1:250000	Registro Único Nacional de Áreas Protegidas – RUNAP	2018
Conflict	Points	United Nations Office for the Coordination of Humanitarian Affairs (OCHA)	2019
Reservations	1:500000	Agencia Nacional de Tierras (ANT)	July 05, 2018
Populated zones	1:150000	Instituto Geográfico Agustín Codazzi (IGAC)	2019
Roads	1:150000	Instituto Geográfico Agustín Codazzi (IGAC)	2019

Figure 4: Maps of the sub-criteria used as a reference for the investigation



and sub-criterion of the hierarchical structure were obtained. Additionally, using the software, the consistency calculation for each expert was performed.

Thus, it was obtained that 5 of the consulted experts were consistent with values for the consistency ratio ≤0.1. Five experts had a consistency ratio between 0.1 and 0.3, for which the correction method detailed in section 2.4.2 was applied. Finally, 5 experts were discarded for having a consistency ratio greater than 0.3 Table 7.

Figure 5 shows the results obtained with Expert Choice for the consistency ratio of the experts. The results framed in the boxes correspond to the 10 experts who were finally considered for the present investigation (these results include the 5 experts whose consistency was improved).

After processing the judgments of the experts, the results shown in Figure 6 were obtained for the 3 criteria (social, environmental, local infrastructure). From a general perspective, the experts consulted assessed the criteria located on the first level of the hierarchy as follows: social (0.434), environmental (0.369) and local infrastructure (0.197). The relevance given by the experts to the social and environmental criteria is highlighted, which indicates that aspects such as the presence of indigenous communities, the armed conflict, the existence of 3 natural parks and the solar-wind potential of the study area were considered. These results also reflect the reality of the city of Santa Marta, which has a weak local infrastructure in energy, accessibility, and sanitation aspects.

Figure 7 shows the results obtained in the prioritization of the sub-criteria. According to the experts consulted, for these projects it is more valuable to consider the social aspects related to indigenous communities or reservations (0.534) and zones of armed conflict (0.434). It is followed by environmental aspects related to the availability of renewable energy resources such as solar irradiation (0.470) and wind speed (0.174), as well as the presence of protected natural areas (0.376).

With the weights obtained for the different criteria and sub-criteria of the hierarchical structure, the ranges of interest are defined to obtain the optimal values of the variables and thus reclassify the maps. The reclassification process is a procedure prior to the operation of the different maps in raster format. It is important to note that each map represents a sub-criterion.

3.2. Reclassification of Maps

The seven layers that make up the geographic information system of this research were processed using the reclassification function (Reclassify), which is part of the spatial analysis tools of ArcGis 10.3 (Spatial Analyst Tools). This processing allows creating polygons around the areas of the original information layers and additionally, with the definition of a scale of values, categorizing each aspect of interest in colors. Figure 8 shows the reclassified maps for the seven sub-criteria.

