Correlación energética entre la radiación solar global y la velocidad del viento en el Caribe colombiano

Energy correlation between global solar radiation and wind speed in the Colombian Caribbean

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Abstract

Introduction— Nearly 69.18% of Colombian electric matrix (2018) depends on hydraulic resources, which make it vulnerable to rainfall shortage periods, impacting on high energy prices and increasing greenhouse gas emissions due to incorporation of fossil fuel, since these sources contribute with 26.36% to the energy matrix. This led to take actions to expand the participation of Non-Conventional Renewable Energy Sources (NCRES), based on the potential of the different regions where energy sources such as wind, solar and biomass stand out. For large-scale energy production, wind energy and solar energy have great potential in the Caribbean Region; thus, this work intends to assess the wind and solar resources of this region to identify and establish reverse correlation behaviors between them, in order to guarantee that the participation of these energies will maintain the sustainability of the energy matrix by incorporating these energy sources.

Objective— Apply a statistical methodology that allow to assess the degree of correlation between the wind and solar resources present in the Caribbean Region, in a time horizon of 5 years (2014-2018).

Methodology— Based on data (2014 - 2018) of global solar radiation and wind speed measured on the ground by means of the Automatic Satellite Meteorological Stations (EMAS) from the network of meteorological stations of the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM in spanish), a characterization is carried out through a descriptive analysis in order to obtain a representative value of each variable, the daily and monthly averages of the time series are calculated to evaluate the correlation of each resource separately as joint correlation, using a statistical method based on the calculation of Pearson's correlation coefficients.

Results— The determined time series allow us to understand that the complementarity of the resources separately, such as by combining them, presents a greater number of correlation coefficients close to -1, when the resources are analyzed together, which means that when a resource increases the other is reduced, complementing each other in their behaviors.

Conclusions— Both the distance between the measurement points and the temporal resolution modulate the negative correlation presented by the wind and solar resources of the Caribbean Region, consequently continuous availability of resources is obtained by considering a joint utilization

Keywords— Renewable energy sources; solar energy; wind power; energy correlation; diversification

Resumen

Introducción— Cerca del 69,18 % de la matriz energética de Colombia (2018) depende del recurso hidráulico lo cual la hace vulnerable ante periodos de escasez de precipitaciones, provocando como consecuencia altos precios de la energía y aumento de emisiones de gases de efecto invernadero por la incorporación de fuentes de energía de combustibles fósil dado que estas contribuyen con un 26.36% a la matriz energética. Lo anterior llevó a tomar medidas para ampliar la participación de Fuentes No Convencionales de Energía Renovable (FNCER), basado en el potencial que tienen las diferentes regiones donde destacan fuentes energéticas como la eólica, la solar y biomasa especialmente para producción de energía a gran escala la energía eólica y solar cuyo mayor potencial lo presenta la región Caribe, de manera que en este trabajo se pretende evaluar el recurso eólico y solar de esta región para identificar y establecer las correlaciones y los comportamientos con correlación inversa entre estos, con el fin de garantizar que la participación de estas energías mantendrá la sostenibilidad de la matriz energética al incorporar estas fuentes de energía.

Objetivo— aplicar una metodología estadística que permita evaluar el grado de correlación entre los recursos eólico y solar presentes en la región Caribe en un horizonte temporal de 5 años (2014-2018).

Metodología— Basados en datos (2014 – 2018) de radiación solar global y velocidad del viento medidos en tierra por medio de las Estaciones Meteorológicas Automáticas Satelitales (EMAS in spanish) pertenecientes a la red de estaciones meteorológicas del Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM), se realiza una caracterización mediante un análisis descriptivo con el propósito de obtener un valor representativo de cada variable, se calculan los promedios diarios y mensuales de las series temporales para evaluar la correlación de cada recurso por separado como la correlación conjunta, para lo cual se utilizó un método estadístico basado en el cálculo de los coeficientes de correlación de Pearson.

Resultados— Las series temporales establecidas permiten comprender que la correlación de los recursos por separado o mediante la combinación de éstos, se presenta mayor cantidad de coeficientes de correlación cercanos a -1 cuando se analizan los recursos en conjunto, lo que significa que cuando un recurso aumenta el otro se reduce, correlacionándose inversamente entre sí en sus disponibilidades.

Conclusiones— Tanto la distancia entre los puntos de mediciones como la resolución temporal modulan la correlación negativa que presenta el recurso eólico y solar de la región Caribe, por lo que se obtiene una disponibilidad continúa de los recursos al tener en cuenta el aprovechamiento en conjunto de estos.

Palabras clave— Fuentes de energía renovable; energía solar; energía eólica; correlación energética; diversificación

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I. Introduction

The governments of the world, in their effort to stop the advance of global warming, gathered in the Conference of the Parties (COP), that took place in its first version in Berlin, 1995. The participating countries proposed international policies, which are revised in annual meetings, to analyze the progress in the commitments assumed by the member countries. It was until 2015 at COP21 -known as the Paris Climate Conference- that for the first time in more than 20 years of UN negotiations, it was proposed to legally achieve a binding and universal agreement on the climate, with the main objective of maintaining the warming of the world below 2°C [2]. In this context, Colombia committed to contribute to the global objective of imposing strategies and measures to reduce its greenhouse gas emissions by 20%, compared to the emissions projected for 2030, even though the country is responsible for only 0.46% of global emissions [3].

At COP21, Colombia proposed to fairly address the climate change problem - including mitigation, adaptation, and implementation- by assuming different commitments through Sector Action Plans (SAP), in which identified key actions in the short, medium, and long term. One of these sectors is the basis of this study, namely, the energy sector, which in the SAP is addressed by promoting energy efficiency in all production sectors through non-conventional renewable energies and more efficient energy management [3]. In keeping with this action, the Congress of the Republic issued Law 1715 on May 13, 2014, which seeks to integrate non-conventional energy, particularly renewable energy, in the Colombian electricity market and Non-Interconnected Zones (ZNI in spanish), to reduce greenhouse gas emissions, enhance security of energy supply and promote energy efficiency [4].

The main sources that make up Colombia's power generation park —with cut-off to December 2018— were, firstly, hydroelectric plants with a 69.18% and, secondly, thermal plants with a contribution of 26.36% [5]; It shows the high dependence of the water resource, putting the country at regular risk of shortage and high prices, given the need for resorting to the installed thermal generation capacity. In addition to the hydro dependence that the country exhibits, and considering the developed countries as a model, where the growth trend is linked to investment in technological advance projects, allowing the extensive development and implementation of other types of energy sources, being the ultimate goal to strengthen and diversify the energy matrix [6], [7], so Colombia considers the need for a diversification of the electric generation matrix, focusing on other types of non-conventional renewable energy sources. For this, the national office in charge of planning the electricity system, the Mining and Energy Planning Unit (UPME, in Spanish) incorporated the evaluation of different scenarios —adding Non-Conventional Sources of Renewable Energies (NCRES)— within its studies included in expansion plans, displacing the energy generated by thermal plants, according to what is presented in scenarios 9, 10 and 11 of the Expansion Plan 2014-2028 [8], [9].

The UPME, in the National Energy Plan 2020-2050, proposed two scenarios, the first titled *scenario 266*, which analyzes the impulse to non-conventional sources of energy, both in the generation of electricity and in consumption sectors, directing efforts towards the incorporation of cleaner and more efficient technologies. The second scenario, called *new bets*, in which the challenges of bringing the energy system to the limit were raised, seeking the greater penetration of renewable sources, allowing the economy to be electrified; thus, energy efficiency policy would aim at a strong incorporation of new technologies and cleaner energy [9].

Colombia has great potential for developing NCRES, highlighting the Caribbean Region, with wind energy potential (wind speed peak values around 5 m/s in the center and south of the region [10]), the incident solar potential on the La Guajira peninsula (with an annual solar radiation of 6 kWh/m^2 and an average of 10 hours of sunshine per day [10]), and the biomass potential (with an annual production of over 5 m of sugar cane bagasse, 457000 tons of rice husks and a total of 29 m of biomass from agricultural residues [1], [11]).

The diversity of energy resources in the Caribbean Region, from a large-scale perspective in the process of electricity generation, can be converted into alternatives for demand supplying over other types of sources. Referring only to the availability of the wind potential of the region, this is 10 times greater than the availability of the earth's water resources [12].

Based on the potential to develop NCRES in Colombia, this study focuses on the analysis of wind and solar power potential, supported on the results of NCRES first auction through UPME, where generation responsibilities were assigned to eight projects with a total effective capacity of 1 298 MW of installed capacity, 5 of them wind and 3 solar [13], highlighting the importance of this work

According to the Electricity Generation Project Registration Report submitted by the UPME with cut to 31 December 2020 [14], a total of 325 projects are registered at different stages of progress, of which 20 are wind projects and 220 are solar projects, the latter representing a major advance and greater importance in the development of the resource. For the Caribbean Region, 107 out of 325 projects throughout the country were reported, accounting for 33% of the projects at the national level, which are distributed in 22 for the department of Atlántico (1 wind project and 21 solar), 3 wind and 17 solar projects in department of Bolívar, 13 solar projects in department of Cesar; as in Cesar, in department of Cordoba only solar projects are registered, totaling 16 projects; for department of La Guajira 13 wind and 4 solar projects were registered. In department of Magdalena only 5 solar projects are registered and finally in department of Sucre 10 projects with solar exploitation were reported.

As for the capacity of the registered projects, the department of La Guajira stands out with 3,320 MW distributed in the use of the different NCRES, followed by the department of Magdalena with 1 667 MW; in the third place is the department of Cesar with 983 MW registered, then department of Atlántico with a capacity of 931 MW, next department of Bolivar with 711 MW, following department of Córdoba with 358 MW and finally department of Sucre with 125 MW installed capacity registered, summing a total of 8 095 MW of the total installed capacity for the projects reported in the UPME for the Caribbean Region. Considering that for the whole country a total of 16 130 MW was recorded, distributed among the different types of sources, the Caribbean Region represents about 50% of installed power projected for wind and solar projects registered in the UPME, becoming in a key area for the development and use of this type of energy.

Having recognized the Caribbean Region of Colombia as the area with high potential for wind and solar resources, it makes it the target area of this study. However, identifying the high values present in the north of the country, this area can be considered strategic for the development of wind and solar projects, however, as pointed out by the authors of the work "Complementariedades Anuales e Interanuales de Fuentes de Energías Renovables en Colombia" [15], the use of these resources could not be a definitive solution for the adverse effects produced by phenomena on a global scale such as the warm phase of El Niño Southern Oscillation (ENSO), although within the study the intra-annual evaluation is not carried out, the authors consider it convenient for future studies to expand the time window and thus within the analyzes incorporate the effects of higher order climate variability events such as ENSO both in its warm and cold phases.

Within the literature consulted, no complementarity studies for both resources have been found, so it is proposed to identify the existence of possible behaviors with negative correlation between them, so that we can obtain continuous energy production by leveraging both sources at the same time or identifying a "smoothing"[1] in their availability, so that a characterization of the resources will initially be carried out, evaluating their availability, seasonalities and behaviors over time, and identifying possible areas of use for conversion to electrical energy.

II. Methodology

The study of correlation arises from different questions about behavior, availability and possible combination of wind and solar resources in the Colombian Caribbean Region, likewise, it can provide a vision of how energy production —thanks to the use of these sources— can be "softened" by the combination of both resources as demonstrated by the authors Joakim Widén, Christina E. Hoicka, Ian H. Rowlands, F. Monforti, T. Huld, K. Bódis, L. Vitali, M. D'Isidoro and R. Lacal-Arántegui [16], [17], [18]. In addition to reducing the variability that each source

[1] It consists of an effect presented when the variability in resource availability is reduced when analyzed in the dispersion and combination of resources.

presents, if each is to be leveraged separately, the correlation analysis can represent a primary source for planners and operators of the electricity system, in the development landscape and increased participation of NCRES in the energy matrix. In this way, conventional fossil generation and high production costs would be relegated.

To analyze and understand the possible relationship between wind and solar resources in the Caribbean Region, following a literature review of different methodologies for measuring the degree of association or inverse correlation between renewable energy resources, a statistical methodology based on the calculation of Pearson correlation coefficients was selected and developed, which is mostly utilized and accepted because of its use in the quantification of the degree of association between pairs of renewable variables [19], [18], [20], [21], [22], [23], [24]. This methodology is applied to the time series of wind speed and global solar radiation, measured in-situ, considering the daily and monthly averages series to evaluate the local correlation at different time scales.

As an initial step, based on records of five years (January 2014 to December 2018) about hourly data of the solar resource and 10-minute interval data of the wind resource, the climatic variables: *global solar radiation* in W/m^2 and *wind speed* in m/s were obtained for the Caribbean Region, from field measurements carried out by EMAS belonging to the IDEAM network.

