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Article

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Reference: Garcia, Gonzalo Romeno/Rojas, Jhan Piero et. al. (2021). Renewable energies resources evaluation using a geographic information systems in the Colombian Caribbean Region. In: International Journal of Energy Economics and Policy 11 (6), S. 7 - 15.
https://www.econjournals.com/index.php/ijeep/article/download/11612/6096.
doi:10.32479/ijeep.11612.

International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2021, 11(6), 7-15.

Renewable Energies Resources Evaluation using a Geographic Information Systems in the Colombian Caribbean Region

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Received: 17 May 2021 **Accepted:** 12 August 2021 **DOI:** https://doi.org/10.32479/ijeep.11612

ABSTRACT

This manuscript presents an integral evaluation of the use of wind and solar resources in the Colombian Caribbean region. For the use of solar and wind energy sources, spatial restrictions according to topography, natural parks, water reserves, indigenous and sacred reserves were taken into account. In addition, studies of the energy potential of wind and solar radiation were carried out through geostatistical analysis of different points in meteorological stations located in the region. Finally, areas with wind and solar potential were determined using the Geographic Information System for Renewable Energies (SIGER). The results show that the department of Guajira has the highest values of solar brightness (229-240 Month day), while the departments of Valledupar, Cesar, and part of Magdalena decrease in the range of 229 to 207 Month day. In terms of solar radiation, the departments of Guajira and Atlántico showed global solar radiation values of up to 6,015 W/m^2. The departments of Cesar, Magdalena, and part of Bolivar showed values close to 5,259 W/m^2; while Sucre, and Cordoba showed low solar radiation values of 4,502 W/m^2. It is concluded that the departments of Atlántico and Guajira are excellent candidates for solar and wind energy projects due to their characteristics. The results of this manuscript are a fundamental basis for future technical-economic feasibility studies of renewable energy in the Colombian Caribbean region. In addition, it allows the elaboration of energy policies that encourage the execution of this type of study at a real level.

Keywords: SIGER, Renewable Energies, Solar Energy, Wind Energy, Wind Potential
JEL Classification: Q42

1. INTRODUCTION

Worldwide, dependence on fossil fuels, which are not infinite, contributes to global pollution, generating a significant increase in climate change (Fairbrother et al., 2019). Renewable Energy Sources (RES) are a solution to the problems created by fossil fuels as they are almost inexhaustible sources of energy. (Montoya et al., 2021; Sarkodie et al., 2020), Renewable energy sources such as solar, wind, and biomass play a vital role in meeting the growing energy demands of developing countries. India showed an increase in investment capacities in solar and wind energy, due to its strong investment policies on both fronts (Fairbrother et al., 2019). In South American countries, governments have been working hard to implement government policies that encourage the use of renewable energies. In this sense, the United States has the highest density of renewable energy policies, followed by Canada, Mexico, Brazil, and finally, Argentina (Pischke et al., 2019).

In developed countries, there has been a trend towards the implementation of RES, as in the case of the United State, which is approaching China in the race to be the main investor in renewable energies, with a 57% jump in its expenditure (Fairbrother et al., 2019). Due to this increased interest in supporting these new energy sources, several tools have been managed and integrated to achieve more efficient results; this is the case of the geographic information systems (GIS), which is a valuable tool for the evaluation and development of the use of renewable energy resources in large regions, as it is a tool that is particularly suitable for the analysis of the spatial variability of resources, as well as for the resolution of management and planning problems of the installation programs of decentralized systems, which are characterized by a large spatial dispersion (de Livio et al., 2019; Castro-Santos et al., 2019).

Countries such as Turkey, Spain, Italy, among others, have developed RES with the help of geographic information systems (Aydin et al., 2013; Camporeale and Mercader-Moyano, 2021; Dénarié et al., 2021), as GIS is a tool that allows the integration and processing of information from various sources.

In Colombia, the Clean Energy for Colombia Program (CCEP) of the United States Agency for International Development (USAID) was carried out with the support of Colombian government entities, which sought to increase access to renewable energy sources and improve energy efficiency practices in Colombia, estimated at USD 18.6 million for a period of 5 years between 2012 to 2017 (USAID, 2012). The Colombian Low Carbon Development Strategy involving the World Bank's Partnership for Market Readiness (PMR) program, which seeks to encourage the implementation of market mechanisms that promote alternative energy and energy efficiency in the transportation sector (Ministerio de Ambiente y Desarrollo Sostenible 2010). Some of these experiences are the Jepírachi park, which consists of a wind farm located in La Guajira, with 19.5 MW of nominal power (epm 2004), the 2.8 kWp solar system installed by the former ICEL (Colombian Institute of Electric Energy, now IPSE) in La Venturosa, Vichada, in 1996, which supplies energy to a community of 12 families and a school (Rodríguez Murcia, 2008).

At the level of RES studies with GIS, there are many projects of great impact (Lezcano Oquendo, 2011; Rodríguez Murcia, 2008), highlighting the ModerGIS that was developed by the National University of Colombia with the advice and support of the Center for Energy, Environmental and Technological Research (CIEMAT) of Spain, which is a tool for sustainable energy (Quijano et al., 2010) and the PIEC model developed by the Mining and Energy Planning Unit, which allows detecting areas with high potential for renewable natural resources (UPME, 2013).