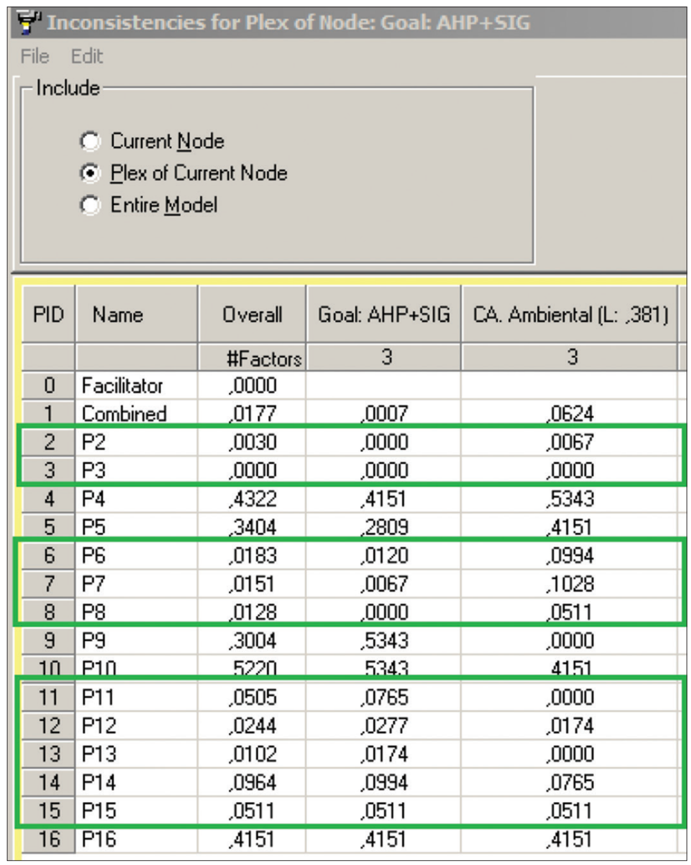
3.3. Maps Obtained with AHP Weights

Once the initial layers have been processed in the reclassification process, a map is obtained for each criterion that is the result of considering the judgments of the experts and the reclassification scale presented in Table 6. For example, the map of the environmental criteria obtained in Figure 9, it is the result of considering the layers of the Global Horizontal Irradiance, Wind Speed and Protected Areas sub-criteria, reclassified and weighted by the value obtained with the AHP (Table 8). Thus, Figure 9 presents the maps obtained for the three criteria considered in this work.

3.4. Final Map with the Suitable Areas

As a final result, the map presented in Figure 10 was obtained, in which the environmental, social and local infrastructure criteria

Figure 5: Consistency ratio calculated for each expert


Inconsistencies for Plex of Node: Goal: AHP+SIG
File Edit
Include
Current Node
Plex of Current Node
Entire Model

PID	Name	Overall	Goal: AHP+SIG	CA. Ambiental (L: ,381)
		#Factors	3	3
0	Facilitator	,0000		
1	Combined	,0177	,0007	,0624
2	P2	,0030	,0000	,0067
3	P3	,0000	,0000	,0000
4	P4	,4322	,4151	,5343
5	P5	,3404	,2809	,4151
6	P6	,0183	,0120	,0994
7	P7	,0151	,0067	,1028
8	P8	,0128	,0000	,0511
9	P9	,3004	,5343	,0000
10	P10	,5220	,5343	,4151
11	P11	,0505	,0765	,0000
12	P12	,0244	,0277	,0174
13	P13	,0102	,0174	,0000
14	P14	,0964	,0994	,0765
15	P15	,0511	,0511	,0511
16	P16	,4151	,4151	,4151

Table 6: Scale used for the suitability study

Scale	Environmental criteria			Local infrastructure criteria		Social criteria	
	GHI (kWh/m²)	Wind speed (m/s)	Protected areas (m)	Armed conflict (m)	Indigenous reservations (m)	Populated zones (m)	Roads (m)
1	≤4.08	0.02–3.42			0–500		
2	4.47	3.42–6.81			500–1000		
3	4.87	6.81–10.21			1000–2000		
4	5.27	10.21–13.60			2000–3000		
5	≥5.67	13.60–16.99			>3000		

were considered with the valuation provided by the experts, with a scale of areas suitable for the development of solar-wind projects. These zones result from the combination of the different variables of interest, which were classified according to their value in a range from 1 to 5. Thus, an area classified with a value of 1 indicates that it is very close to protected areas with low levels of solar irradiation and wind speed. On the contrary, the areas with a value of 5 correspond to the zones optimally suitable for the implementation of solar-wind projects.

To obtain the final map, all the GIS layers available in raster format were processed. Using the raster calculator of the ArcGis map algebra tool, a representation that contains both the reclassification of the values in the defined scale and the weighting with the AHP was obtained.

Table 7: Consistency ratio range obtained for experts

Expert	Consistency ratio obtained
P2, P3, P6, P7, P13	0≤CR≤0.1
P8, P11, P12, P14, P15	0.1<CR≤0.3
P4, P5, P9, P10, P16	0.3<CR≤0.55

4. CONCLUSIONS

With a review of the literature, the aspects that affect the development of projects with solar and wind energy in different countries were defined. For the choice of the factors of interest to develop this work, only the implementation of distributed systems was considered. This way, the determination of suitable areas became the objective to be developed using a multi-criteria analysis with geographic information systems.

