Identification of areas for photovoltaic projects in La Guajira Using GIS and multicriteria analysis

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Abstract

The advancement of alternative energy in Colombia reflects a strong and shared commitment from both the national government and its citizens. The objective of this work is to characterize the potential areas for the implementation of photovoltaic projects in La Guajira, a region whose solar potential is high, but also has a complex social and environmental context. GIS and AHP were employed to evaluate several parameters including technical, environmental and socio-economic factors (solar irradiation, temperature, slope, aspect, nearness to infrastructure). The results reveal that 14.4% of La Guajira's land is very suitable for solar projects, most of it being in the southwest of the department. It is consistent with the government's national policies to encourage renewable energy and supports the diversification of Colombia's energy complex and fosters development in vulnerable regions. The approach can be adapted in comparable contexts, contributing to global action on clean energy transitions and climate change.

Keywords: photovoltaic energy; GIS; multi-criteria decision analysis; analytic hierarchy process.

Identificación de áreas para proyectos fotovoltaicos en La Guajira mediante SIG y análisis multicriterio

Resumen

El avance de las energías alternativas en Colombia refleja un compromiso fuerte y compartido tanto del gobierno nacional como de sus ciudadanos. El objetivo de este trabajo es caracterizar las áreas potenciales para la implementación de proyectos fotovoltaicos en La Guajira, una región cuyo potencial solar es alto, pero que también tiene un contexto social y ambiental complejo. Se emplearon SIG y AHP para evaluar varios parámetros, incluidos factores técnicos, ambientales y socioeconómicos (irradiación solar, temperatura, pendiente, aspecto, proximidad a la infraestructura). Los resultados revelan que el 14.4% de la tierra de La Guajira es muy apta para proyectos solares, la mayoría de ellos en el suroeste del departamento. Es coherente con las políticas nacionales del Gobierno para fomentar las energías renovables y apoya la diversificación del complejo energético de Colombia y fomenta el desarrollo en regiones vulnerables. El enfoque puede adaptarse en contextos comparables, contribuyendo a la acción mundial sobre las transiciones a la energía limpia y el cambio climático.

Palabras clave: energía fotovoltaica; SIG; modelo de decisiones multicriterio; proceso analítico jerárquico.

1 Introduction

Renewable energy is currently the focus of developing countries, aiming to replace fossil fuels with clean energy sources that do not harm the environment [1,2]. For this reason, solar energy is one of the main projects intended to meet global energy demand, which has enabled the development of this type of project in various countries [3].

In Colombia, where fossil fuels have historically dominated the energy sector, solar photovoltaic energy has emerged as a sustainable alternative to diversify electricity generation sources and reduce greenhouse gas emissions [4]. This research focuses on identifying suitable areas within the department of La Guajira, a region with high solar potential

yet facing socioeconomic and environmental challenges that require a comprehensive approach for the successful implementation of photovoltaic energy projects [5].

La Guajira, recognized for its high solar irradiation levels and arid climate, presents an optimal setting for the development of photovoltaic energy projects [6]. Due to its geographic location and high solar irradiation levels, with a daily average of 6,0 kWh/m², La Guajira is an ideal site for solar energy projects [7]. However, the region faces critical challenges, including poverty, lack of infrastructure and development, and the presence of sensitive ecosystems, necessitating a careful approach in site selection for energy initiatives [8]. These factors need a careful approach in site selection for energy projects, balancing technical feasibility with environmental and social considerations [9].

Several studies have used Geographic Information Systems (GIS) and multi-criteria analysis to determine the best locations for solar power plant installations [10]. In Valencia, Spain, [11] integrated criteria such as solar radiation intensity, terrain, environmental and climatic factors, and proximity to roads and electrical substations, alongside GIS data-including time series of solar radiation, digital elevation models (DEM), and temperature to identify high potential areas for photovoltaic parks. In Rajasthan, India, [12] identified 20.881 km² of suitable land for solar plants by developing integrated models that combined geographic, social, political, and environmental criteria. In Ecuador, [13] utilized GIS and multi-criteria analysis for siting photovoltaic plants, optimizing solar farm distribution based on national energy demand. In Kenya, [14] applied multi-criteria analysis methodologies within a GIS environment, considering nine criteria related to climate, environment, location, and topography, determining that 2,41% of the land was highly suitable for solar systems. In Egypt, [15] identified optimal areas for photovoltaic parks by assessing location, environmental, meteorological, and climatic categories using multi-criteria decision-making techniques and GIS tools. In Pakistan, [16] evaluated ten factors grouped into four categories (geographic, technical, economic and flood susceptibility), using the FUCOM method and weighted overlay analysis in ArcGIS Pro, concluding that only 2.02% of the country's area is suitable for solar power plants. Finally, developed a multi-criteria analysis using GIS to selecting optimal solar plant sites in New Aswan, Egypt, considering factors such as solar radiation, distance to road networks and distance to buildings, (0,35, 0,1 and 0,1, respectively), showing the effectiveness of the proposed model in assessing site suitability [17].