After obtaining the measurements of the variables from the EMAS, a second step was carried out over the study horizon, and it had to do with a data validation by IDEAM technical staff, consisting of labeling each observation and, thus, deciding on the inference on the same data and the certainty of the observed value. In this way, night recorded data by the EMAS for global solar radiation were dropped.

In order to understand the behavior and the relationship of the availabilities of each variable, as the joint evaluation of both, in different time scales, the daily and monthly averages were calculated for the data series of the climatic variables, as a third step developed in the methodology.

Prior to the calculation of the correlation coefficients and due to the characteristic behavior of the annual climatological cycle in Colombia, as well as given that the variables to be evaluated have different units of measurement, it was necessary to perform a fourth step where the time series were standardized by means of (1), to eliminate the effect of seasonality and identify the annual cycle of the variables under study.

$$z_{ij} = \frac{x_{ij} - \mu_j}{\sigma_j} \tag{1}$$

Where x_{ij} represents the i-th observation of the j-th month of the year, μ_j represents the mean value of the j-th month of the year, σ_j represents the standard deviation of the j-th month of the year, and z_{ij} represents the standardized value associated with the i-th observation taken by the weather station for the j-th month of the year. In this same step of the methodology, a descriptive analysis was performed to the time series.

Later, in the fifth step of the developed methodology, the wind-solar correlation coefficients were calculated between the measurement points of the meteorological variables —where each EMAS is geographically located in the region— and the correlation was also found for each resource individually, by establishing its linear relationship in a given area, also known as *spatial complementarity* [25], or for a great geographic variability [26]; the same source can complement itself when used in scattered points, since it would take advantage of the availability of the resource for a specific area.

To validate the results of the calculated correlations, the significance levels were found for each matrix of correlation coefficients, as well as for each pair of time series, analyzed with respect to the results of their correlations, through the p-values; this, to understand and decide if the correlations are significant.

Finally, by means of graphic aids, an analysis of the results is performed, consisting of the graphic interpretation of each matrix of correlation coefficients, represented by means of matrices with color scales to observe the direction and magnitude of each calculated coefficient, and by means of the graphs of the time series for the measurement points with significant correlation values. The development of the study was based on the methodology presented in the schematic diagram shown in Fig. 1.

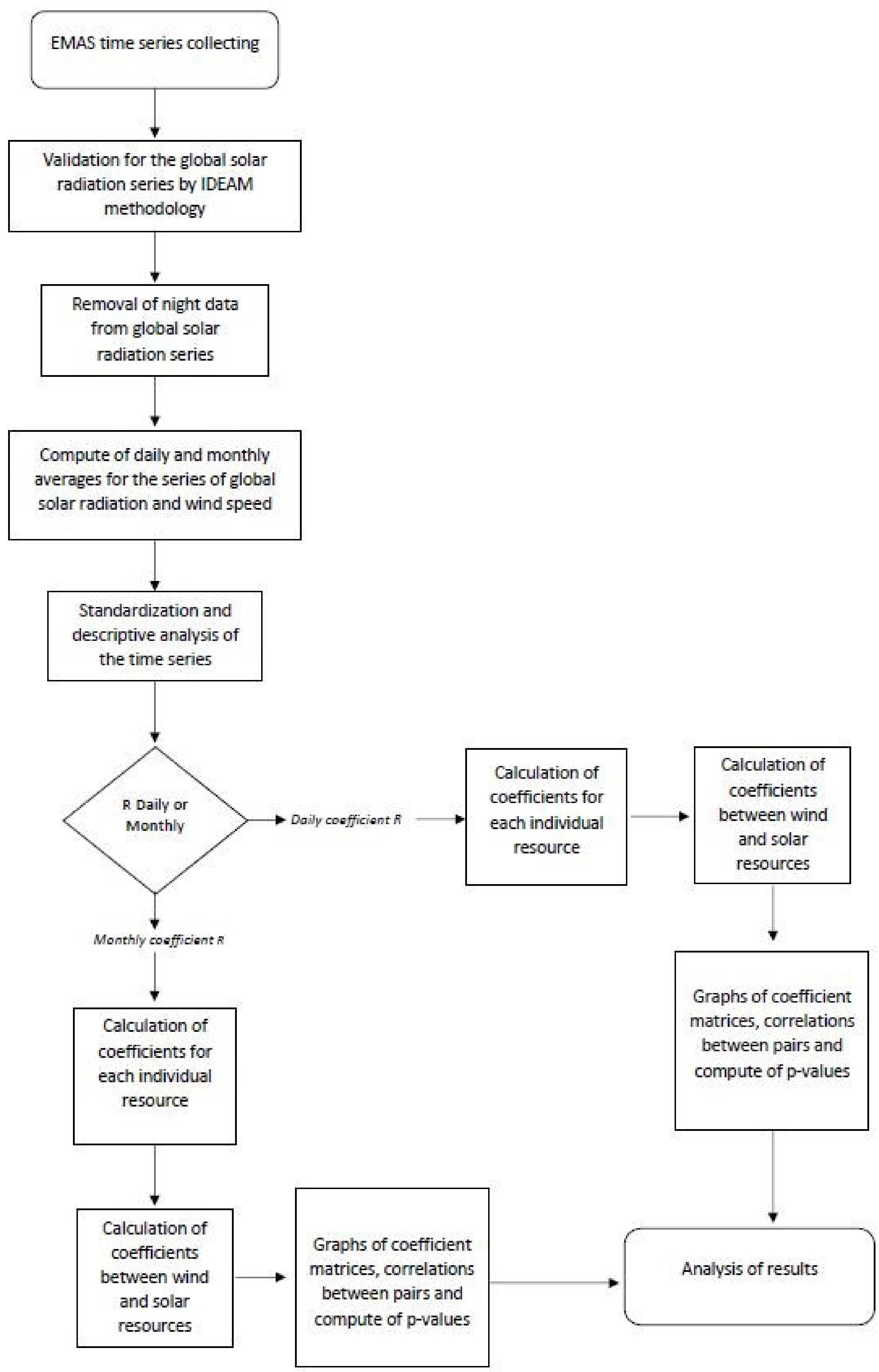

Fig. 1. Schematic diagram of the methodology implemented in the study.
Source: Author(s).

A. *Collection and evaluation of databases*

The databases are analyzed on a regional scale, where the purpose of the study focuses on the local inverse correlation of the two energy resources in the Caribbean Region of Colombia. The characterization of the resources was carried out with the climatic variables, namely, global solar radiation, and wind speed.

The data on global solar radiation and wind speed cover a period of five years (2014-2018) and were provided by IDEAM under the work "Complementariedad de Fuentes no Convencionales de Energía en Colombia" carried out by the Research Group on Power, Energy and Markets (GIPEM, in Spanish) of the Universidad Nacional de Colombia – Manizales and the sponsoring offices UPME and IDEAM. The correlation is calculated only on the common geographic area of the two datasets, extending approximately from 6° to 12°N and from 76° to 76°W. For the purposes of this study, knowing the meteorological observations of climate variables in the Caribbean Region is key to further analysis of energy potentials. The acquisition of these data was obtained from surface meteorological stations, coming from the EMAS network of IDEAM, in order to obtain the behavior throughout the Colombian Caribbean [27].

The country has 160 EMAS from the IDEAM [27] under different classifications (limnigraphic, agrometeorological, ordinary climatic, main climatic, limnimetric, stations measuring at sea level, special meteorological, pluviometric and special synoptic) [28]. With these 160 automatic stations, IDEAM carried out a diagnosis and a prior validation of the time information, for which 105 pyranometers[2] were selected to be calibrated between the years 2014 and 2015. The calibration constants were found, and they were later applied to the data of these sensors, thus, implementing another validation to this information, and then selecting 96 sensors for the elaboration of the Atlas de Radiación Solar, Ultravioleta y Ozono de Colombia [27].

Given the low number of EMAS in Caribbean Region, the authors suggest that efforts between public and private entities should be made to augment the number of EMAS, so that these stations can be geographically distributed in a larger area of the region. With the increase in data measurement points, these EMAS should include sensors that simultaneously measure the variables of global solar radiation and wind speed at the same point, to obtain a reliable evaluation of the resource.

The 20 stations selected for this study are located among the 7 departments that make up the continental Caribbean region, which measure the variables of wind speed and global solar radiation. The selection of EMAS took into account the previous analysis carried out by IDEAM with the stations implemented in the Atlas of Solar Radiation, but an extra selection and validation of the time series of global solar radiation was carried out by IDEAM staff in the framework of the work developed "Complementariedad de Fuentes No Convencionales de Energía en Colombia", developed by the GIPEM research group.

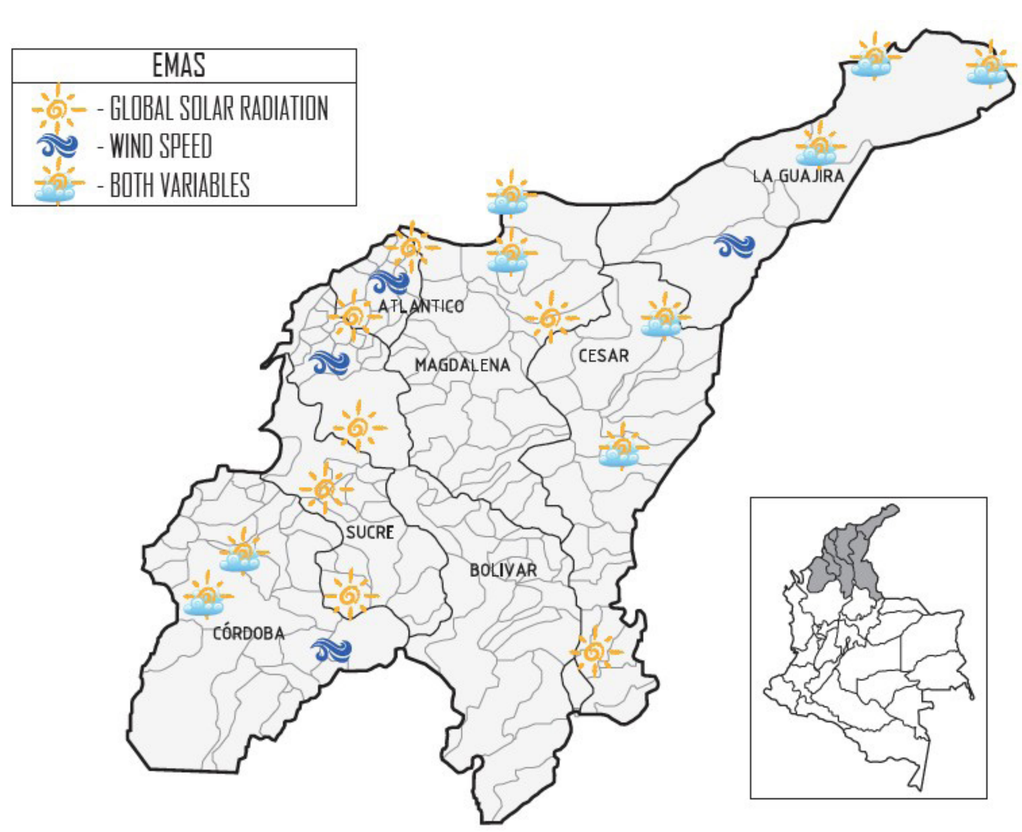

Fig. 2. Geographic localization of EMAS in the IDEAM's network for Caribbean Region.
Source: Author(s) with IDEAM data.

[2] A pyranometer is a meteorological instrument used to precisely measure incident solar radiation on Earth's surface.

To obtain the measurements of the solar resource, of the 20 selected stations, 15 stations were considered for the solar resource, and 13 for the wind resource, highlighting there are 8 stations measuring both variables. Those 8 stations are identified as Universidad Tecnológica de Magdalena, Paici, Fedearroz, La Gran Vía, La Loma Carbones del Cesar, Toromana, Aeropuerto Los Garzones, and INCODER. Table 1 shows the list of the 20 EMAS of the IDEAM, with the characteristics of each, and Fig. 2 presents the geographical distribution of EMAS in the territory of the Caribbean Region.

Table 1. List of selected EMAS for the correlation study, located in Caribbean Region.