Conventional electric energy comes from non-renewable sources and this process over time has contributed to alterations in the climatic conditions of the environment. According to information from the National Energy Balance, in 2019 Colombia had an electric energy production of 66,458 GWh of which 68 GWh (0.10%) comes from wind power plants, while 21,272 GWh (32%) from thermal power plants, and 67.23% equivalent to hydroelectric power plants. On the other hand, in terms of coverage, the national interconnected system has evolved in the number of users; during the last 10 years, it grew at an average annual rate of 4.7% to reach approximately 12.1 million in 2012. Moreover, in 2014, Colombia had a high demand coverage of around 96-98% Therefore, renewable energy sources are considered an important alternative to cover the remaining demand (Hoyos et al., 2020).

Considering that unelectrified communities are generally located in remote, difficult to access and scattered locations and that in many of these cases connection to the grid is an unfeasible option, electricity generation based on renewable energy sources becomes a solution with great potential, economically and technically feasible, capable of meeting the existing demand to a large extent (Shorabeh et al., 2021). The characteristics of the Colombian Caribbean region lead to different territorial conditions in each department of the coast; this disparity, however, makes it possible to have at least one indigenous source in practically any place and thus obtain better coverage.

The importance of dividing the geographic space into homogeneous zones using Geographic Information Systems (GIS), allows determining according to the conditions and geographic typologies the use of areas with more potential for the development of renewable energies. Currently, the use of GIS technology allows the manipulation of a large amount of information in an accurate and timely manner with a minimum of time and effort, which positions GIS as an excellent alternative to support the development of renewable energies (Castro-Santos et al., 2019). For this reason, it is intended to make a graphic representation of the Colombian Caribbean Coast in which the different alternatives for the use of renewable energies can be defined according to the conditions.

In this sense, the objective of this manuscript is to carry out the zoning of wind and solar renewable energy sources in the Colombian Caribbean region with emphasis on La Guajira, according to their potential use and exploitation for energy generation. This will be done through the elaboration of maps using geographic information that will allow evaluating the wind and solar potential.

First, an analysis will be made of the main spatial restrictions for the use of renewable wind and solar sources, according to topography, natural parks, land cover, reserves, and sacred places. Then, the energetic potential of wind and solar radiation will be studied through geo-statistical analysis of the data available from meteorological stations in the Caribbean region. Subsequently, the areas of wind and solar potential will be determined using the Geographic Information Systems for Renewable Energies (SIGER) model.

2. METHODOLOGY

2.1. Description: Demographic Characteristics and Electric Power Coverage

The Colombian continental Caribbean is located between 12° 60 and 7° 80 north latitude and 75° and 71° west of Greenwich longitude. It has an area of 536,574 km^2 in the Caribbean Sea. The continental zone has approximately 1,600 kilometers of coastline. It has a territorial extension of 132,288 km^2 -corresponding to 11.6% of the country's total surface-, divided into a continental area of 132,218 km^2 and an insular area of 70 km^2. Its administrative structure is made up of seven continental departments (La Guajira, Atlántico, Bolívar, Cesar, Córdoba, Magdalena, and Sucre) and one department in the insular area (San Andrés and Providencia, Santa Catalina).

The Caribbean Region is made up of six subregions, which are distinguished by climatic and/or geographic factors characteristic of each. For example, the Guajira Peninsula is one of the most exotic subregions of the Colombian Caribbean, considered the driest part of the region. The Sierra Nevada de Santa Marta, extends from the Caribbean plain, at sea level, to a height of 5,775 meters at the Bolivar and Colon peaks. The Bajo Magdalena depression includes the fluvial-deltaic plain of the Magdalena River. The Momposina depression, comprising part of the territory of the departments of Sucre, Córdoba, Magdalena, and Bolívar. The Caribbean Plain, comprising the coastal strip from the Magdalena River delta to the limits of the Abibe, San Jerónimo and Ayapel mountain ranges.

On the other hand, regarding the coverage of the electric power system (EE), Table 1 shows the number of homes that make up each department (at the municipal level), as well as the number of them which have the electric power service (EE); it also shows the percentage of coverage obtained in the period 2012-2013 by the Unidad de Planeación Minero-Energética de Colombia (UPME).

Similar results are presented in Table 2; in this case, we considered the number of non-municipal housing, that is, houses that are in rural areas such as towns, hamlets, villages, etcetera.