The use of GIS combined with multi-criteria analysis models like AHP has been effective for renewable energy planning globally [11-15,17-24]. In this study, this methodology was applied to evaluate key variables including solar irradiation, air temperature, topography, and accessibility, ensuring that photovoltaic projects are not only technically feasible but also environmentally and socially sustainable [25].
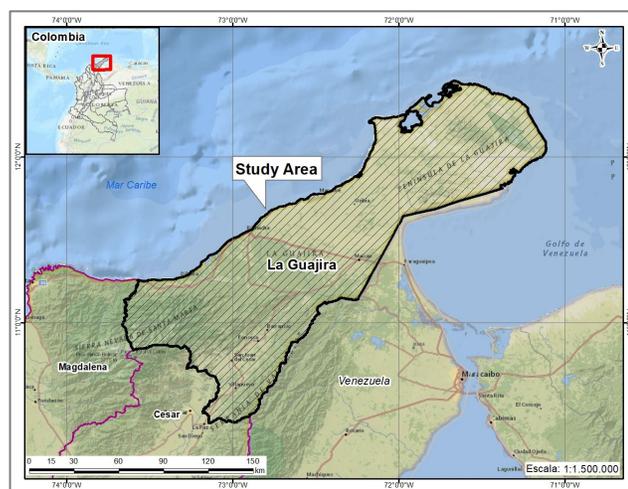

Figure 1. Location
Source: The authors

The aim of this research was to identify suitable areas for the implementation of photovoltaic energy projects in the department of La Guajira using GIS and AHP multi-criteria analysis models. Specific environmental criteria were chosen, and a geographic model was created to assess the feasibility and suitability of the proposed areas for project development.

2 Methodology

2.1 Study area

The study area corresponds to the department of La Guajira, located in the Caribbean region of Colombia. Geographically, La Guajira is bordered by the Caribbean Sea to the north and Venezuela to the east, with its capital, Riohacha, serving as the economic hub of the region (Fig. 1). Covering an area of approximately 20,848 km², La Guajira has a predominantly arid and semi-desert climate, characterized by temperatures ranging from 22 to 40°C and annual precipitation levels between 300 and 600 mm. [26].

2.2 Data

2.2.1 Solar Irradiation

Sunlight is a fundamental natural resource and an important energy source due to solar irradiation, which is used in the construction of photovoltaic projects because of its irradiation level [27]. Therefore, it is essential to understand what it is and how it is measured. Solar irradiation represents the accumulated energy over a period and is calculated using Global Horizontal Irradiation (GHI), which results from the diffuse radiation from the sky (DHI) and the direct irradiation from the sun (DNI), multiplied by the cosine of the angle between the sun's direction and the vertical (zenith). The result is measured in watts per square meter (W/m²) [27-29].

$$GHI = DHI + DNI * Cos(Z)$$

Considering the above, this study used solar irradiation (GHI) values in kWh/m², obtained directly from the SOLARGIS global solar model for the La Guajira department in Colombia. These values were provided by the Global Solar Atlas as part of the global renewable energy resource mapping initiative [30].

2.2.2 Air temperature

The temperature of solar panels directly affects their energy production. It is recommended that they operate at temperatures below 25°C, which has been shown to ensure optimal system performance [11]. Several studies have confirmed a decrease in energy production. This reduction ranges between 0.4% and 0.5% for every 1°C increase in the reference temperature [31]. For this study, the annual mean temperature values were obtained from the report *"Departmental Analysis of Vulnerability and Risk to Climate Change in the Agricultural Sector – La Guajira,"* developed by the Food and Agriculture Organization (FAO) [26].

2.2.3 Digital Elevation Model (DEM)

For this analysis, a Digital Elevation Model (DEM) with a resolution of 1 arcsec (~30 m) was used, generated by NASA's Shuttle Radar Topography Mission (SRTM) sensor, adapted to the specific topography of the La Guajira department [27,32] (Fig. 2).

2.2.4 Slope

The slope of the terrain is an important factor in selecting sites for photovoltaic energy projects, due to solar panels may cast shadows on others in terrains is too steep, reducing the system's efficiency [11-25,27-29]. Although there is no accepted exact value, experts agreed that slopes greater than 10% are not ideal for installing solar energy projects [27,33].
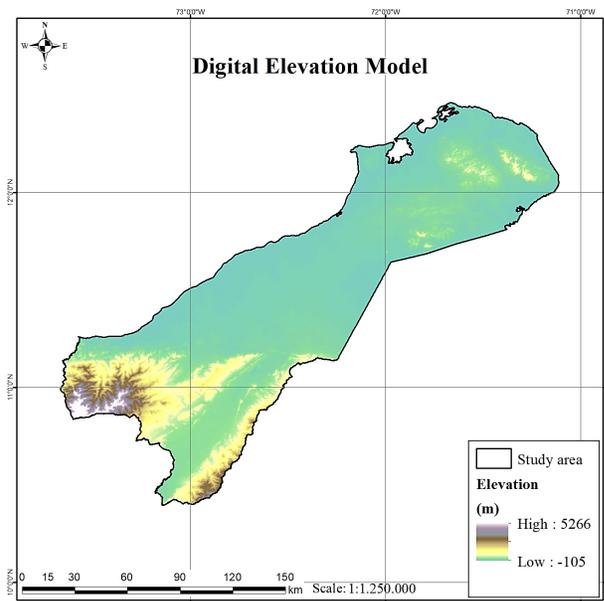

Figure 2. The elevation-based map upon the suitability classifications.
Source: The Authors.

This analysis was conducted using a digital terrain model with specialized software (ArcGIS), aiming to identify land with slopes close to 0° - that is, less inclined areas - to enhance solar irradiation reception.