Name	Category	Municipality	Deparment	Elevation masl	Latitude	Longitude	Instalation date
Universidad Tecnologica - Aut	Climática principal	Santa Marta	Magdalena	7	11°13'23" N	74°11'9.3" W	2007-09-13
Paici - Aut	Agro-meteorologica	Uribia	La Guajira	45	11°35'41.8" N	72°19'32.7" W	2004-10-14
Aguachica - Aut	Agro-meteorologica	Aguachica	Cesar	103	8°7'24.3006" N	73°34'47.499" W	2005-08-19
San Marcos - Aut	Climática principal	San Marcos	Sucre	31	8°35'48.5988" N	75°8'33.6984" W	2005-10-07
Fedearroz - Aut	Climática principal	Valledupar	Cesar	184	10°27'49" N	73°14'53" W	2005-08-16
Carmen de Bolivar - Aut	Climática principal	El Carmén de Bolívar	Bolívar	152	9°42'56.6994" N	75°6'23.1006" W	2004-03-01
Repelon - Aut	Climática principal	Repelón	Atlantico	10	10°29'24" N	75°7'36.9978" W	2007-09-12
Batallon No. 6 - Aut	Climática principal	Fundación	Magdalena	1280	10°27'55.299" N	73°55'40.0008" W	2006-02-24
La Gran Via - Aut	Agro-meteorologica	Zona Bananera	Magdalena	30	10°51'0" N	74°8'0" W	2008-10-01
La Loma Carbones - Aut	Climática principal	El Paso	Cesar	60	9°38'26.2" N	73°31'26.2" W	2010-03-02
Aeropuerto Puerto Bolivar - Aut	Climática principal	Uribia	La Guajira	10	12°13'27.5" N	71°58'58,4" W	2014-08-21
Toromana - Aut	Climática principal	Uribia	La Guajira	144	12°5'0.7" N	71°12'39.4" W	2005-04-18
Aeropuerto Los Garzones	Sinóptica principal	Montería	Córdoba	20	8°49'33" N	75°49'30.5" W	2015-02-06
Ayapel - Aut	Meteorologica especial	Ayapel	Córdoba	20	8°17'42.2298" N	75°9'52.4016" W	2014-12-11
Incoder - Aut	Agro-meteorological	Montería	Córdoba	37	8°44'49" N	75°54'50" W	2004-11-17
La Paulina - Aut	Climática principal	Fonseca	La Guajira	170	10°53'53.3004" N	72°49'42.4992" W	1966-09-14
Sabana-larga - Aut	Climática principal	Sabana-larga (Atlántico)	Atlantico	100	10°38'12.1992" N	74°55'7.9998" W	2013-05-05
Sincerin - Aut	Climática principal	Arjona	Bolívar	10	10°8'33.2988" N	75°16'41.8008" W	2013-05-04
Aeropuerto E. Cortissoz - Aut	Sinóptica principal	Soledad	Atlantico	14	10°55'4.00" N	74°46'46.99" W	2005-05-04
El Tesoro Ideam - Aut	Agro-meteorologica	Morroa	Sucre	168	9°21'25,5" N	75°17'21.3" W	2004-12-01

Source: Author(s) with IDEAM data.

1. *Global solar radiation time series*

For the study, the radiation data series were taken from the EMAS selected for the Caribbean region over a 5-year horizon (2014-2018); they use a sensor that measures global solar radiation, the pyranometer CM11 from the German company Adolf Thies GmbH & Co. KG [27]. The measurements taken by the stations have a measurement frequency in minutes and add or store the information on an hourly basis.

After filtering the data between 6:00 and 18:00 hours, corresponding to the daytime cycle of solar radiation, 30 time series were built for the 15 measurement points of the solar resource. In this way, the time series of global solar radiation were calculated their daily and monthly averages to perform the analysis using the R-CRAN statistical software, observing the results over the five (5) year horizon.

Although the period under study was selected to minimize the risk of data loss, and because some of the EMAS went into operation in 2014, in some cases gaps occur. When performing an analysis of the amount of data for each station over the 5-year horizon, the station with the highest amount of data was Fedearroz with 93% complete data. Table 2 shows the percentages and amount of data for each station.

Table 2. Number and percentage of observations of the selected EMAS.

Name	Number of observations		Fill Percentage [%]		Measured variable	
	Solar Radiation	Wind Speed	Solar Radiation	Wind Speed	Solar Radiation	Wind Speed
Universidad Tecnologica - Aut	19976	221820	84.2	84.4	X	X
Paici - Aut	12418	139088	52.3	52.9	X	X
Aguachica - Aut	9898		41.7		X	
San Marcos - Aut	16290		68.7		X	
Fedearroz - Aut	22256	250171	93.8	95.2	X	X
Carmen de Bolivar - Aut	18155		76.5		X	
Repelon - Aut	6473		27.3		X	
Batallon No. 6 - Aut	20516		86.5		X	
La Gran Via - Aut	19760	236216	83.3	89.9	X	X
La Loma Carbones - Aut	16706	238697	70.4	90.8	X	X
Aeropuerto Puerto Bolivar - Aut		175400		66.7		X
Toromana - Aut	17738	143582	74.8	54.6	X	X
Aeropuerto Los Garzones	15554	153364	65.6	58.4	X	X
Ayapel - Aut		174696		66.5		X
Incoder - Aut	13248	140924	55.8	53.6	X	X
La Paulina - Aut		252413		96.0		X
Sabanalarga - Aut		175861		66.9		X
Sincerin - Aut		203819		77.6		X
Aeropuerto E. Cortissoz - Aut	21292		89.7		X	
El Tesoro Ideam - Aut	16018		67.5		X	

Source: Author(s) with IDEAM data.

Fig. 3 shows the daily global solar radiation and a trend line (red line) with a 95% confidence interval (gray shadow) for the 15 solar resource measurement points. Given the amount of missing data, the analysis of the seasonality of the solar resource at each measurement point may tend to overestimate or underestimate such behavior, since there are gaps which may be due to the malfunction of the EMAS or possible failures in the validation processes. However, looking at the series of the 15 stations, three of them (Fedearroz, Battalion No. 6 and University of Technology) have the greatest amount of data in their series. According to Fig. 3, for the first quarter of the year and the months of June and July, the global solar radiation has a high average value above 500 W/m^2 for Fedearroz and 1 100 W/m^2 in the Universidad Tecnológica station; this seasonal behavior is the same in every year under study.

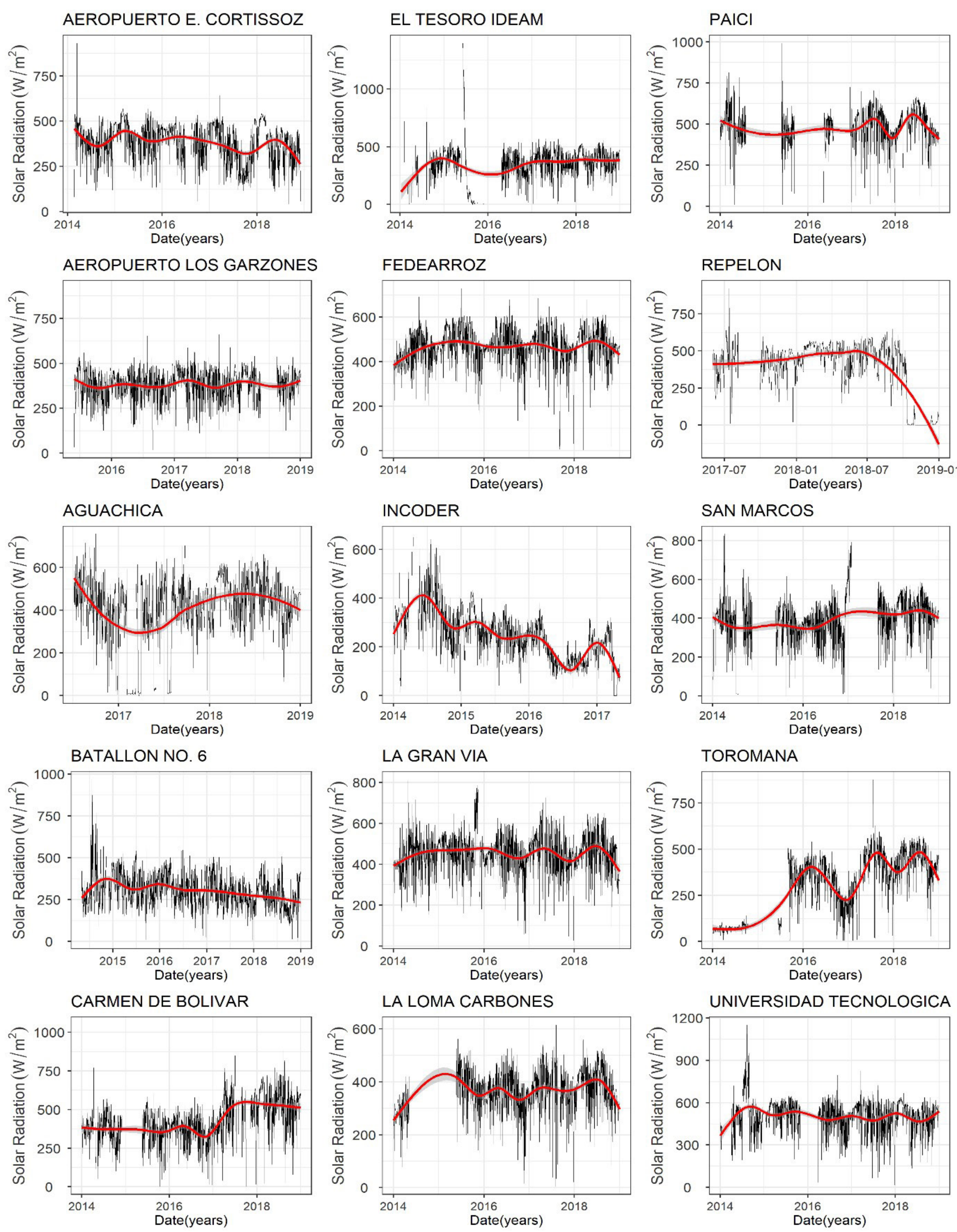

Fig. 3. Time series of daily averages of global solar radiation for the analysis horizon of 5 years (2014-2018). Source: Author (s).

In the case of monthly averages for the time series in Fig. 4, less variability can be observed with respect to daily averages due to day-long climate dynamics, for example, the rapid displacement of clouds and other astronomical factors. The greater local variability of solar irradiance is due to the tilt of the Earth's rotational axis to its orbit, known as obliquity. This causes variation in both the hours of sunlight and the intensity of the global radiation incident (amount per unit area). These astronomical factors have two key characteristics: they are completely predictable and dominate the seasonal variability of irradiance [30].

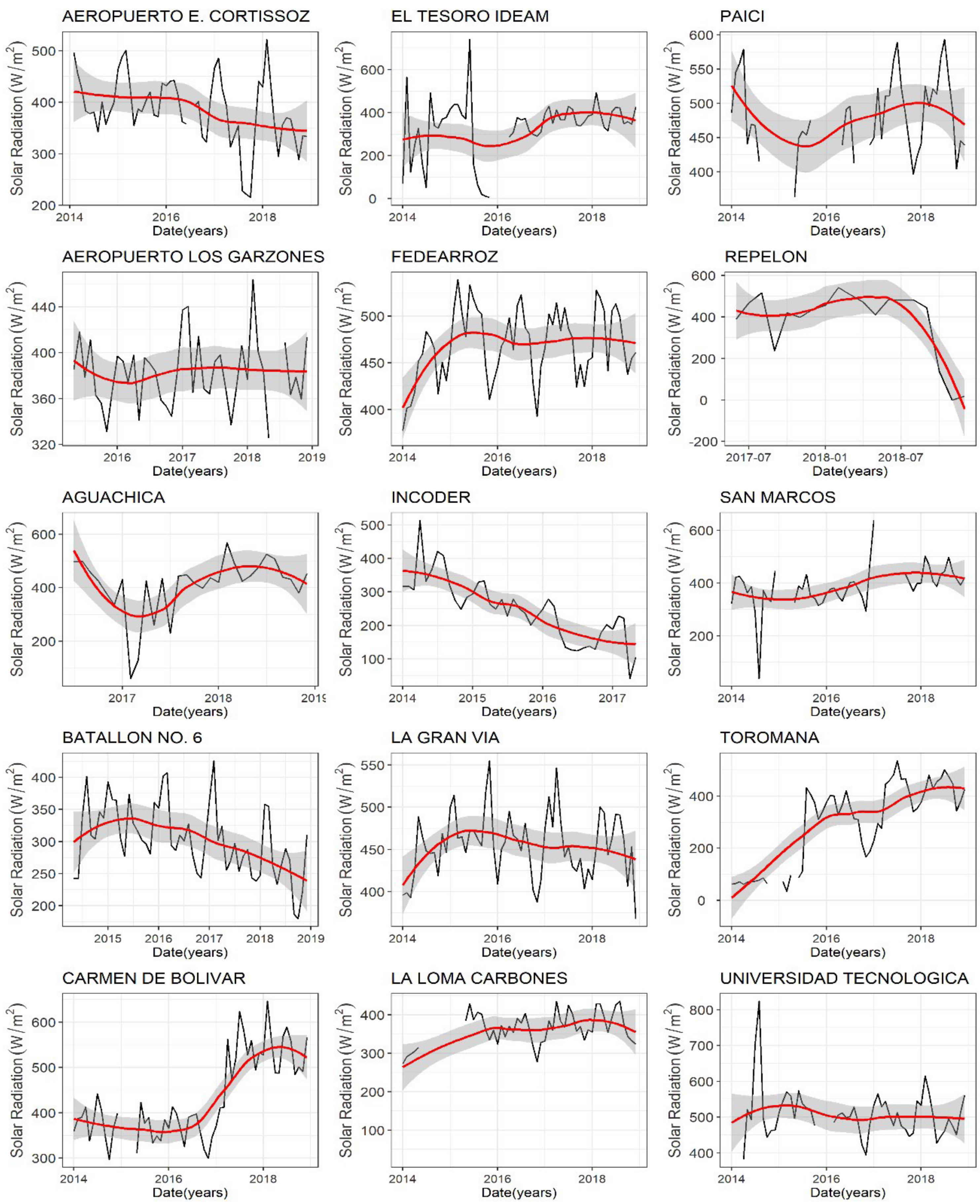

Fig. 4. Time series of monthly averages of global solar radiation for the analysis horizon of 5 years (2014-2018).
Source: Author (s).