Finally, Table 3 shows the percentage of departmental coverage, considering the total number of houses, that is, municipal houses plus non-municipal houses

Table 1: Municipal electric power coverage

Department	Housing	Housing with EE	Coverage (%)
Atlántico	505,947.78	505,947.78	100
Bolívar	347,539.12	347,539.12	100
Cesar	191,205.14	191,205.14	100
Córdoba	203,693.15	203,693.15	100
Guajira	96,742.45	96,742.45	100
Magdalena	266,178,63	266,178,63	100
Sucre	129551,96	129551,96	100

Table 2: Non-municipal electric power coverage

Department	Housing	Housing with EE	Coverage (%)
Atlántico	23589.47	20392.22	85.45
Bolívar	88088.96	67823.89	76.99
Cesar	49884.31	39274.86	78.73
Córdoba	174198.5	140016.49	80.38
Guajira	65518	29545.55	45.10
Magdalena	7054.57	40994.37	58.11
Sucre	62394.89	58399.04	93.60

Table 3: Total coverage by department

Department	Coverage (%)
Atlántico	99.40
Bolívar	95.35
Cesar	95.60
Córdoba	90.95
Guajira	77.83
Magdalena	91.23
Sucre	97.92

2.2. Energy Planning

Global climate change is strongly related to fossil fuel dependence. Therefore, many countries have identified new ways to produce and consume energy using renewable energy sources. In this sense, setting energy targets from an energy planning point of view has been one of the most viable routes, to limit and prevent climate change (Krog and Sperling 2019). Therefore, Energy Planning is the set of activities aimed at supporting the design and implementation of policies and regulations whose purpose is to seek a balance between energy supply and the useful energy needs of users without compromising the resources of future generations (Gholami et al., 2020).

In Colombia, little attention has been paid to the development of successful policies aimed at including the use of non-conventional energy sources in the energy mix and promoting energy efficiency programs that contribute to the better use of available resources. Colombia's current plan for the energy sector, PLAN ENERGÉTICO NACIONAL 2006–2025 CONTEXTO Y ESTRATEGIAS (PEN)), includes among its main proposals the sustainable development that allows the country's economic growth, raising the quality of life and social welfare, without putting at risk the renewable natural resources on which it is based, nor deteriorating the environment or the right of future generations to use it to satisfy their own needs.

2.3. Software Used

In this study, the analysis was carried out using ArcGIS software (ArcMAp, ArcInfo, Geostatistical Analyst, Spacial Analyst, 3D Analyst, 3D Analyst).

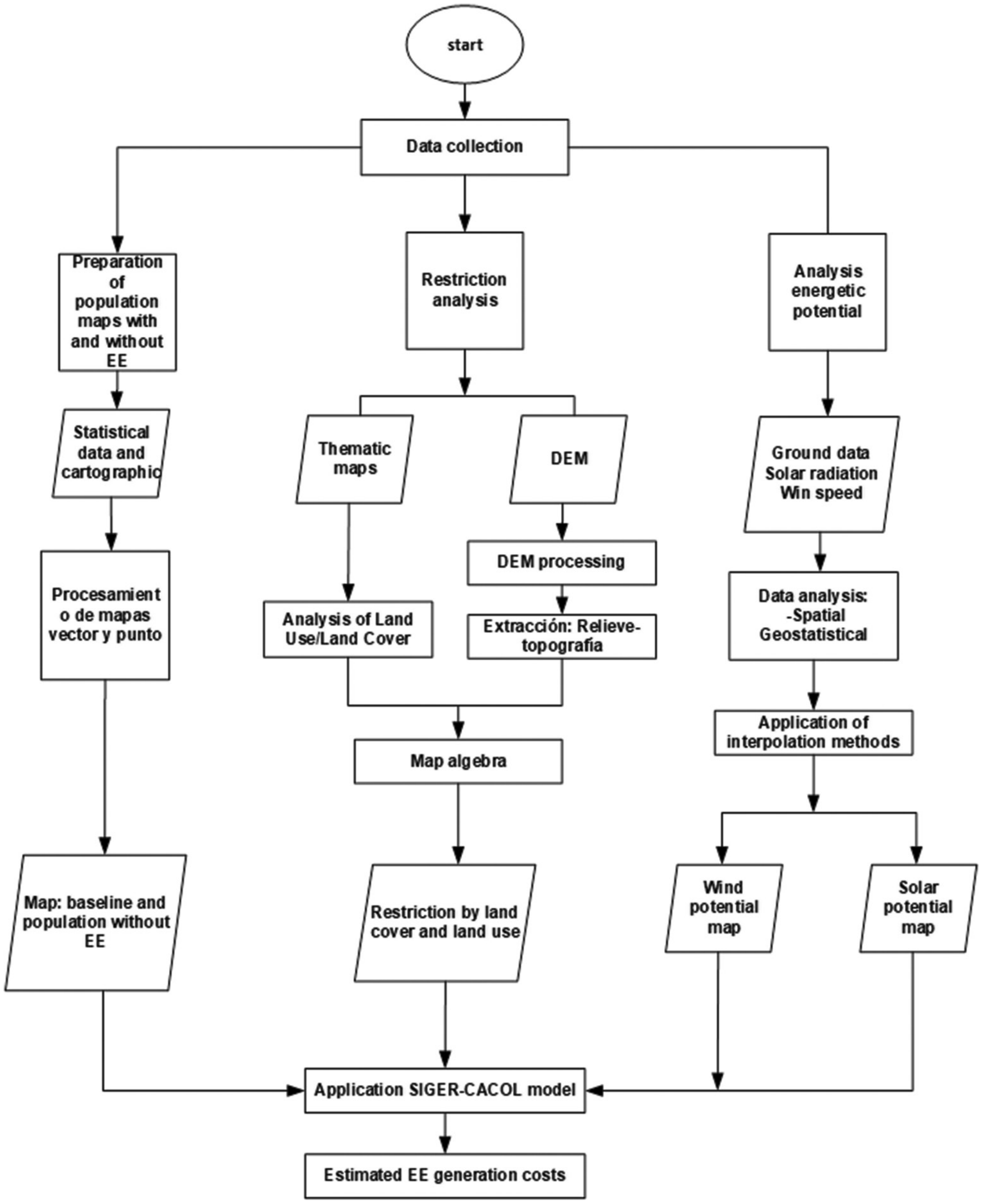
Software (ArcMAp, ArcInfo, Geostatistical Analyst, Spacial Analyst, 3D Analyst). This tool made it possible to perform an advanced analysis with statistical functions, applying algorithms and map algebra, generating the necessary graphic information as a product. Figure 1 shows the procedure to be carried out to achieve the goal of evaluating the solar and wind potential for electric power generation.