2.2.5 Terrain aspect (Orientation)

The orientation of solar panels in photovoltaic energy projects plays a key role in system efficiency, as it allows for greater solar irradiation capture during peak sunlight hours. Countries in the Northern Hemisphere, such as Colombia, receive higher solar irradiation when solar panels are positioned facing south [11,14].

2.2.6 Distance urban areas

The distance between photovoltaic energy projects and urban areas has both positive and negative aspects. On one hand, proximity to urban areas could limit and affect the growth and development of communities; however, it also creates job opportunities and reduces transportation costs for personnel and materials. Thus, a 500-meter distance from urban areas was established for La Guajira department in this study [17,18,20,21,27].

2.2.7 Distance to main roads

The distance to main roads in photovoltaic projects helps reduce costs, as it facilitates the transport of personnel and materials to the project site and avoids the need to build additional roads for accessibility. Based on this, a maximum distance of 500 meters from main roads was determined as the optimal area for the study [11,13,16,17,20].

2.2.8 Distance to power lines

One of the key factors in minimizing energy loss in photovoltaic projects is proximity to transmission lines. Being close to these lines avoids construction costs and reduces energy losses, since longer distances increase energy loss during transmission. Therefore, an optimal area of 500 meters near existing transmission lines was determined [11,16-18,20]. In Table 1, it describes the parameters used along with the sources of information.

Table 1.
Data Sources

Data	Type	Source
Solar Irradiation	Raster data	https://globalsolaratlas.Info/
DEM data	Raster data	https://earthexplorer.usgs.gov/
Temperature air	Vector	https://cambioclimatico.fao.org.co/la-guajira/
Urban area	Vector	https://geoportal.dane.gov.co/servicios/descarga-y-metadatos/datos-geoestadisticos/
Roads	Vector	https://www.colombiaenmapas.gov.co/#
Water bodies	Vector	https://www.colombiaenmapas.gov.co/#
Transmission lineas	Vector	https://geovisor.anla.gov.co:8446/geovisor/#/visor
Protected areas	Vector	https://runap.parquesnacionales.gov.co/cifras
Indigenous reserves	Vector	https://www.colombiaenmapas.gov.co/

Source: The authors

This study employed a quantitative approach, focused on identifying optimal areas for photovoltaic projects using numerical data analysis and mathematical models [9,15-19,20-25,27, 29,33-40]:

- Data Collection: information obtained from meteorological, satellite, including solar irradiation (kWh/m²), air temperature (°C), terrain slope (°), terrain aspect (°), distance to urban areas and roads (km), and distance to transmission lines (km).
- Analytical Model: the Analytic Hierarchy Process (AHP) was applied within GIS software ArcMap 10.8, allowing quantitative weighting and evaluation of multiple criteria.
- Data Processing: GIS layers were created and managed, incorporating environmental data (GHI, air temperature, topography), and socioeconomic data (urban areas, roads and power lines). The criteria were normalized and adjusted to ensure uniformity in the analysis.
- Weighting and Mapping: Using AHP, the criteria were weighted, generating a suitability map that highlights optimal zones for photovoltaic projects. (Fig. 3).

2.2.9 Analytic Hierarchy Process (AHP) based on multi-criteria decision-making

The AHP process is used for multicriteria decision-making. Its hierarchical structure allows for an organized evaluation of key elements [43]. These elements are crucial for problem-solving and are assigned weight factors. Priorities are established using a comparison matrix based on preference or relevance, enabling the identification of optimal and suitable solutions [20]. This methodology ensures quality and accuracy in decision-making, facilitating the assessment of strategies, requirements, and alternatives [15,17,19,21-22,24-25,27,29,35].
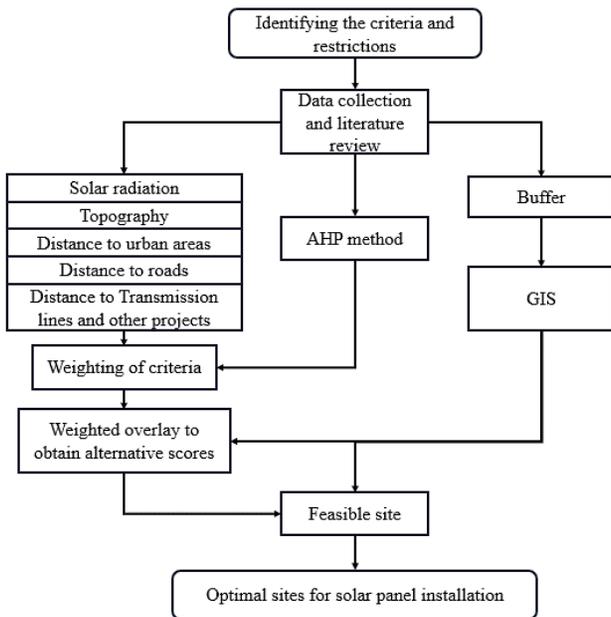

Figure 3. Flow chart of the proposed methodology
Source: The authors

Furthermore, the Consistency Index (CI), introduced by Saaty in 1980 [20], assesses the coherence of the parameters established in pairwise comparison matrices used in the AHP methodology. If the index indicates significant deviations, adjustments must be made to improve consistency and enhance the reliability of results [25,27]. The CI is calculated using eq. (1), where λmax is the principal eigenvalue of the matrix and n is the matrix size.

$$CI = \frac{\lambda max - n}{n - 1} \qquad (1)$$

The Random Index (RI) depends on the matrix size and is used to compare the CI. Finally, the Consistency Ratio (CR) is obtained by dividing the CI by the RI (eq. 2):

$$CR = \frac{CI}{RI} \qquad (2)$$

A CR less than or equal to 0.1 indicates that the comparisons are within an acceptable threshold of consistency. To select locations for photovoltaic energy plants, the suitability index was generated using seven thematic layers integrated into a GIS. To perform this assessment, the weighted overlay method was applied (eq. 3).

$$SI = \sum_{i=1}^{n} (W_i \times C_i) \qquad (3)$$

Where W_i is the weight assigned to the i-th thematic layer, C_i is the reclassified value of the i-th thematic layer, and n is the number of thematic layers.