For the consultation of experts, profiles of professionals with experience in the development of renewable energy projects were selected, in order to provide their judgments from the academic, technical, commercial, social and business fields. In the surveys, the experts assessed a hierarchical structure in order to obtain a weighting of the 3 criteria and 7 sub-criteria defined for the suitability study. Each of the sub-criteria was represented by a map that allows the graphic representation of the variables. In order to achieve greater robustness of the results and given the limited availability of experts, it was necessary to implement a correction method for the consistency ratio in some of the

Table 8: Weighting of the criteria and sub-criteria

Environmental criteria (0.369)			Social criteria (0.434)		Local infrastructure criteria (0.197)	
Global horizontal irradiance	Wind speed	Protected areas	Indigenous reservations	Armed conflict	Populated zones	Roads
0.470	0.376	0.154	0.534	0.466	0.644	0.356

Figure 6: Results obtained for the criteria

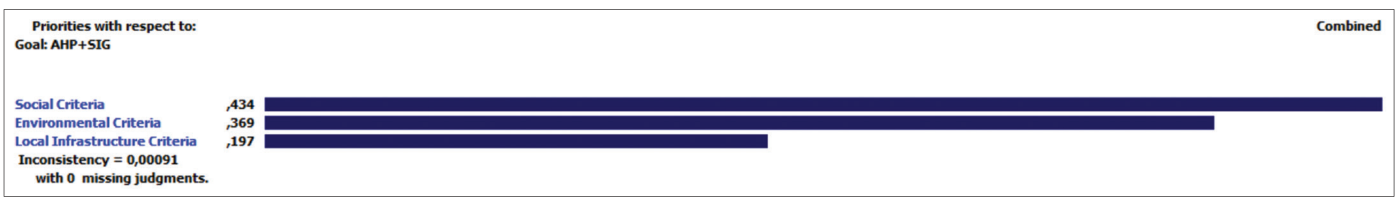


Figure 7: Results obtained for the sub-criteria

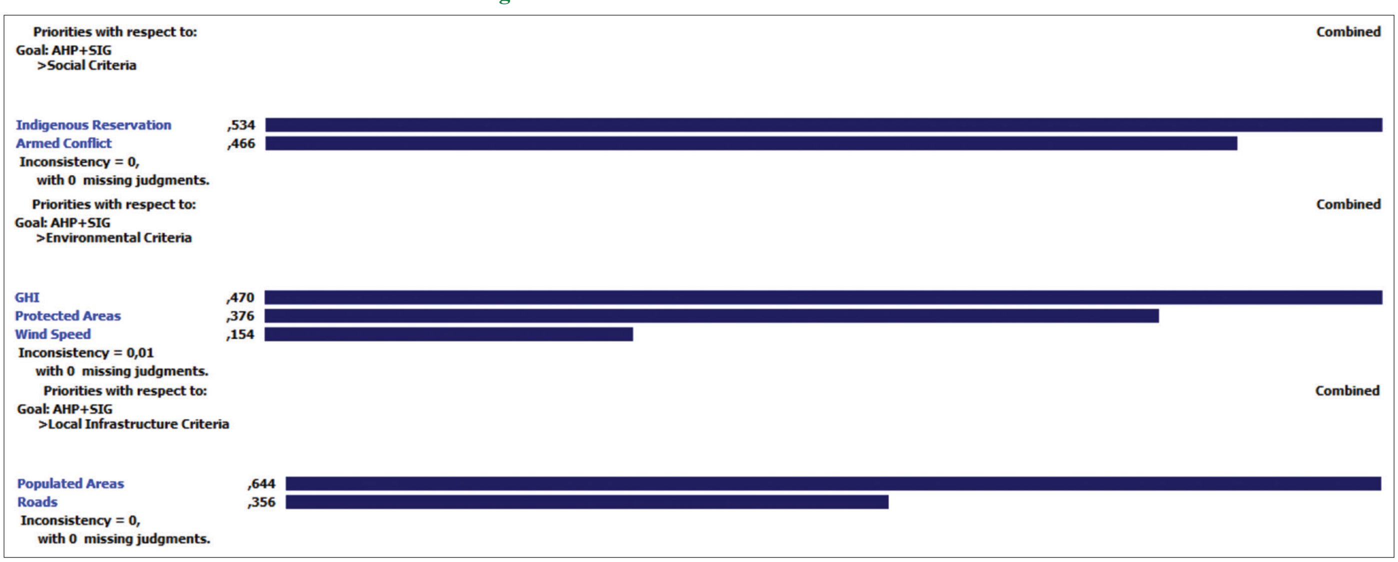


Figure 8: Maps reclassified for the sub-criteria

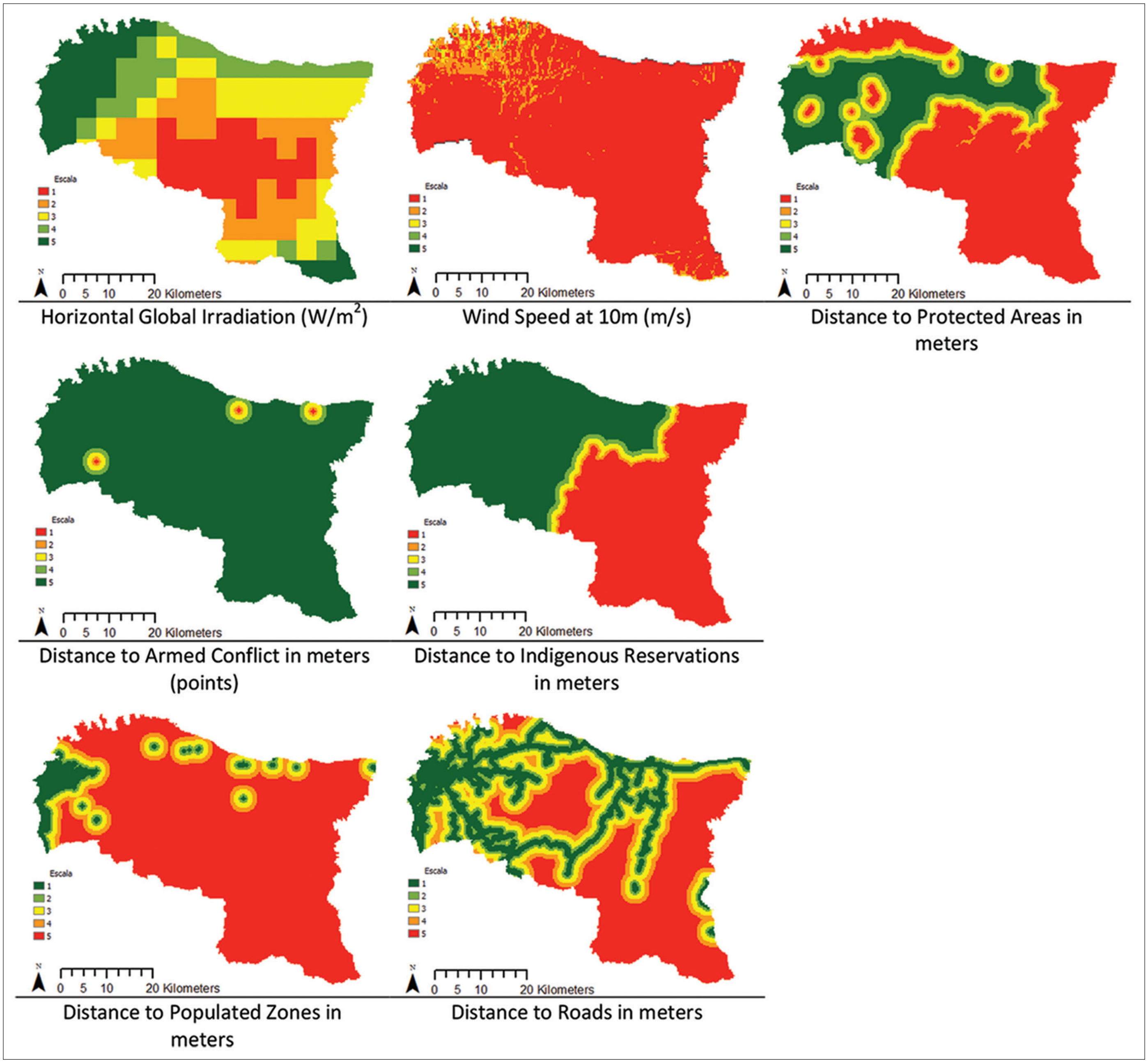


Figure 9: Maps for the three criteria with the weighting obtained in the AHP