2.4. Description of the Proposed Model

This model arises within the methodology of the project in question-based on GIS technologies in renewable energies and specifically in the Colombian Caribbean region. The GIS functions as a geographic information database; whose function is to capture, store, manipulate, analyze and display this information in all its forms.

Nowadays, geographic information systems (GIS) are used in a wide variety of areas of knowledge. The area of renewable energies has been no stranger to this and that is when the SIGER model arose. This project was initiated by the Management of Non-Conventional Energies (GENC) of the Institute of Electrical Research of Spain.

Figure 1: Methodological diagram



The SIGER is a system composed of maps in raster and vector format and data in tabular form, which contain information on renewable energies and those geographic elements that influence the determination of sites for the use of renewable energies. For this research, the geographic system used is the Geographic Information System for territorial planning and management (SIGOT). The basis of this system is the ArcView package of the ArcGIS software. The SIGER- CACOL model has been planned as a support tool for decision-making in the use of renewable energies from the point of view of energy potential and restrictions.

SIGER-CACOL requires information that falls into the following categories. First, cartographic layers or spatial data of the study area must be identified in the form of political division maps. Next, infrastructure maps such as power lines, roads, distances to population centers, etc. must be identified. Finally, develop the data processing and solve by developing a schematic of how the maps will interact.

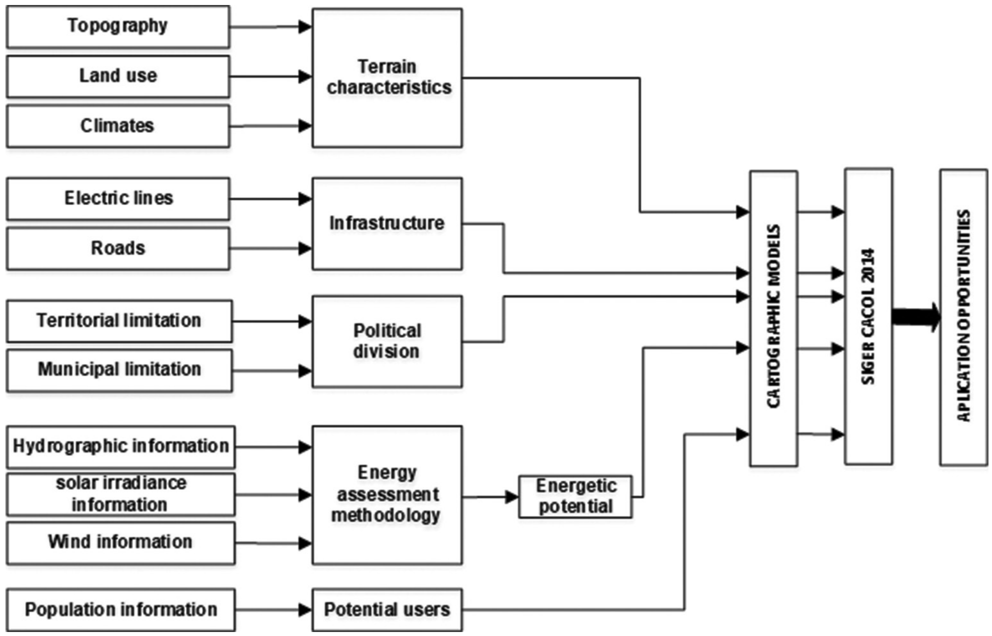
Create a flow diagram with steps that graphically represent the work process, i.e. it must be known which cartographic layer will interact with another. Figure 2 shows the input variables for the model.

2.5. Description of Activities

The research started initially with the collection of information, i.e., the search for the layers (shapes) of the geographic information system. In this way, the algebra maps required to define the energy potential in each of the points (cells) of the Caribbean region were made. Some of the layers were: basic cartography, departmental limits, relief, water bodies, and access roads. In addition, the location of the stations and their historical series of wind speed and radiation data measurements were compiled.