2.2.10 Site selection restrictions

Factors such as municipal capitals and population centers (urban areas), protected areas, significant road networks, and bodies of water were chosen as limiting variables for the suitability research. In comparable evaluations of optimal areas for solar panel installation, these four limitations are frequently used [13,16,23,27]. However, there is a differential factor in La Guajira, as it is one of the departments with the most indigenous communities, which was important to consider [44]. The geographic source of the protected areas corresponds to the Registro Único Nacional de Áreas Protegidas (RUNAP), the urban areas are found in the Departamento Administrativo Nacional de Estadística (DANE), the indigenous reserves are found in the Agencia Nacional de Tierras (ANT), and the roads as well as the water bodies are regulated by the Instituto Geográfico Agustín Codazzi (IGAC). According to RUNAP, La Guajira has 20 protected areas. The buffer distances used in this analysis were collected from the literature and are presented in Fig. 4.

2.2.11 GIS processing

ArcGIS 10.8 was used to create a suitability map with spatial data from public online resources. Five constraints and seven criteria were evaluated to identify optimal and suboptimal locations for photovoltaic energy projects. Table 2 outlines the selected geospatial analysis model parameters, which were determined based on the study area's characteristics and expert opinions [9,15-19,20-25,27,29,33-41].
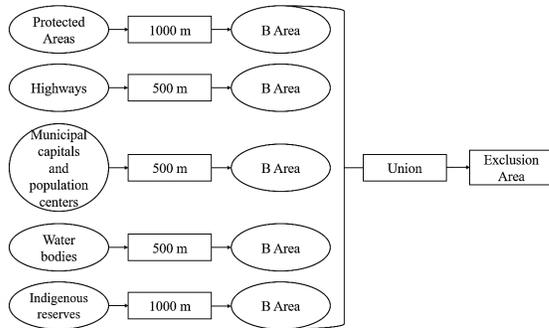
Figure 4. Restriction part of the model
Source: The authors.

3 Results and Discussion

The results of the AHP-GIS analysis of suitable locations for the development of a photovoltaic project in the department of La Guajira are presented, including the map of the identified and weighted optimal location.

3.1 AHP results

This study applied the MCDM technique based on AHP to assign weights to seven criteria influencing the selection of locations for photovoltaic plants (C1: solar irradiation (GHI); C2: temperature; C3: slope; C4: terrain aspect; C5: proximity to urban areas; C6: distance from roads; C7: proximity to transmission lines). The most important criterion was solar irradiation (C1), with a weight of 35%, followed by other factors such as proximity to urban areas (17%), temperature (16%), slope, aspect and distance from roads (9%), and proximity to transmission lines (5%). The consistency ratio obtained was CR = 0,007 (0,77%), and the preference levels of the criteria were illustrated in Table 3 and Fig. 6.

In other studies, different weights were assigned to parameters like those analyzed in the La Guajira department. However, it was found that the most relevant parameter was solar irradiation (C1), ranking above others such as slope, orientation, or temperature, as observed in Ecuador, where it was considered for the expansion of electrical substations [23], in Bangladesh, where a site suitability assessment for
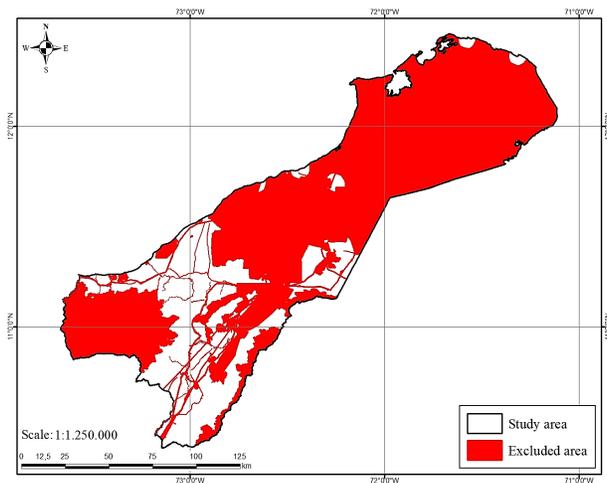
2.2.12 Standardized suitability map

For each criterion in the suitability map, a categorized map was created using GIS software ArcMap 10.8.2. The displayed maps showed the evaluated and rated parameters. Each map was obtained, processed in raster format with cells of 30 m × 30 m, using "Resample" tool in ArcMap, and then classified for each criterion. The digital elevation model (DEM) also served as the basis for slope and aspect. ArcMap's "Slope" and "Aspect" tools were used to build the slope and terrain aspect map. Then, the data was reclassified using the classification tool. To geoprocessing data, it was necessary to project all data to the same geographic coordinate system in WGS-84. Then, data was normalized and the methodology AHP was applied through "Raster calculator" tool in ArcMap. Finally, all criteria were added in the resulting raster map [27]. Fig. 5 shows the limited region of the entire study.