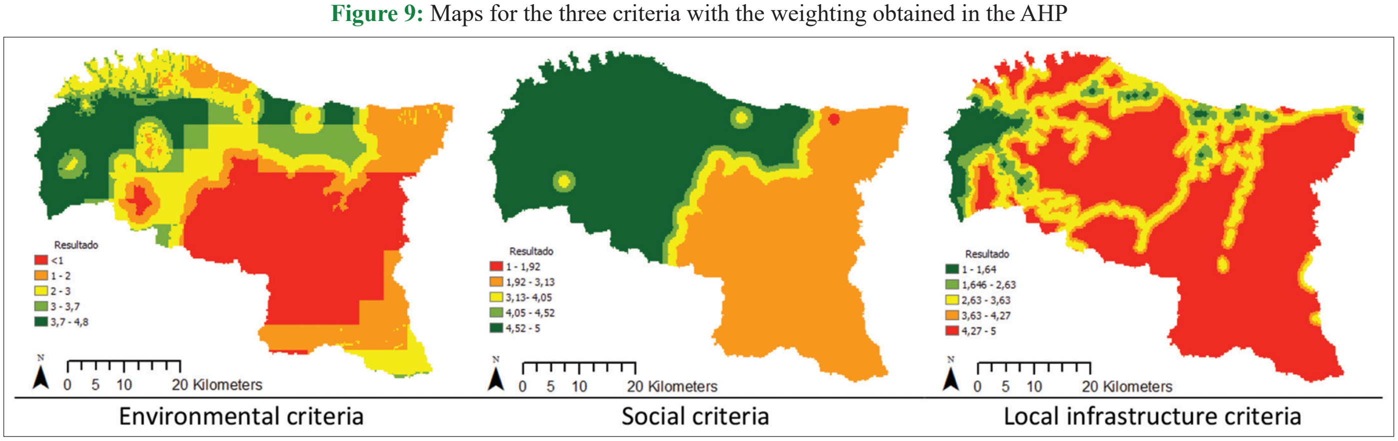
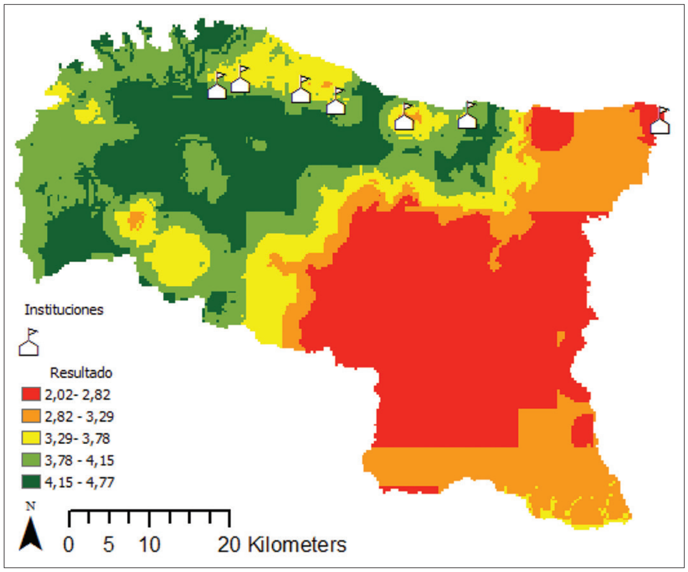


Figure 10: Final map with the suitable areas considering the criteria under study



matrices obtained. For the elaboration of the maps, the ArcGIS software was used, which allowed integrating the judgments obtained with the AHP.

This research was implemented using the district of Santa Marta, Colombia as the study area, however, it can be developed in any other territory of the national geography where decision-making is required for the development of energy projects considering different criteria.

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