Subsequently, the obtained layers were processed to obtain the processed shapes required for the evaluation process. During this activity, coordinate systems were unified (considering the different

Figure 2: Flowchart SIGER-CACOL model



sources of information), non-relevant information was eliminated, layers were joined to obtain a resulting layer; in general, the required actions were performed to obtain the necessary format in the map algebra process. Next, the energy potential criteria were defined and weighted. The score of a site concerning its potential to generate energy depended on the result of the sum of each of the scores for each criterion, taking into account the weighting factor for each of these criteria. These criteria were established based on a bibliographic search and consultation with experts in the field.

Once the historical data series were obtained, two activities were developed. The first consisted of completing the missing data, and the second consisted of using probability distribution functions to obtain the most probable data to occur in each of the points of the Caribbean region.

Once each of the above activities had been completed, the map algebra was performed, in which the entire territory analyzed was divided into cells based on a previously defined resolution. Subsequently, using geographic information systems, it proceeded to obtain the score for each of the criteria defined by its corresponding weighting factor. As a result, a score was obtained for each of the established cells. Based on the operation performed in the previous activity, the scores obtained for each cell were plotted within the framework of the region's cartography. This allowed determining the energy potential based on an established color framework called "Wind and Solar Atlas of the Colombian Caribbean."

3. RESULTS AND DISCUSSION

3.1.Collection of Information

Figure 3 shows the images of some of the layers developed (shape files) to evaluate the energy potential for each site in the Colombian Caribbean region. These layers were created using a geographic information system and can be classified into three main groups: a first group containing reference files such as cartography, political division, access roads, etc.; a second group containing shapes that allow the identification of energy potential, such as wind speed measurements; and finally, a third group containing restrictions to the development of energy projects, such as the presence of indigenous reserves. In Figure 3, only some sample images were considered, which show the political-administrative division of the Caribbean region (Figure 3a); Figure 3a-3d shows the digital elevation models for the departments, which is a basic input to consider the relief criterion.

3.2. Solar Potential of the Caribbean Region

The evaluation of the solar potential in the Caribbean region is of great importance since it allows determining the availability of solar radiation necessary for feasibility studies in renewable energy projects. It also provides data on thermodynamic variations of each of the elements that absorb extraterrestrial radiation. The information from the stations was supplied by the Instituto de Hidrología, Meteorología, y Estudios Ambientales de Colombia (IDEAM), which are the base for the study of solar radiation and brightness, for the design of solar thermal and photovoltaic energy projects. These results are shown in Figure 4 where the total average values of global solar radiation in [W/m²] and solar brightness [Month day] are observed for each of the meteorological stations of the Colombian Caribbean region considered in this study with historical information from 2005 to 2013.

Next, the hourly radiation data were processed for the stations considered in the study. Figure 5 shows the behavior of radiation for the particular case of the Las Flores station located in the department of Atlántico. Four representative months were taken, July being the month with the highest radiation peaks.

Figure 3: Mapping of the region Caribbean: (a) Political-administrative division; elevation models, (b) Atlántico; (c) Córdoba, Sucre, Bolívar, Cesar, and Magdalena; (d) Atlántico, Cesar, Magdalena, and Guajira

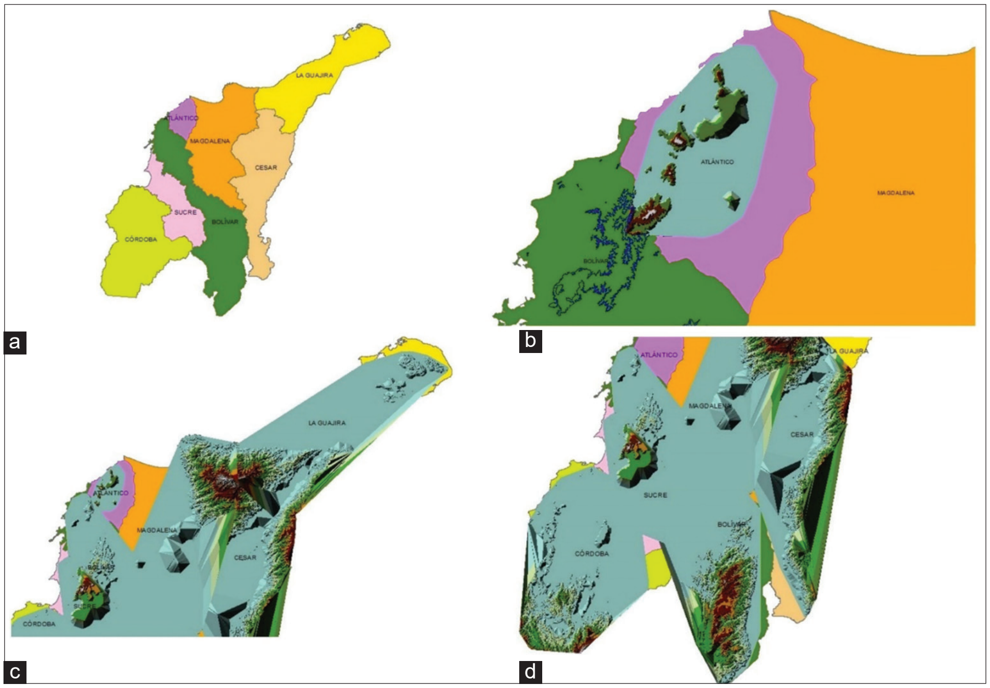


Figure 4: Brightness and radiation of meteorological stations in the Colombian Caribbean region