Table 2.
Weight and suitability categories for each criterion

Criteria	Suitability	Score	Range
GHI (kWh/m² year)	Very low	1	1.179 - 1.500
	Low	2	1.501 - 1.800
	Moderate	4	1.801 - 2.000
	Very high	5	2.001 - 2.347
Temperature (°C)	Low	2	1 - 10
	Moderate	4	26 - 35
	High	6	11 - 25
Terrain Slope (°)	Very low	1	43 - 50
	Low	2	28 - 42
	Moderate	3	17 - 27
	High	4	6,3 - 16
	Very high	5	0 - 6,2
Terrain Aspect	Very low	4	North
	Low	5	Northeast, Northwest
	Moderate	4	East, West
	High	6	Southeast, Southwest
	Very high	7	South
Distance from urban areas (km)	Low	1	10 - 20
	High	2	5 - 10
	Very low	3	0 - 5
Distance from roads (km)	Very high	8	0 - 0,5
	High	6	0.5 - 2
	Moderate	4	2 - 5
	Low	2	5 - 10
Distance from transmission lines (km)	Very high	8	0 - 0,5
	High	6	0.5 - 2
	Moderate	4	2 - 5
	Low	2	5 - 10

Source: The authors.

Figure 5. Restricted locations in the study area.
Source: The authors.

Table 3.
Comparison table of the selected criteria for making decisions

Parameters								Weight
	C1	C2	C3	C4	C5	C6	C7	
C1	1	3	5	4	2	3	5	0,35
C2	1/3	1	2	2	1	2	3	0,16
C3	1/5	1/2	1	1	1/2	1	2	0,09
C4	1/4	1/2	1	1	1/2	1	2	0,09
C5	1/2	1	2	2	1	2	3	0,17
C6	1/3	1/2	1	1	1/2	1	2	0,09
C7	1/5	1/3	1/2	1/2	1/3	1/2	1	0,05

Source: The authors.

solar power plants was conducted [27], in Kayseri, Turkey, where GHI was identified as the most critical factor with a weight of 0,447, followed by 'slope' (0,212), and 'aspect' (0,177) [41]. These findings suggest the optimal development of the methodology and the validity of the results obtained.

3.2 Site selection criteria maps for solar power plants solar irradiation (GHI)

The solar radiation used in this study was obtained directly from the SOLARGIS global solar model for the La Guajira department in Colombia, provided by the Global Solar Atlas as part of the global renewable energy resource mapping initiative [30]. Fig. 7 shows that La Guajira has an annual solar radiation ranging from 1,179 kWh/m² to 2,347 kWh/m², determining that 90,82% of the area is optimal for the construction of photovoltaic energy projects, according to the classification (Table 4). These findings align with other studies, which identified optimal solar irradiation values for photovoltaic projects ranging from 1,568 kWh/m²/year to 1,918 kWh/m²/year and 1,425 kWh/m²/year to 1,821 kWh/m²/year [11,27].
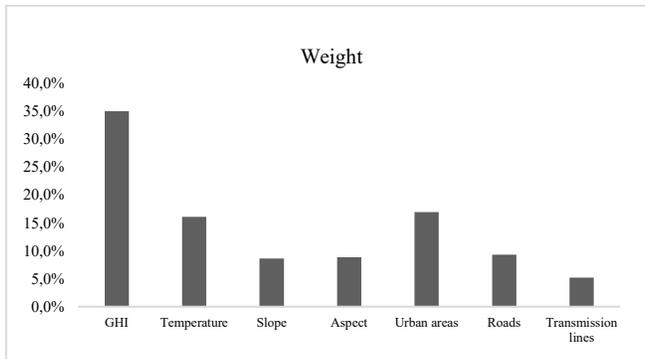
Table 4.
Classification of GHI Suitability in La Guajira

Suitability	Score	Area (km²)	Area (%)
Very low	1	134,08	0,65
Low	2	1.753,76	8,53
Moderate	4	2.799,75	13,61
Very high	5	15.882,85	77,21

Source: The authors.

Table 5.
Classification of temperature suitability in La Guajira

Suitability	Score	Area (km²)	Area (%)
Low	2	233,21	1,13
Moderate	4	17.695,80	86,03
High	6	2.641,42	12,84

Source: The authors.

3.3 Annual mean temperature map

The temperature range identified in La Guajira department varies between 1 and 35°C, representing a wide and diverse climate in the area. However, the optimal temperatures for photovoltaic energy projects in this study were identified between 11 and 25°C, which account for 98.87% of the annual average temperature in the department (Table 5 and Fig. 8). These conditions enhance solar irradiation captured by the panels.