In general, all time series of global solar radiation presented large variations, making it difficult to determine a trend due to the lack of continuity in the series. Universidad Tecnológica station had the highest monthly value, with values around 824 W/m^2. Repelon, Incoder and Battalion No. 6 stations had a negative trend line, indicating that solar irradiance was reduced in these places during the 5 years under study. Los Garzones Airport, Fedearroz, La Gran Via and Universidad Tecnológica can be said to have had lower seasonal amplitudes in daily averages. The lowest monthly value of global solar radiation was observed for the El Tesoro station, with a value of 5.23 W/m^2.

To understand the behavior of the global solar radiation variable —registered by the different EMAS—, it is related to the monitoring of El Niño and La Niña phenomenon in Colombia, through the bulletins published by IDEAM between the years 2014-2018. At the beginning of the analysis horizon, in the first quarter of 2014, ENSO is not present in any of its phases, however, historically in January the first dry season of the year begins in much of the country

[31]. At the beginning of the second quarter of 2014, "El Niño" phenomenon began between July and September 2014, coinciding with the Oceanic Niño Index (ONI), which is an index that represents the ENSO measurement, showing the existence of the warm phase in red and the cold phase in blue (Fig. 5) [32].

Year	DJF	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ
2010	1.5	1.2	0.8	0.4	-0.2	-0.7	-1.0	-1.3	-1.6	-1.6	-1.6	-1.6
2011	-1.4	-1.2	-0.9	-0.7	-0.6	-0.4	-0.5	-0.6	-0.8	-1.0	-1.1	-1.0
2012	-0.9	-0.7	-0.6	-0.5	-0.3	0.0	0.2	0.4	0.4	0.3	0.1	-0.2
2013	-0.4	-0.4	-0.3	-0.3	-0.4	-0.4	-0.4	-0.3	-0.3	-0.2	-0.2	-0.3
2014	-0.4	-0.5	-0.3	0.0	0.2	0.2	0.0	0.1	0.2	0.5	0.6	0.7
2015	0.5	0.5	0.5	0.7	0.9	1.2	1.5	1.9	2.2	2.4	2.6	2.6
2016	2.5	2.1	1.6	0.9	0.4	-0.1	-0.4	-0.5	-0.6	-0.7	-0.7	-0.6
2017	-0.3	-0.2	0.1	0.2	0.3	0.3	0.1	-0.1	-0.4	-0.7	-0.8	-1.0
2018	-0.9	-0.9	-0.7	-0.5	-0.2	0.0	0.1	0.2	0.5	0.8	0.9	0.8
2019	0.7	0.7	0.7	0.7	0.5	0.5	0.3	0.1	0.2	0.3	0.5	0.5

Fig. 5. Oceanic Niño Index values.
Source: NOAA [32].

The second year (2015) of the horizon under analysis was presented supported by the ONI values published by the National Office of Oceanic and Atmospheric Administration (NOAA) of the United States throughout 2015, presenting positive values and evidencing the presence of the phase warm from ENSO. This was confirmed by the signals of the ocean-atmosphere coupling recorded by IDEAM and its declaration on the presence of "El Niño" in the country during 2015 [33]. For 2016, the presence of "El Niño" continued and extended its maximum intensity between February and March, which was evidenced in the series of global solar radiation in Fig. 4, where there is a peak in radiation levels in the first quarter of the year. Then, in the middle of the same year, there is a neutrality in the ENSO conditions, to then give way in the last quarter of that year to a "cooling" phase where the ONI value was –0.8°C, being at the threshold of La Niña conditions, which is reflected in the time series of solar radiation with a reduction towards the end of 2016 [34].

By 2017, the presence of ENSO is already neutralized, however, the behavior of the Inter Tropical Convergence Zone (ITCZ) must be considered as it influences this variable, presenting two seasons of drought, evidenced by the presence of two peaks in global radiation levels in some stations such as Fedearroz, Paici, La Gran Via and Batallón No. 6. In addition, by the end of 2017, IDEAM reports ONI values of –0.8°C considered as a fairly robust indicator to determine the cold phase of ENSO [35].

For the year 2018 La Niña winds continues, reducing in this way radiation levels, reason why negative trend lines are present in the radiation values measured by those EMAS implemented in the study.

2. *Wind speed time series*

Measuring surface wind is difficult, as it has daytime and local variations within large-scale dynamics [37]; local variations are caused by moving climatic fronts [16] and the daytime variation of the surface wind also plays a very important role in local circulations and in some meteorological events associated with them. Between these circulations, we can emphasize both the sea-land breeze and the valley-mountain breeze [37]. But understanding the behavior of wind currents is a fundamental task for meteorological and energy studies. Generally, wind currents are analyzed based on two criteria, their direction and speed, where the measurements of these variables are taken in situ or by remote sensors, the second being an alternative to in situ measurements [24]. Techniques for remote measurement of wind with sound (sodar), light (lidar) and electromagnetic waves (radar) are rare in routine meteorological networks [38]. As for *in situ* measurements, these are usually carried out at a height of 10 m to avoid disturbances caused by friction with the surface [37].

The wind speed data for the Caribbean Region, as well as the solar resource data, were taken from IDEAM's EMAS network. The time series resulting from the measurements taken by the EMAS have a 10-minute time scale for the 5-year horizon of the study (2014-2018). From the measurements obtained, 26 time series were formed for the 13 measurement points of the wind resource. In this way, the 10-minute series of wind speed were averaged on daily and monthly scales, observing the results throughout the study horizon in Fig. 6 and Fig. 7 respectively.

Fig. 6 shows the daily averages of wind speed at 10 m elevation and a trend line (blue line) with a 95% confidence interval (gray shadow) for the 13 measurement points. The stations with the highest number of records are Fedearroz, La Loma Carbones and La Paulina; This last station presents 96% of data for the horizon of the study, with a daily average value of 4 m/s, however, at the end of 2017 and at the beginning of 2018 it presented an increase with values around 6 m/s, possibly due to the passage of a tropical storm or a hurricane, given the high probabilities of occurrence of these events in the region under study, which is observed with the general increase in average wind speeds [39]. Furthermore, these values can also occur due to a malfunction of the sensors that measure wind currents. Notwithstanding, the Colombian Caribbean area is mostly vulnerable to storms in the San Andrés archipelago [40], an example of this happened in 2020 with the passage of hurricane Iota, which reached category 4 when it touched land [41] leaving behind a dead person and 98% of the infrastructure of the island of Providencia affected [42]; This vulnerability also occurs on the continental coast.

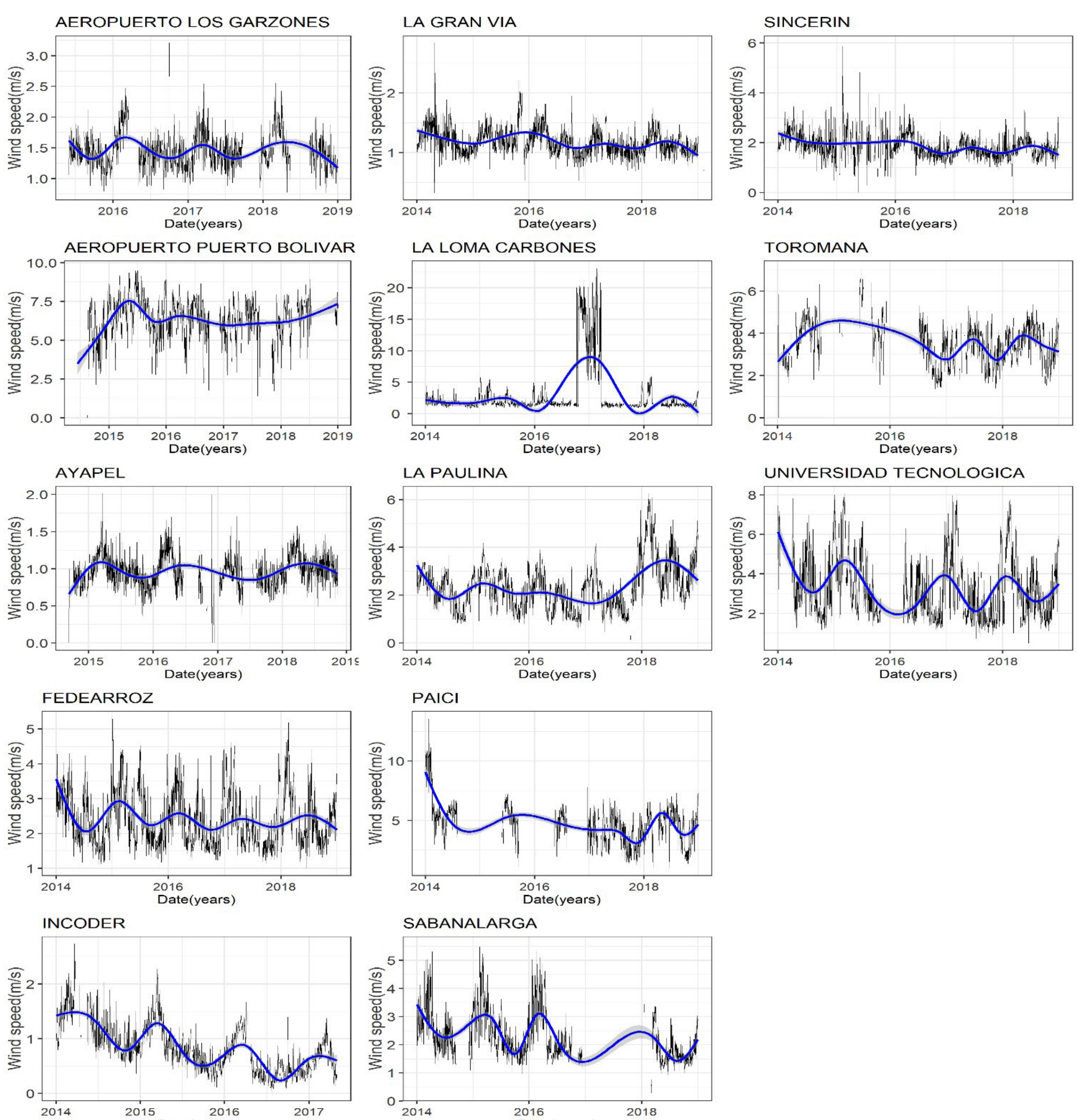

Fig. 6. Time series of daily wind speed averages for the 5-year analysis horizon (2014-2018).
Source: Author(s).