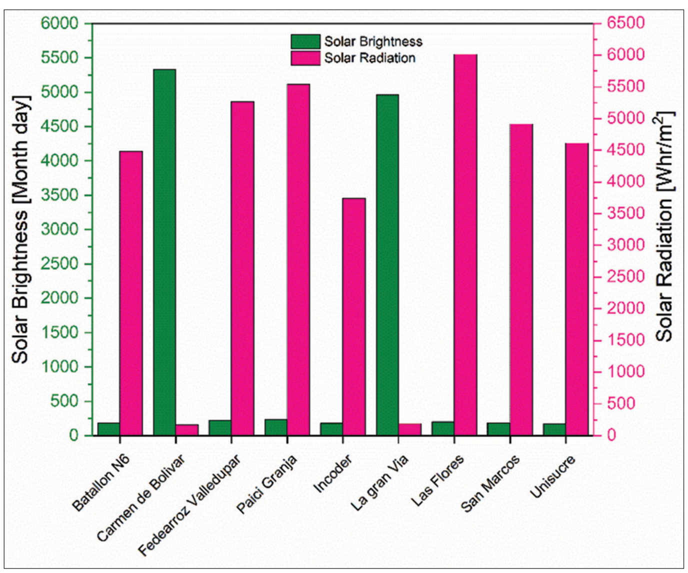
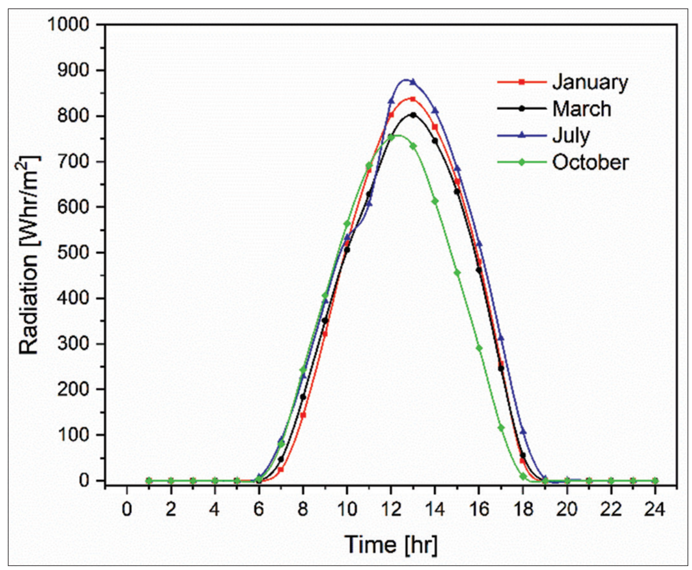


Figure 5: Hourly variation of radiation, Las Flores station



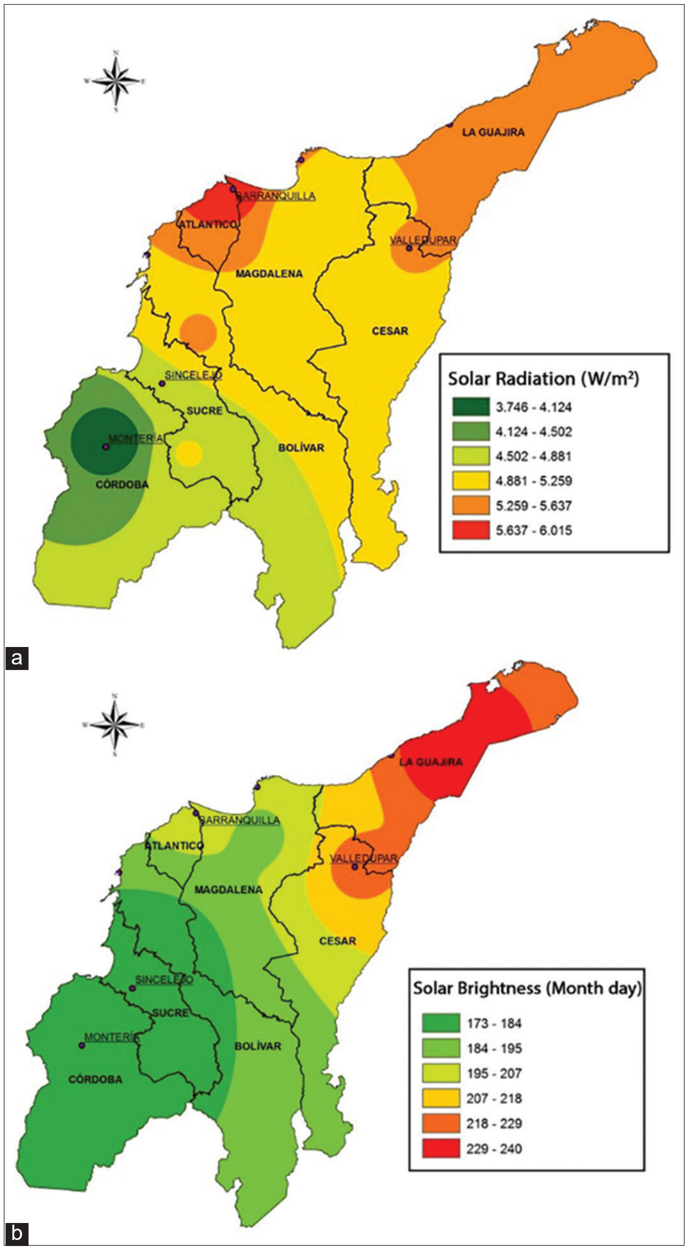
Then, based on the monthly average radiation values for each of the stations considered in the study, preliminary multiannual maps (monthly averages and annual averages) of global radiation and solar brightness were developed, as shown in Figure 6.