3.4 Slope

The slope characteristics in La Guajira department range from 0° to 50°. For this study, an optimal slope range between 0° and 16° was identified, representing 7,45% of the study area (Table 6 and Fig. 9). These findings align with studies where recommend optimal slopes between 0 and 13°, such as in Ecuador [13], and between 0° and 5° in Iran [34].
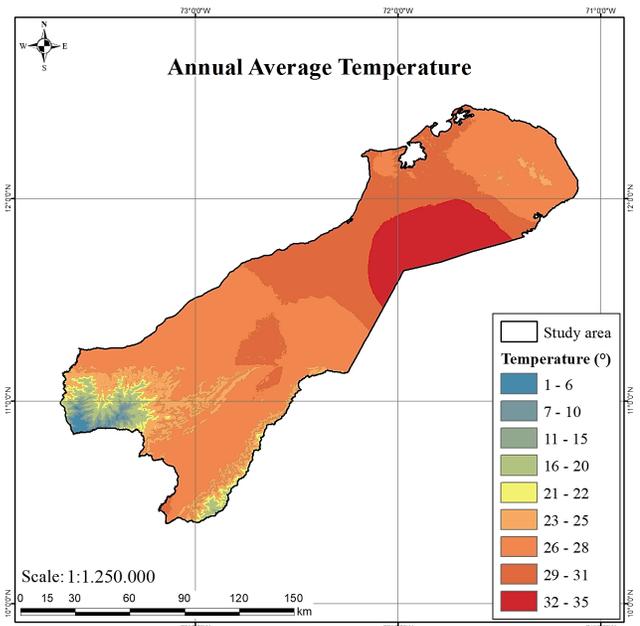
Figure 6. Tre criteria's priority weights
Source: The authors.
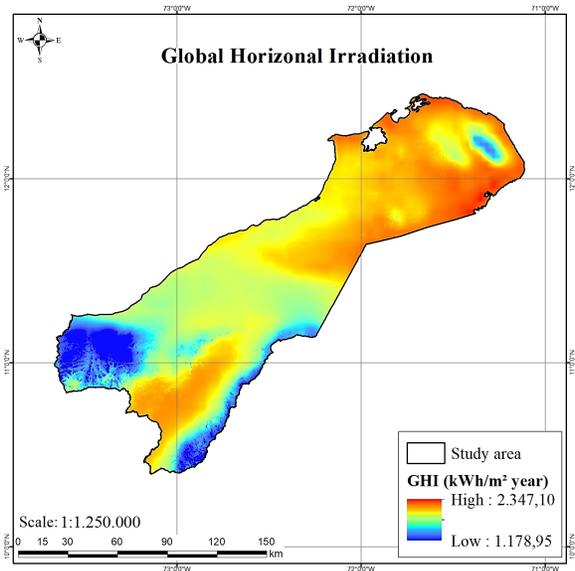
Figure 7. La Guajira's yearly GHI
Source: The authors.

Figure. 8. Temperature-based suitability classifications
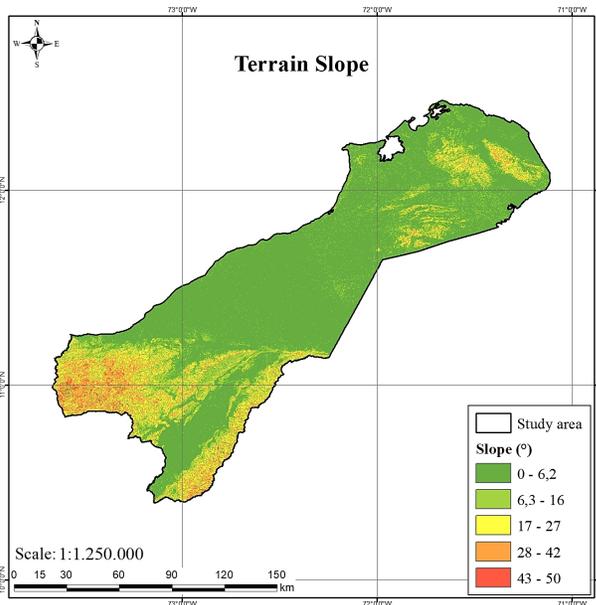Source: The authors.

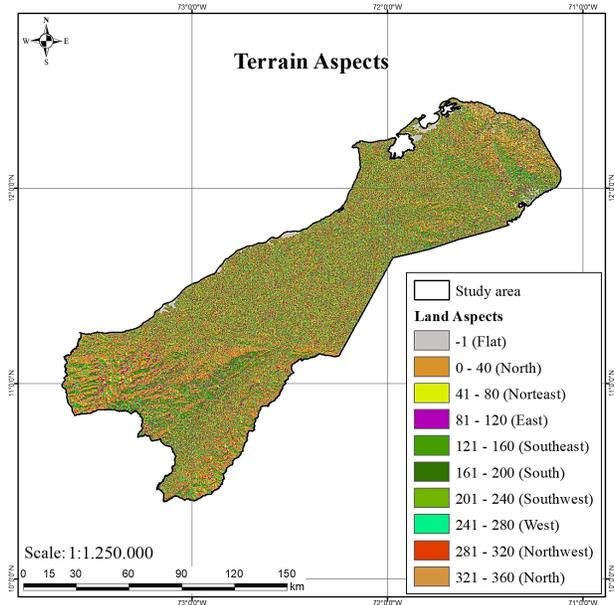Figure 9. Land slopes-based suitability categories.
Source: The authors.

Figure 10. Land aspects-based suitability categories.
Source: The authors.

3.5 Terrain aspect (orientation)

The orientation of solar panel systems in photovoltaic energy projects in Northern Hemisphere countries like Colombia allows for optimal solar irradiation capture when positioned facing south. After conducting this study, it was determined that 30.86% of the total area in La Guajira is suitable for photovoltaic project development based on orientation (Table 7 and Fig. 10). These findings align with previous studies in the same hemisphere, such as in Bangladesh, which focused on site selection for solar power plants [27], and in Iran, where research in Guilán province reached similar conclusions [34].