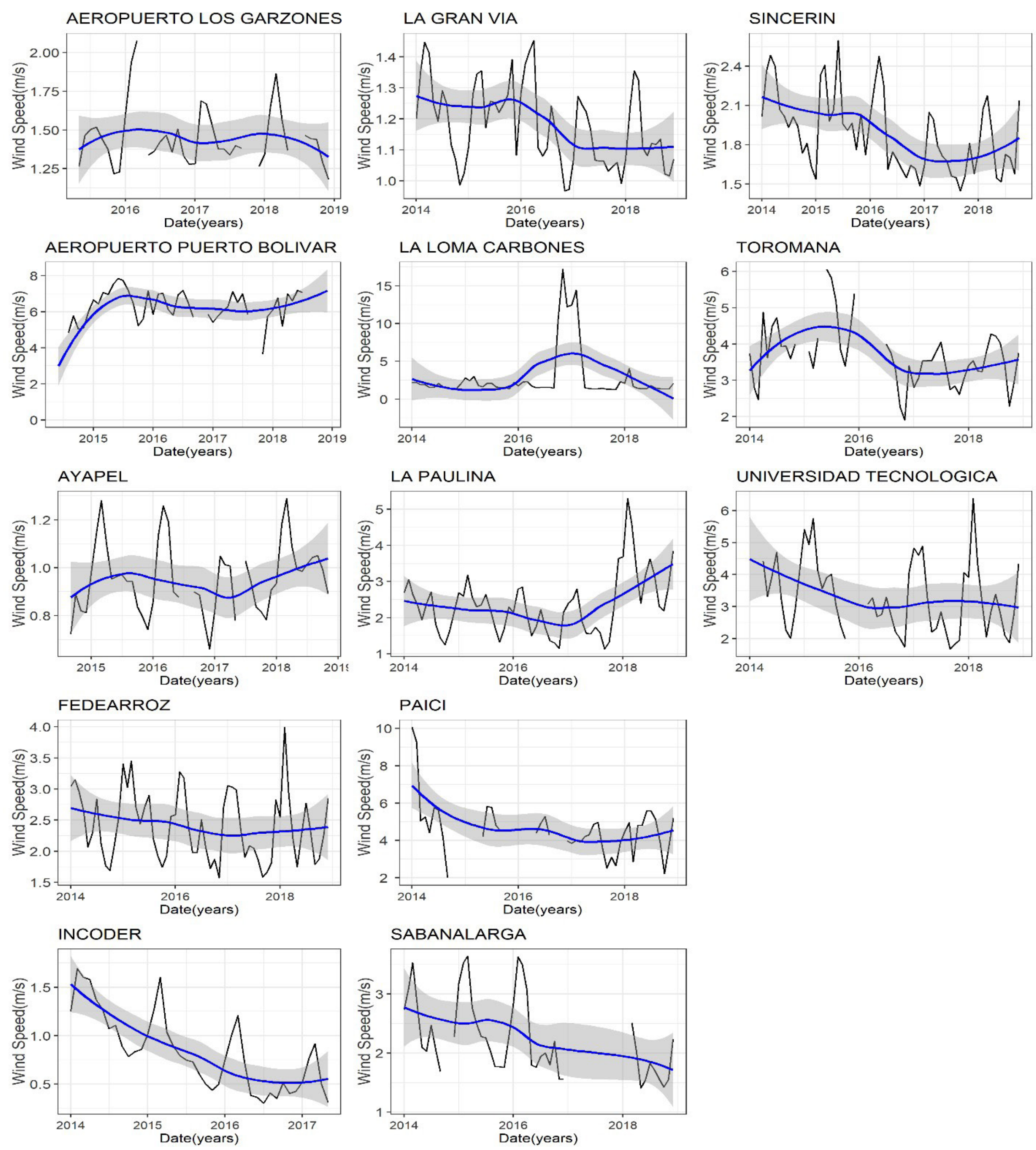

Fig. 7. Time series of monthly averages of wind speed for the analysis horizon of 5 years (2014-2018).
Source: Author (s).

Regarding the monthly averages, Fig. 7 shows the 13 graphs with monthly averages of the measurement points in the 5 years of data collection. In the monthly series of wind speed, Fig. 7 shows how a bimodal climatological cycle is experienced in several series [43] due to the southern migration of the ITCZ, an elongated area along the equator where convective clouds are formed [15], [44], [45], showing fluctuations for the beginning of 2016 on the latitude of 2°N while for December of the same year the fluctuations on latitude were between 7°N - 13°N [46] and the dynamics of surface currents controlled the general climate of the Colombian Caribbean, thus determining two climatic periods defined by the range of rainfall: *a period of drought*, which occurred from December to March characterized by the increase in the north trade winds. agreeing with the seasonal wind analysis carried out by the authors of the work "Complementariedades Anuales e Interanuales de Fuentes de Energías Renovables en Colombia" [15], and *a rainy phase* from April to November. At the end of May, there is a short summer known as "Veranillo de San Juan" (a transitional period originated as a consequence of the arrival of the southeast trade winds) [47].

With regard to the effects caused by the presence of global events such as the ENSO on the availability of wind resources in the country, and especially in the Caribbean Region, in 2014 there was a weakening of the winds coming from the East by significant pressure variations in the South Pacific. West winds begin to predominate in an anomalous way [31], this effect being noticed in the low values of the wind currents measured by the Toromana, La Paulina and Incoder stations. Focusing on La Paulina —since it has 96% data for the study horizon—, with data for the whole year 2014, the weakening of the winds exhibited with values below 3 m/s were identified. For the following year 2015, a similar condition is presented in the winds for the region, where, although there is little cloud formation due to the presence of the warm phase of ENSO, it favors high radiation levels but weakens winds coming from the East [33], a behavior that does not vary in the series with respect to 2014, showing values close to 3 m/s, however, this affectation had no impact on the measuring points located further north of the region, where the Airport Puerto Bolívar and Toromana stations —municipality of Uribia—, are located, recording values with speeds above 6 m/s by 2015.

By 2016, where the beginning of La Niña event is evidenced according to the ONI values of Fig. 5, it implied that the trade winds that normally come from the northeast and southeast, strengthened by increasing the speeds of the wind currents in the Caribbean [34]. According to IDEAM, the hurricane season in the Caribbean Sea began "officially" on June 1 and lasted until November 30, 2017, however, there was no cyclonic activity until June 2017 [35], which is evidenced by sudden high values of wind speed in the EMAS Fedearroz, La Loma Carbones and La Gran Vía.

The year 2018 saw a noticeable strengthening of the Eastern winds, coinciding with the development phase of the event La Niña, which is observed in the trend of increase in wind values in the EMAS Incoder, Ayapel, La Paulina, Puerto Bolívar and Sincerin. Then, in the middle of the same year, a pattern associated with the neutrality conditions of the ENSO event was observed [36].

B. *Calculation of Correlation Coefficients*

Given the wind speed series, $W_j(x, y, t)$ and global solar radiation, $S_j(x, y, t)$ for the days $t = 1$, N_{tot} (where, $N_{tot\text{-}d} = 1.825$ represents the total number of days or, $N_{tot\text{-}m} = 60$ for the number of months in the 5 years of study), correlation coefficients are calculated theoretically by equation (2) and in a practical manner by means of the R-CRAN free-code statistical software.

$$R_j(x,y) = \frac{\sigma_{j,WS}}{\sqrt{(\sigma_{j,W})(\sigma_{j,S})}} \tag{2}$$

With:

$$\sigma_{j,WS} = \sum_{t=1}^{N_{tot}} \{[W_j(x,y,t) - W(x,y)][S_j(x,y,t - s(x,y))]\} \tag{3}$$

$$\sigma_{j,W} = \sum_{t=1}^{N_{tot}} [W_j(x,y,t) - W(x,y)]^2 \tag{4}$$

$$\sigma_{j,S} = \sum_{t=1}^{N_{tot}} [S_j(x,y,t) - S(x,y)]^2 \tag{5}$$

Where $W(x, y)$ and $S(x, y)$ are the daily or monthly averages of wind speed and global solar radiation, respectively. The correlation coefficients can vary between the range [–1, 1]. When comparing two groups of data (W and S) a value of 1 describes a linear relationship between W and S perfectly, with all the data aligning with a positive slope. A value of –1 indicates that when the values of S increase, the values of W decrease or in the opposite way, presenting an inverse behavior, and a value of 0 indicates that there is no linear relationship between the variables.

Given that the units of the correlation coefficients are dimensionless and that they seek to measure the strength or magnitude of the correlation of the two variables or how one variable is supplemented with the other, it is necessary to carry out a standardization process to the series of resources, in addition, a scaling is also needed, due to the fact that the units of the meteorological variables are different, which implies that the step of converting dimensionless units must be carried out prior to the calculation of the correlation coefficients.

The daily correlation between solar radiation and wind speed is less influenced by the day-night cycle, due to local climatic effects, for instance, the rapid movement of clouds and the rotational effect of the earth, where it may indicate a short-to medium-term complementarity between resources, while the monthly correlation is a good indicator of seasonal effects.

For this study, data from night observations are not considered for calculations of averages and correlations. Including measurements at night would only make sense when wind speed is high enough to compensate for the absence of radiation. Only eventually, as explained by the negative correlation values-correspond to an effective anti-correlation or inverse correlation of resources.

III. Results

The assessment of the possible relationship between the solar radiation and wind speed variables is initially carried out by evaluating the spatial correlation of each variable individually, in order to analyze and understand the distribution of the availability of each resource in the region area; in this way, it provides information on possible strategic points for the placement of generation plants that take advantage of energy resources and obtain continuous production of the same source. The daily and monthly correlation assessment of each variable separately serves to help understand the variability of the resource, which is key as it should be taken into account in the planning of energy dispatches of centralized plants.

A. *Correlation between wind speed resources and global solar radiation in Colombia's Caribbean region*

The command called "rcorr" of the R-CRAN software obtains the matrix of correlation coefficients "r", the matrix of the number of observations "n" used in the analysis between the pair of variables or for the same variable only and the matrix "p" of the p-values for each resource individually, obtaining, as well as resulting the arrays of daily correlation coefficients exposed in the points below.

1. *Daily correlation of global solar radiation to measurement points in the Caribbean region*

Fig. 8 shows the matrix of correlation coefficients with a color scale for the daily averages of global solar radiation in the Caribbean Region. In general, it can be observed that the solar resource has a weak correlation with an average value between all the points of 0.29, which indicates that, throughout the entire Caribbean territory, this source presents a uniform distribution with almost similar behaviors at all the measurement points.

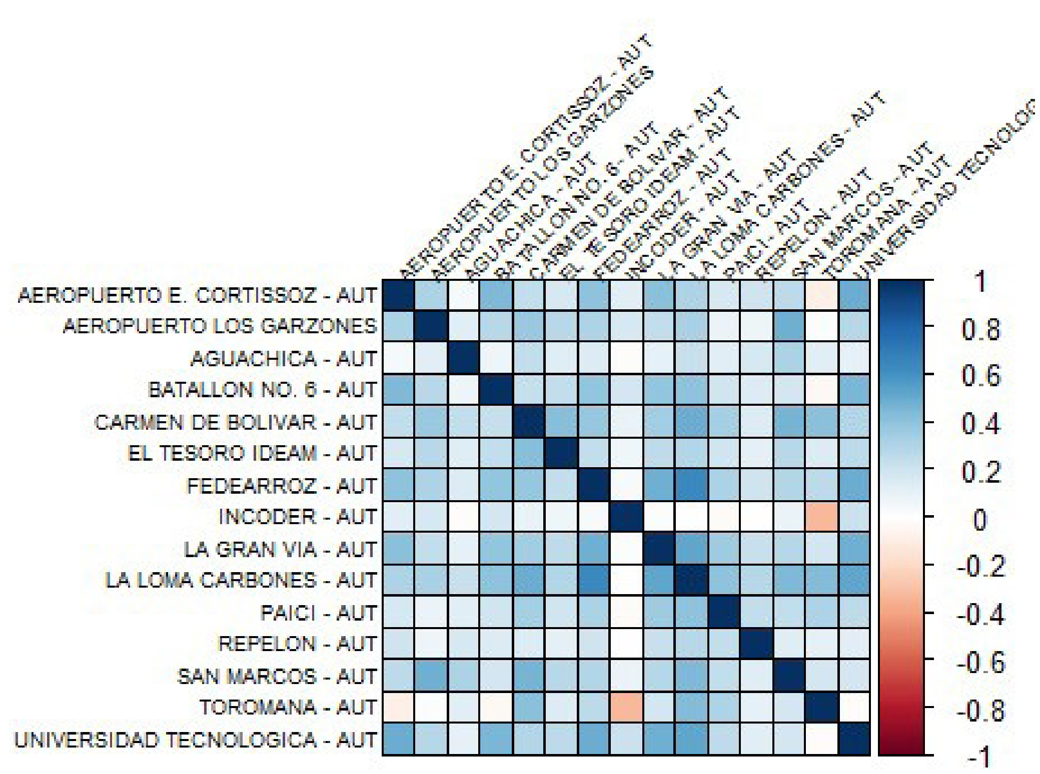

Fig. 8. Matrix of correlation coefficients for daily averages of global solar radiation for all measurement points in the Caribbean Region.
Source: Author(s).

In addition, taking into account the meteorological stations located in places close to each other or in the same department, such as EMAS Batallón No. 6, La Gran Vía and Universidad Tecnológica in the department of Magdalena, they exhibit a behavior that is moderately correlated with an average coefficient of 0.44. In the department of Cesar, where the Aguachica, Fedearroz and La Loma Carbones stations are located, have an average coefficient value of 0.34, indicating that the closer the points are, there is similar or correlated behavior [16], since the seasons follow a very similar seasonal behavior and daytime radiation pattern.

EMAS with complementary behavior, with an inverse correlation one with respect to the other or that exhibit a negative coefficient value are: Toromana, located in the department of La Guajira and Incoder, located in the department of Córdoba, which have a correlation coefficient of –0.32, indicating that when low radiation values are present in the north of the region, high values may be present in the south that make up for this radiation deficit in the north, or it may appear in the opposite way, behavior that can be seen in the Fig. 9.