Based on the results shown in Figure 6a, the ranges of solar radiation variation by department can be observed. In this sense, it is evident that the department of Atlántico presents the highest range of radiation (5637-6015 W/m^2), followed by the department of Guajira (5259-5637 W/m^2). As for brightness, the department of Guajira (229-240 Month day) and Magdalena (218-229 Month day) have the highest variations in the Caribbean region. Therefore, the department of La Guajira is a subregion with a high potential for renewable energy generation. However, although the rest of the departments, especially the departments of Sucre, Córdoba, and Bolívar and part of Magdalena and Cesar, do not have the advantages of the departments of Guajira and Atlántico, they are not exempt from being candidates to be evaluated for future renewable energy project.

3.3. Wind Potential of the Caribbean Region

The objective of this section is to evaluate the wind energy potential in the Caribbean region. For this purpose, wind roses

Figure 6: Map of: (a) Solar Radiation; (b) Solar Brightness for the Colombian Caribbean region



were generated based on the monthly frequencies of wind directions. Figure 7 shows the wind roses for the department of Atlántico, in the city of Barranquilla (Ernesto Cortissoz Airport Station) for four months (January, February, March, and April). The results show that the distribution of the headings in the four months, i.e. the wind orientation and the highest intensities, are displayed on the east side; while, on the northeast side with less intensity. This behavior is explained by the influence of the arid zone, the proximity and influence of the Caribbean Sea surrounding the Colombian coasts, in addition to the low vegetation and the flat terrain.

An additional study was carried out to analyze the wind behavior for 2012, Figure 8. In this case, three points in the northern part of the Caribbean Region: Barranquilla (Ernesto Cortissoz Airport Station), Guajira (Almirante Padilla Airport Station), and Santa Marta (Simon Bolivar Airport Station) were taken into account. The results show that March presents the highest wind speed peaks for Barranquilla (4.6 m/s), Santa Marta (3.8 m/s), and Guajira (2.9 m/s); while in April and May, the wind tendency is to decrease, and then present peaks in July and December, as shown in Figure 8a.

However, Figure 8b reveals that throughout 2011 wind speed variations are very similar at the three station locations. Note that the peak presented in April for the city of Barranquilla (4.5 m/s) may be associated with the influence of a tropical storm that may have hit this specific area. Additionally, stable and constant winds are observed throughout the year with few peaks in the points located in the city of Santa Marta and Guajira, for the months of march and June with speeds of 3 m/s and 2.8 m/s respectively. In general terms, the results show that the wind potential is high for the departments of Guajira, followed by Barranquilla and finally Magdalena.

4. CONCLUSIONS

This manuscript presents an integral evaluation of the use of wind and solar resources in the Colombian Caribbean region. For the use of solar and wind energy sources, spatial restrictions according to topography, natural parks, water reserves, indigenous and sacred reserves were taken into account. In addition, studies of the energy potential of wind and solar radiation were carried out through geostatistical analysis of different points in meteorological stations located in the region. Finally, areas with wind and solar potential were determined using the Geographic Information System for Renewable Energies (SIGER) model.

It is concluded that the use of GIS technology tools allowed the generation of brightness and global radiation maps for the Caribbean region, obtaining the different profiles along the study area.

Regarding solar potential, it is concluded that the northern coast of Colombia enjoys the privilege of having high values of solar brightness throughout the year, with the department of Guajira (229-240 Month day) having the highest values, while the departments of Valledupar, Cesar, and part of Magdalena decrease in the range of 229 to 207 Month day.

In terms of solar radiation, the departments of Guajira and Atlántico showed global solar radiation values of up to 6,015 W/m^2. The departments of Cesar, Magdalena, and part of Bolivar showed values close to 5,259 W/m^2; while Sucre, and Cordoba showed low solar radiation values of 4,502 W/m^2. Although the potential of these last departments is not high compared to that of La Guajira, it is not excluded to be considered for future technical-economic feasibility studies in renewable energy projects.