Table 6.
Classification of terrain slope suitability in La Guajira

Suitability	Range (°)	Area (km²)	Area (%)
Very low	43 - 50	14.246,34	69,26%
Low	28 - 42	2.858,13	13,89%
Moderate	17 - 27	1.934,75	9,41%
High	6,3 - 16	1.316,17	6,40%
Very high	0 - 6,2	215,04	1,05%

Source: The authors.

Table 7.
Classification of suitability in La Guajira, about aspect criterion

Suitability	Aspect	Area (km2)	Area (%)
Very low	North	2.806,01	25,24%
Low	Norteast	2.246,14	10,92%
Very low	East	2.160,51	10,50%
High	Southeast	2.225,75	10,82%
Very high	South	2.132,17	10,37%
High	Southwest	1.989,19	9,67%
Very low	West	2.130,78	10,36%
Low	Northwest	2.494,76	12,13%

Source: The authors.

3.6 Distance from urban areas

The distance between photovoltaic energy projects and urban areas in La Guajira department was considered an important factor due to the region's culture and the respect for indigenous territories and traditions. As a result, distances greater than 500 meters from these areas were established, leaving 56,01% of the territory suitable for photovoltaic project development (Table 8 and Fig. 11).

Table 8.
Classification of urban areas suitability in La Guajira

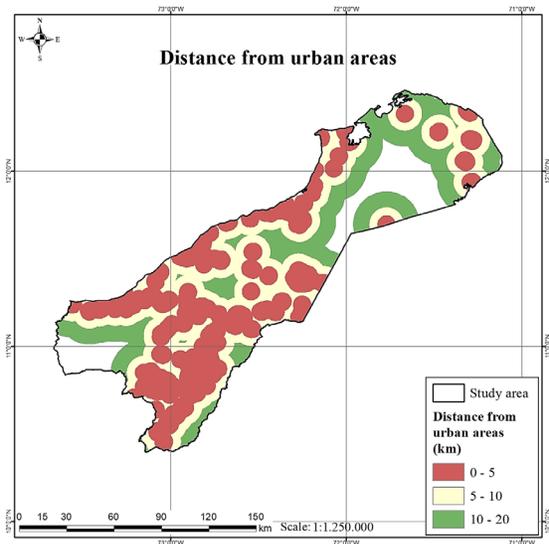| Suitability	Range (km)	Area (km2)	Area (%)
High	0 - 5	9.050,68	44
Low	5 - 10	6.176,53	30,03
Very low	20 - 20	5.343,22	25,98

Source: The authors.

Figure 11. Suitability levels according to their proximity to urban areas.
Source: The authors.

Different perspectives exist regarding this criterion. Some argue that developing projects within 500 meters of urban areas could interfere with community growth and development [27]. On the other hand, others believe that locating these projects near urban areas can promote social growth by creating job opportunities and improving the economic feasibility of the project by reducing transportation costs for personnel and materials [34].

3.7 Distance from roads

The distance to roads is an important factor in the development of any type of project, as it affects construction and operational costs. Therefore, considering the existing road network in La Guajira department, a maximum distance of 500 meters was established for photovoltaic project development. The study found that 38.47% of the study area meets this criterion, ensuring optimal project implementation (Table 9 and Fig. 12). Additionally, previous studies conducted in similar regions considered short distances to main roads to reduce transportation costs, optimize resources, and ensure efficient energy transmission to nearby urban areas [11,34].

3.8 Distance from transmission lines

One of the key factors in ensuring optimal energy transmission in a photovoltaic project is proximity to transmission lines, as it reduces energy losses over long distances and lowers installation costs [17]. After verifying the existing transmission lines in La Guajira, a maximum distance of 500

Table 9.
Classification of suitability in La Guajira about distance from roads

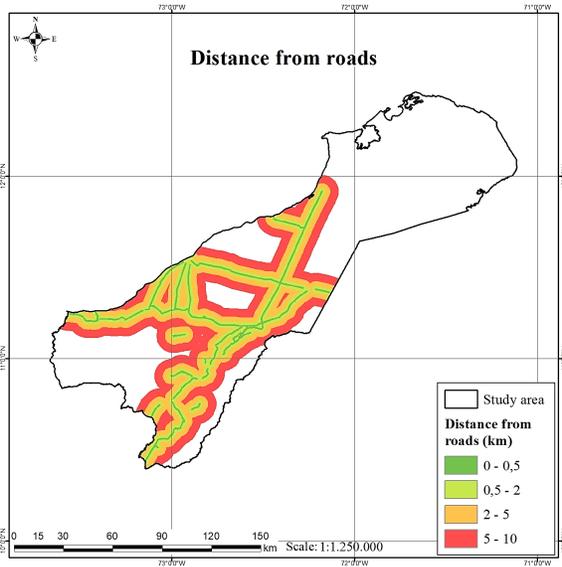| Suitability	Range (km)	Area (km2)	Area (%)
Very high	0 - 0,5	7.914,27	38,47
High	0,5 - 2	6.969,48	33,88
Moderate	2 - 5	4.221,51	20,52
Low	5 - 10	1.465,17	7,12

Source: The authors.

Figure 12. Suitability levels according to their proximity to roads.
Source: The authors.