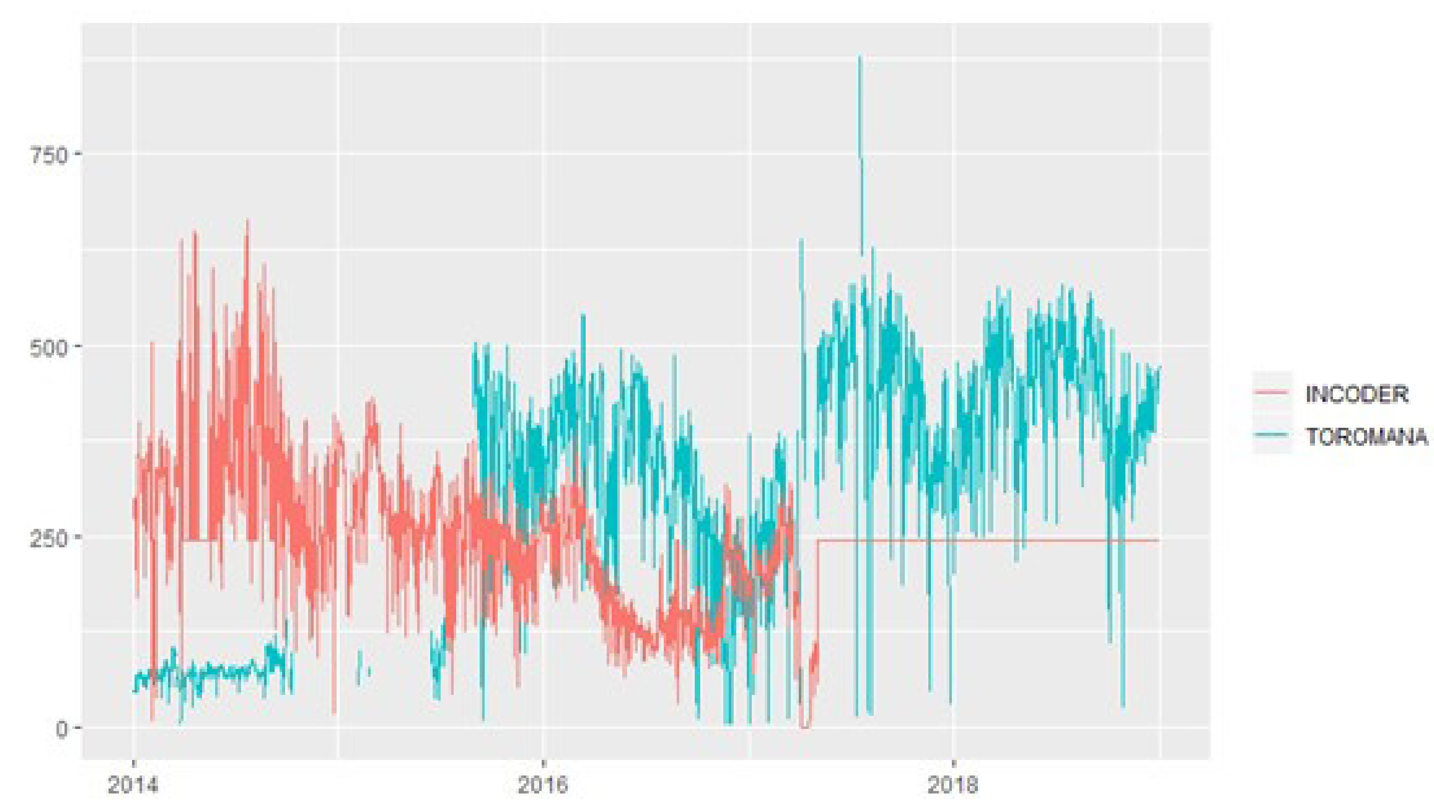

Fig. 9. Time series of daily averages of global solar radiation for EMAS with complementary behaviors.
Source: Author(s).

Although both stations have gaps in their series, between 2015 and early 2017, the Toromana station supplements the low radiation levels presented in Incoder station. This indicates that, throughout the period under study, continuous production of solar energy may occur, as low radiation levels are negatively correlated with places where -in the same fraction of time-, they exhibit high values of the resource.

2. *Daily correlation of wind speed for measurement points in the Caribbean Region*

Similarly, to the radiation series in Fig. 10, the matrix of daily correlation coefficients for wind speed has an average coefficient of 0.29, while that with respect to the solar resource there is slightly more inverse behavior when a greater number of negative coefficients occur. This may indicate that the wind resource may have a continuous profile or a "smoothing" in its production curve since the more dispersed the use of the resource, the more support and continuity it will have given to its inverse correlation.

In the department of La Guajira, when geographically close measurement points are analyzed, an average coefficient of 0.36 is presented, showing a slight correlation between the same resource.

In the opposite case, the point of greatest inverse correlation or with a more significant negative correlation can be noted, obtained between the pair of points of Toromana (department of La Guajira) and La Loma Carbones (department of Cesar), as shown in Fig. 11, separated at an approximately distance of 575 km and a correlation coefficient of –0.28.

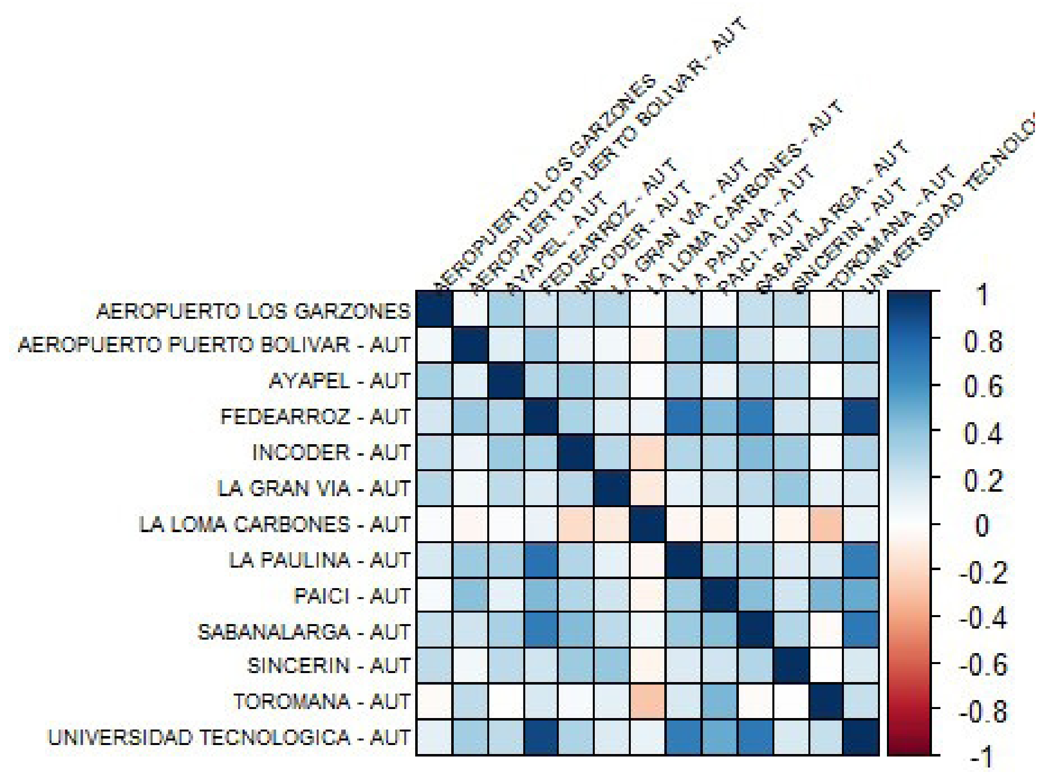

Fig. 10. Correlation coefficient matrix for daily wind speed averages for all measurement points in the Caribbean Region.
Source: Author(s).

Although the value is not close to the lower limit of the range of variation of the correlation coefficients, it should be taken into account that the wind speed presents great daytime and local variability due to the climatic fronts.

Fig. 11. Series of daily wind speed averages for EMAS with complementary behaviors.
Source: Author(s).

In the graph of Fig. 11, the La Loma Carbones station exhibits an atypical behavior towards the end of 2016 and early 2017, presenting values that exceed the average, highlighting that the wind speed data were not subjected to any previous validation process. However, it is observed that for the rest of the series, a malfunction or failure of the sensor or the station may have occurred during this period. On the other hand, it is appreciated that the low values of the air currents measured in La Loma and Carbones can be inversely correlated or supplemented by the wind measured in Toromana.

3. *Daily correlation between wind speed series and global solar radiation for measurement points in the Caribbean region*

The analysis of daily timescale is often used for short-term planning or for operational purposes of the electrical system, such as for setting forecasts and for next-day planning [15].

After analyzing the relationship between the resource individually in the Caribbean Region, the results of assessing the correlation between the two resources together are presented below. Results were obtained by evaluating all possible pairs, in an all-against-all analysis, where prior to the calculation of the coefficients, it was necessary to standardize each series of daily averages to drop the units and effects of the annual cycle of each variable, converting them to the dimensionless values. For this process, the mean was subtracted from each value of the daily series and then divided by the standard deviation as shown in (1).

Just as the correlation coefficients for each resource were calculated separately, for the resource pair, all combinations between the observations —taken by each point selected in the study in the Caribbean Region— were evaluated. This is how the correlation coefficient matrix in Fig. 12 was obtained. For the pair of points with a positive correlation, a coefficient value of 0.48 is obtained between the Carmen de Bolívar (department of Bolivar) and La Paulina (department of La Guajira) stations. Moreover, the stations with the most marked reverse behavior were Toromana and Paici, both located in the municipality of Uribia, department of La Guajira, with a coefficient of −0.30.

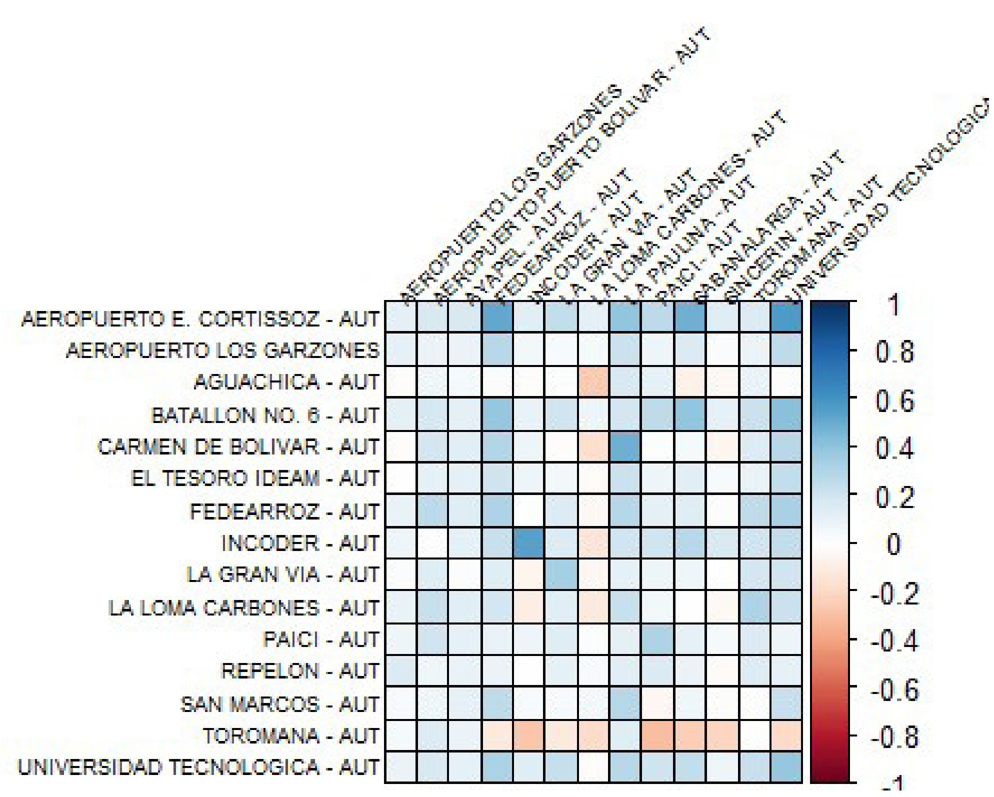

Fig. 12. Correlation coefficient matrix for daily averages of wind speed and global solar radiation at all measurement points in the Caribbean region.
Source: Author(s).

In opposition to the case where each resource is evaluated separately, the stations with best correlation are more distant geographically and the stations with a more marked inverse or anti-correlated behavior have close locations.

Fig. 12 presents the correlation matrix of daily averages of wind speed and global solar radiation at all selected measurement points in the Caribbean region. Fig. 12 shows that the intensity of colors is dim, with most of the coefficient values close to zero, indicating that the relationship between these resources on a daily scale is weak. The correlation between the total daily amount of wind and solar resources is less influenced by the day-night cycle and may provide an indication of the inverse correlation in the short and medium term [18]. In addition, the territory of the region with positive values of correlation between resources correspond to areas where windy and sunny (dry) days occur.