Finally, it is concluded that the city of Barranquilla winds tends to follow the east direction. In addition, it was found that wind speed is higher in Guajira, followed by Barranquilla, and finally

Figure 7: Wind rose Barranquilla - Ernesto Cortissoz Airport Station 2013: (a) January; (b) February; (c) March; (d) April

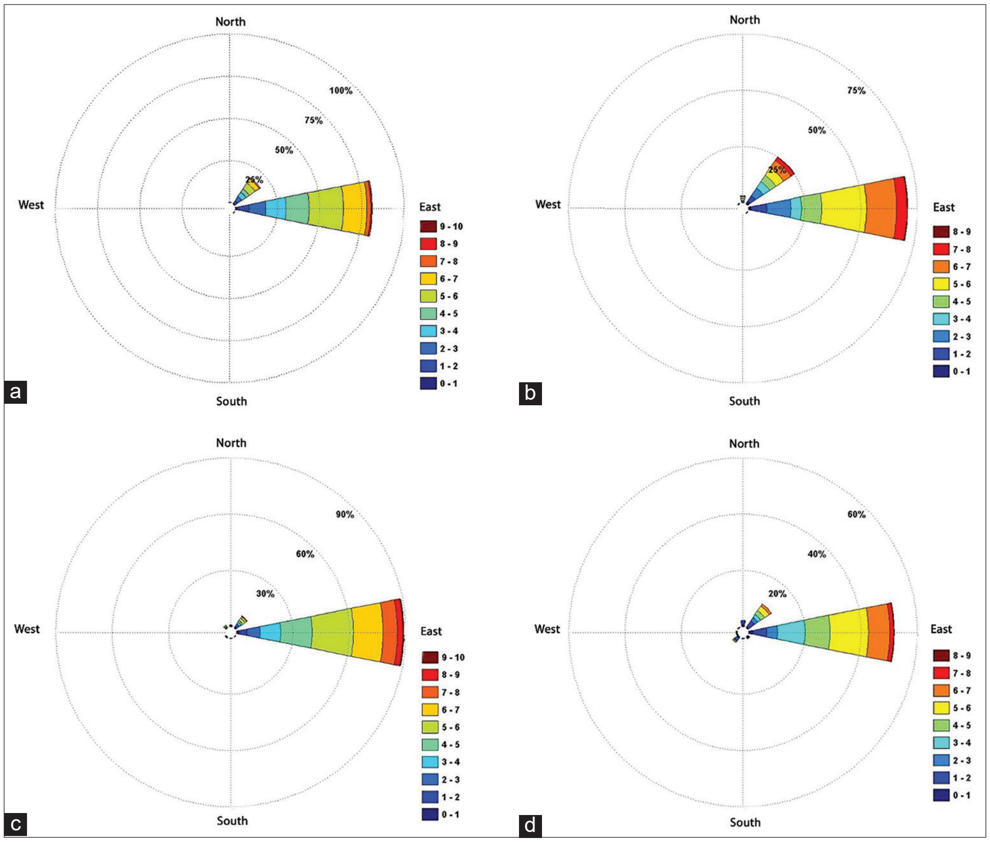
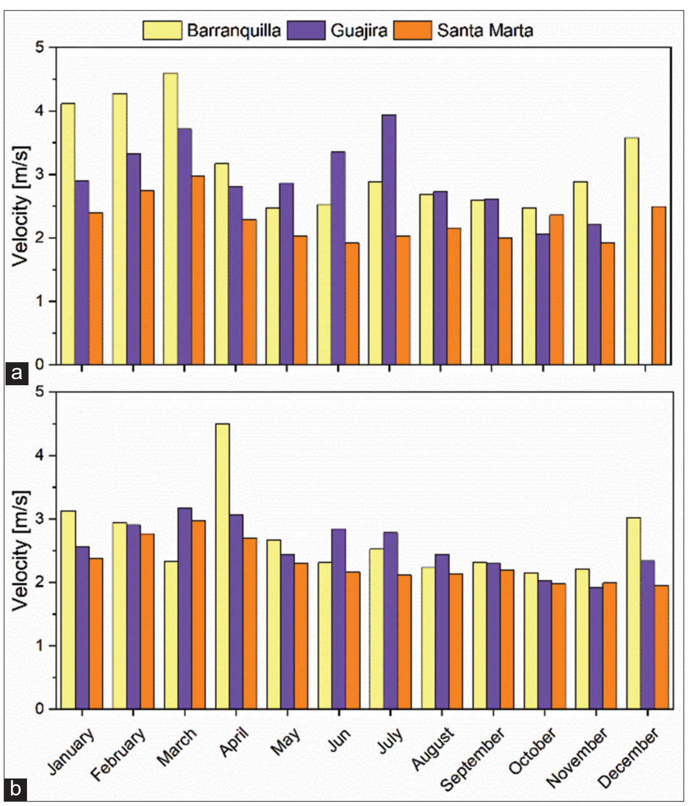


Figure 8: Average monthly wind speed for the Barranquilla, Santa Marta, and Guajira stations: (a) 2012; (b) 2011



Magdalena. It is concluded that the departments of Atlántico and Guajira are excellent candidates for solar and wind energy projects due to their characteristics.

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