Table 10.
Classification of transmission lines suitability in La Guajira

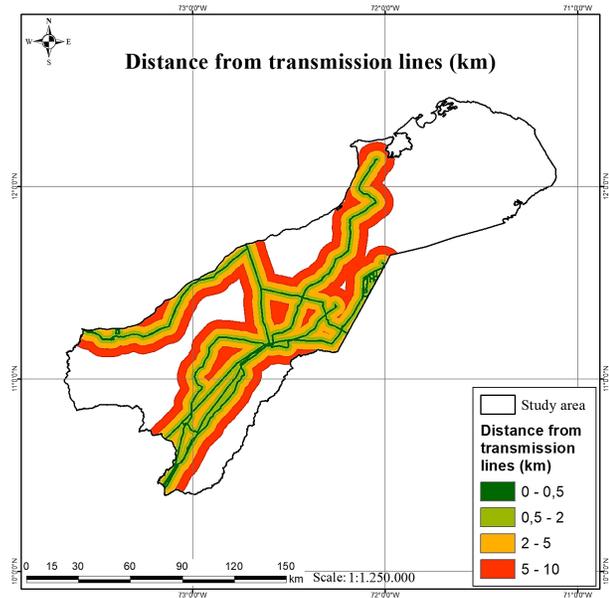| Suitability	Range (km)	Area (km2)	Area (%)
Low	5 - 10	7.222,19	35,11
Moderate	2 - 5	6.617,79	32,17
High	0.5 - 2	4.725,45	22,97
Very high	0 - 0,5	2.005,00	9,75

Source: The authors.

Figure 13. Suitability category map of solar PV plant locations.
Source: The authors.

meters was established for project development. The study found that 9,75% of the area meets optimal conditions for installation (Table 10 and Fig. 13). Previous studies have considered transmission line proximity in a similar way, highlighting the importance of locating projects near existing transmission lines to minimize energy loss and reduce associated costs [11, 17].

3.9 Areas for the implementation of photovoltaic energy projects

According to Table 11, 14.4% of the territory of La Guajira (categorized as High and Very High) has optimal conditions for the establishment of photovoltaic projects, representing a total of 2,981.65 km² of the department's area. Fig. 14 shows the final solar power plant suitability map, which is classified into six categories: Very High, High, Moderate, Low, Very Low and Restricted Area. These categories represent the different priorities to allocate photovoltaic energy projects. According to the resulting map, the most suitable locations for photovoltaic energy plants in La Guajira are concentrated in the southwestern region. Similar results found that suitable areas mainly resulted from high solar irradiation, low average temperatures, and flat terrain [15].

Table 11.
Areas of each suitability class and their percentage in La Guajira

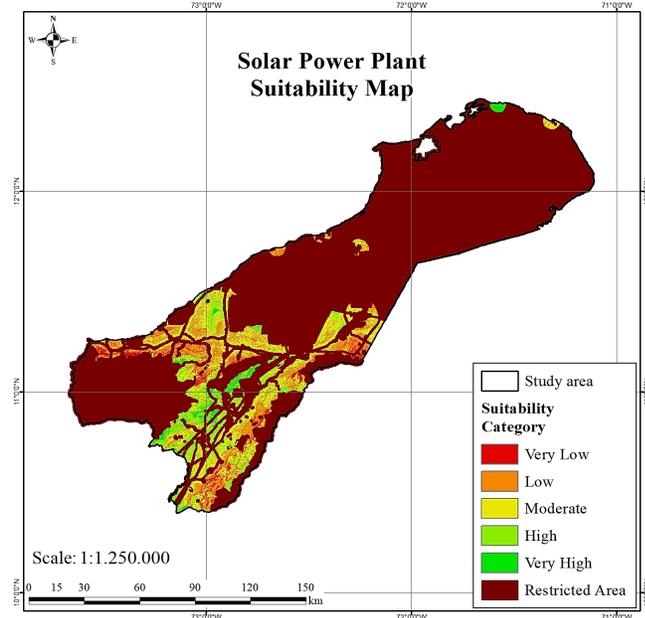| Suitability category	Area (km^2)	Area (%)
Very low	360,75	1,75
Low	2.215,75	10,77
Moderate	4.246,64	20,64
High	2.257,57	10,97
Very high	724,08	3,52
Restricted areas	10.765,64	52,34

Source: The authors.

Figure 14. Suitability category map of solar PV plant locations.
Source: The authors.

4 Conclusions

The integration of GIS and AHP enabled the identification of several highly suitable areas for photovoltaic projects in La Guajira, demonstrating that the combination of these tools gives a relevant approach for planning photovoltaic solar energy initiatives, as it supports informed and balanced decision-making.

This study's results may meaningfully aid Colombia's energy planning, especially considering Law 2099 of 2021, which promotes renewable energy while supporting national economic recovery. Identifying the most favorable zones for solar energy development not only strengthens the diversification of energy sources but also creates opportunities for job creation and social improvement in some of the country's most vulnerable territories.

Although the percentage within suitable area for photovoltaic energy projects may seem low, the Colombian National Government protects a large portion of the territory. For these territories, protection has important environmental value because of rich biodiversity and unique ecosystems. The presence of Indigenous communities, national parks and forest reserves also gives value to them.

This study provides a methodological tool that can be replicated in other regions with similar characteristics, thereby contributing to energy planning at both the national, regional and local levels.

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