Next, the graphs and their relationship are shown, by means of their time series for both, the pair of correlated stations and the pair of stations with inverse correlation.

In Fig. 13, the stations that exhibit the best correlation are present between Carmen de Bolívar —measuring the global solar radiation— and La Paulina —measuring the wind speed. Although the stations are located in places far from each other, they still have a similar pattern with maximum values at the beginning and about half the year.

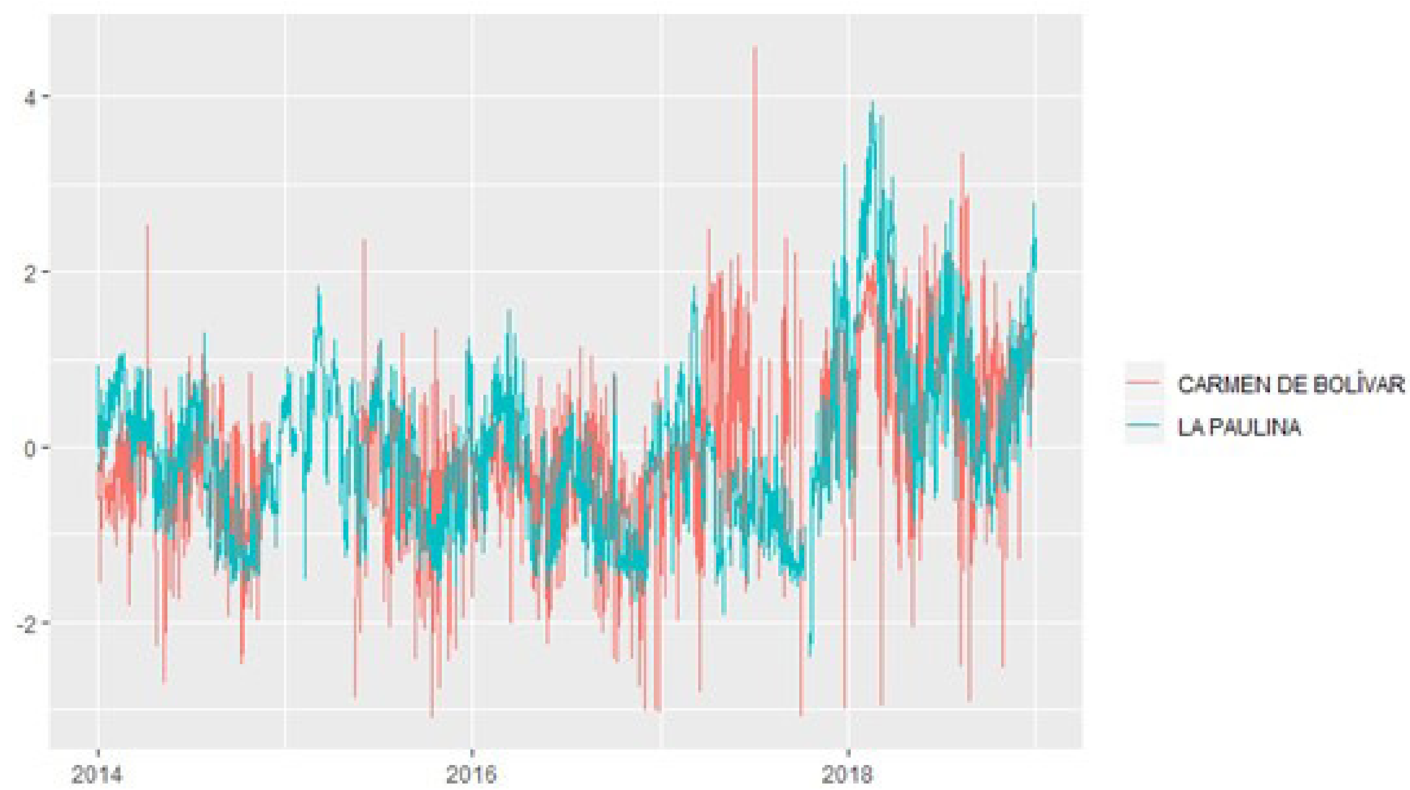

Fig. 13. Scaled time series of daily averages of wind speed and global solar radiation for stations with better correlated behavior (0 < r < 1).
Source: Author(s).

The correlated behavior between these stations is particular, given that geographically they are not close, but it can be interpreted that while the Carmen de Bolívar station presents sunny days, for those same days in the station La Paulina high values of wind speed are measured, and in the same way for the low values of variables. From an energy point of view, the electrical energy that can be produced at these points can be evaluated, so that we can have an overview of how demand can be supplied through joint use of sources with the possibility of having a continuous production profile.

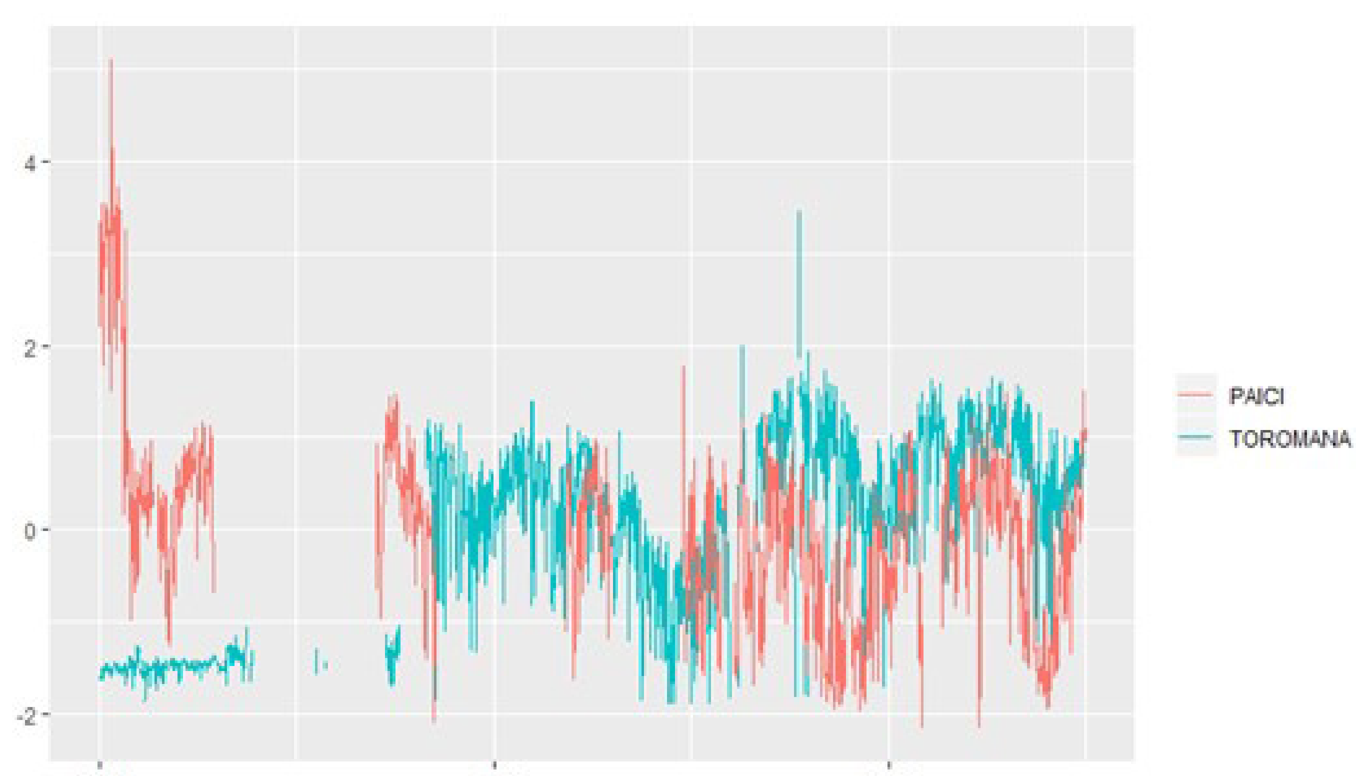

Fig. 14. Scaled time series of daily averages of wind speed and global solar radiation for the stations with the most complementary behavior (0 < r < –1).
Source: Author (s).

For the pair of stations Paici and Toromana —that have an inverse behavior in their daily averages—, a coefficient of –0.31 is obtained, as shown in Fig. 14. It can be noted that at the beginning of the time horizon selected in the study, the low radiation levels presented in Toromana are inversely correlated by the high wind values present at the Paici measuring point. In the years 2017 and 2018 we can also see how radiation would make up for the low daily levels. It is perceived that when the stations are in nearby locations these opposite behaviors are presented in their availabilities, which suggests the possibility of developing hybrid systems that take advantage of both sources in the same place or in very close places.

B. *Monthly correlation between wind speed and global solar radiation resources in Colombia's Caribbean Region*

After calculating the averages of the data series from the 20 EMAS, 20 monthly series were formed with the 60 months in the 5-year study horizon. With the daily averages, 3 matrices of correlation coefficients were calculated, which are analyzed below.

1. *Monthly correlation of global solar radiation for measurement points in the Caribbean Region*

Fig. 15 shows the 15 × 15 matrix, where the correlation coefficients are represented in color scale for the monthly averages of global solar radiation, measured by the 15 EMAS in the continental Caribbean. With an average coefficient of 0.21, a slight correlation is observed between the same resource for the entire region.

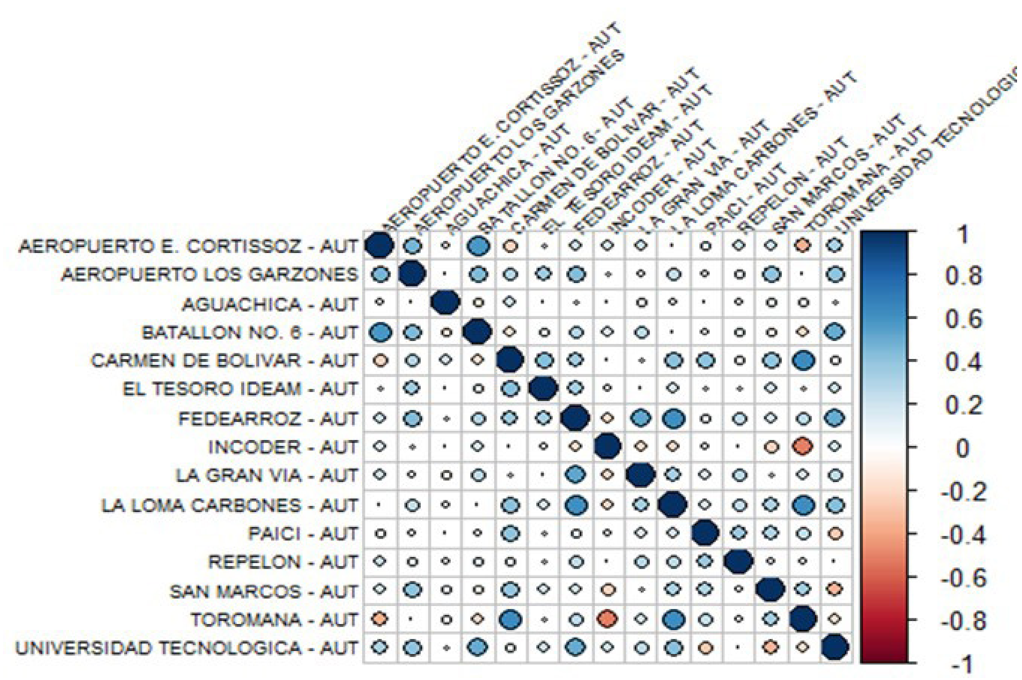

Fig. 15. Matrix of correlation coefficients for the monthly averages of global solar radiation at all measurement points in the Caribbean Region.
Source: Author (s).

The coefficient matrix, in Fig. 15, shows the magnitude of the coefficient by means of the diameter of the circle, and the color scale indicates the intensity of the correlation of each pair evaluated, noting a slight correlation of the resource throughout the territory, being the most correlated pair or with similar behavior between the Toromana and Carmen de Bolívar stations, with a coefficient of 0.6327, indicating that despite of being geographically distant, they exhibit correlated behavior.

For the pair of stations with an inverse behavior, a coefficient with a value of –0.5097 was obtained between the Toromana and Incoder stations, which is the same negatively correlated pair that is presented in the evaluation of the daily averages, only that the absolute value of the coefficient is higher, indicating that strength or intensity increases when analyzed on the monthly scale. To better observe the negative correlation between the pair of stations mentioned above, Fig. 16 shows the time series of the monthly averages for the entire 5-year horizon.

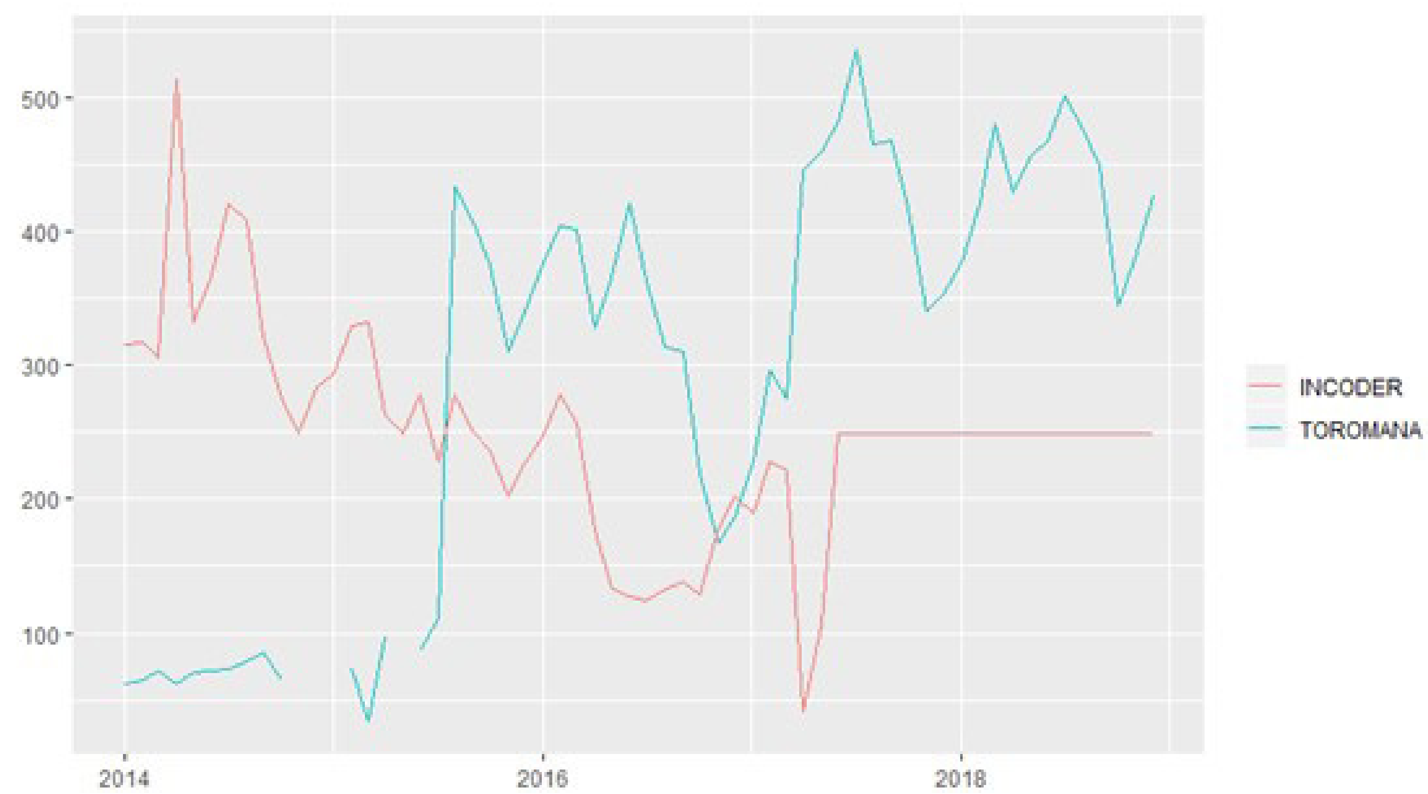

Fig. 16. Time series of monthly global solar radiation averages for EMAS with complementary behaviors.
Source: Author(s).

It can be noted that the variability is reduced when analyzed on a broader time scale, it is worth mentioning the stations have faults, as is the case of the Toromana station, which registers values below the average between 2014 and 2015, perhaps due to sensor malfunction, lack of calibration or some other anomalous behavior because of the lack of periodic maintenance, and for the Incoder station there is an absence of data from mid-year 2017 onwards. Despite the above, these stations show an anti-correlated behavior that can be perceived in the period from mid-2015 to the beginning of the year 2017. The low radiation values presented in the department of Córdoba —where the Incoder station is located— can be inversely correlated by the solar radiation that is measured in Toromana, which reaches its maximum peak in July 2017, with a value of 536.13 W/m^2.

The distribution of radiation in the Caribbean Region has a uniform behavior, with values between 4.5 kWh/m^2/day and 5 kWh/m^2/day according to the Atlas de Radiación Solar, Ultravioleta y Ozono de Colombia [27]. This region is an area suitable for the use of the solar resource, which is feasible due to the smooth and continuous production observed by the points where are located the EMAS that are supplied, leveraging of the high levels of radiation in some points, while in others, the radiation values are low.

2. *Monthly correlation of wind speed for measurement points in the Caribbean region*

Fig. 17 shows the Pearson correlation coefficient matrix for the monthly averages of wind speed for the 13 EMAS that measure this variable. The pair of stations with a more representative inverse correlation is presented by the same pair of daily averages, with a coefficient of −0.37. The Toromana and La Loma Carbones stations exhibit the supplementary behavior, however, there is a greater magnitude with respect to the daily coefficient.

The intensity of the correlations shown in Fig. 17 is stronger than when assessing the correlation of solar resource with its daily averages, showing how the relationship between the same resource for an area of the Caribbean increases when analyzed on a larger time scale.

The seasonality of resources in Fig. 18 tends to overestimate or underestimate the existence of gaps presented by the time series of observations in the EMAS, as is the case of the La Loma Carbones station in the period between the end of 2016 and the beginning of 2017, where also in its time series we can see a seasonality as to the end of each year, wind speed has an increase experiencing two peaks between year and year. This behavior is mainly affected by global climate dynamics, such as the displacement of ITCZ, because when latitudinal migration affects the winds of the north of the country, its speed increases. However, it can be observed that along the study horizon, the resources of the Toromana station compensate for the low

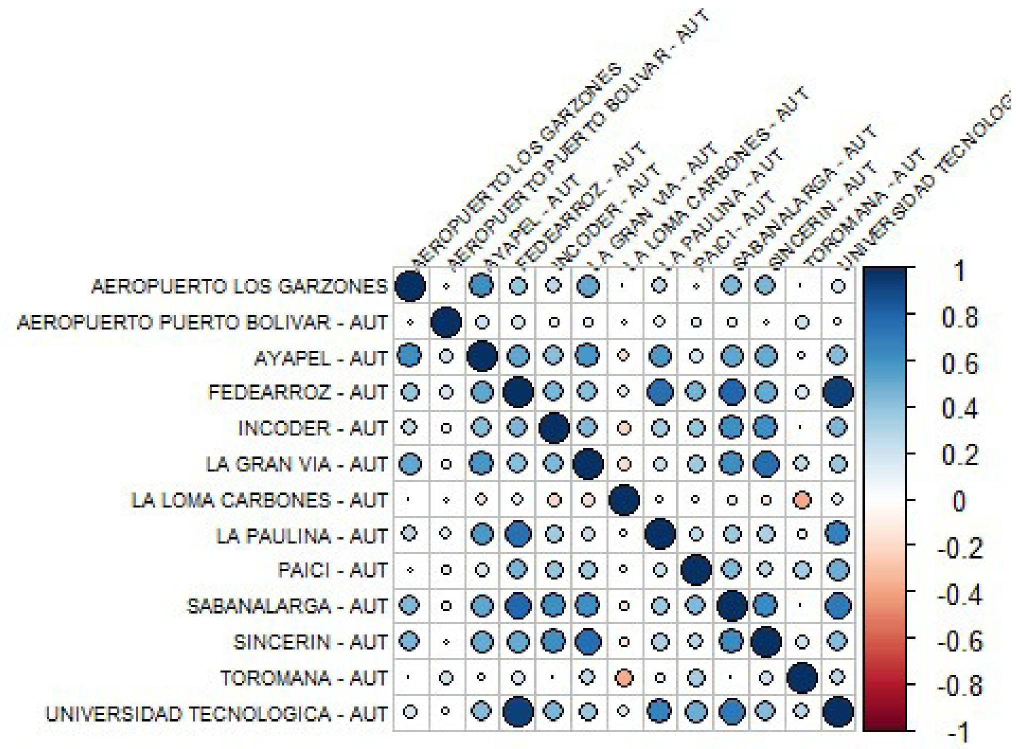

Fig. 17. Correlation coefficient matrix for monthly wind speed averages at all measurement points in the Caribbean region.
Source: Author(s).

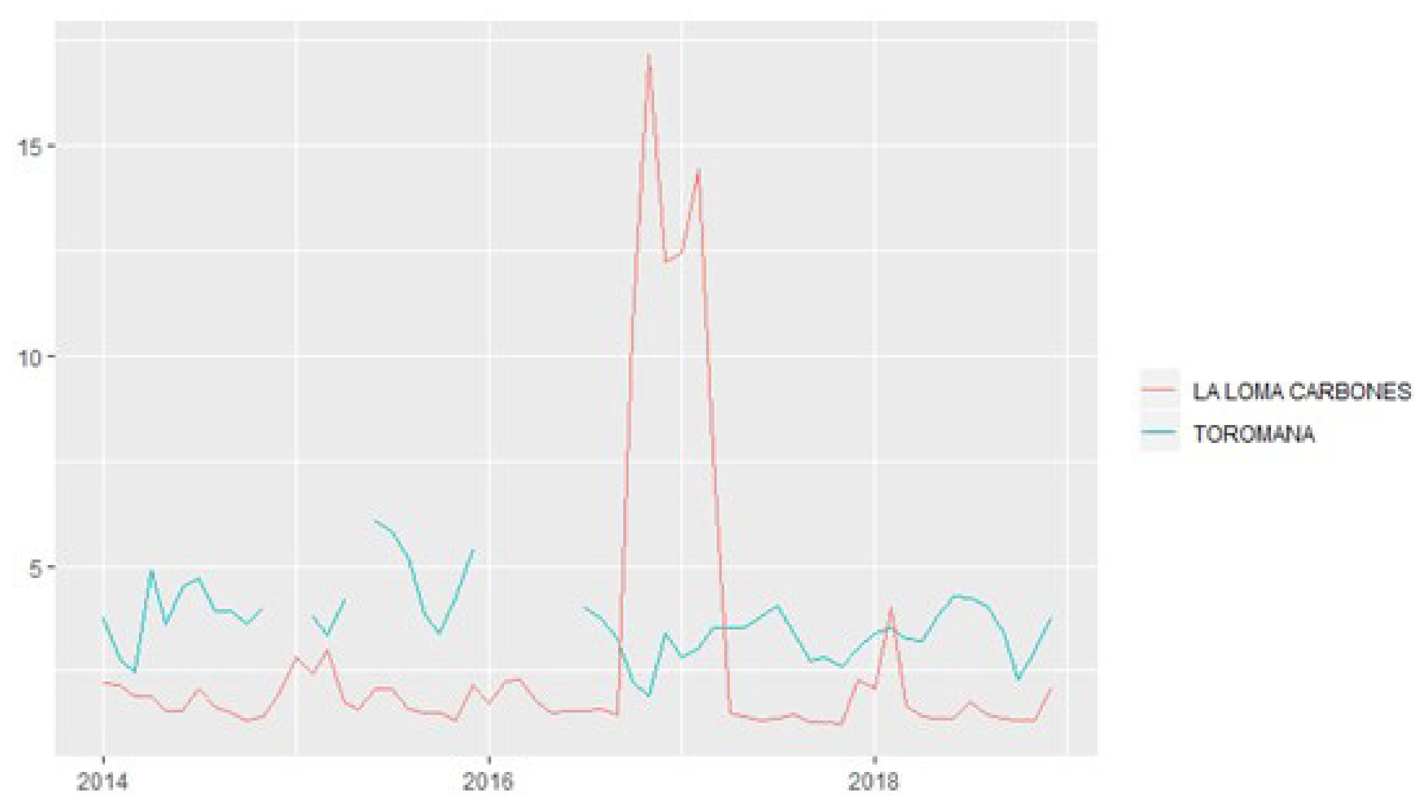

Fig. 18. Time series of monthly wind speed averages for EMAS with complementary behaviors.
Source: Author(s).

wind speed levels of the La Loma Carbones station. To perform a quality analysis, it is necessary to have continuous and complete series of observations, based on the proper functioning of the sensors located in the EMAS, which should be maintained regularly to avoid errors in the taking of measurements.

3. *Monthly correlation between wind speed series and global solar radiation for measurement points in the Caribbean region*

The matrix of correlation coefficients between wind and solar resources is presented in Fig. 19. Negative values of r indicate inverse ratios; in the matrix, the X-axis represents the scaled monthly value of the solar resource or the measurement points of this resource, and on the Y axis the measurement points of the wind speed variable are located. Obtaining a 15 × 13 matrix that provides 195 pairs of Pearson correlation coefficients between the variables wind speed and global solar radiation for their monthly averages. The average correlation coefficient has a value of 0.1136, which indicates a low average level of correlation between these resources for the Caribbean Region.

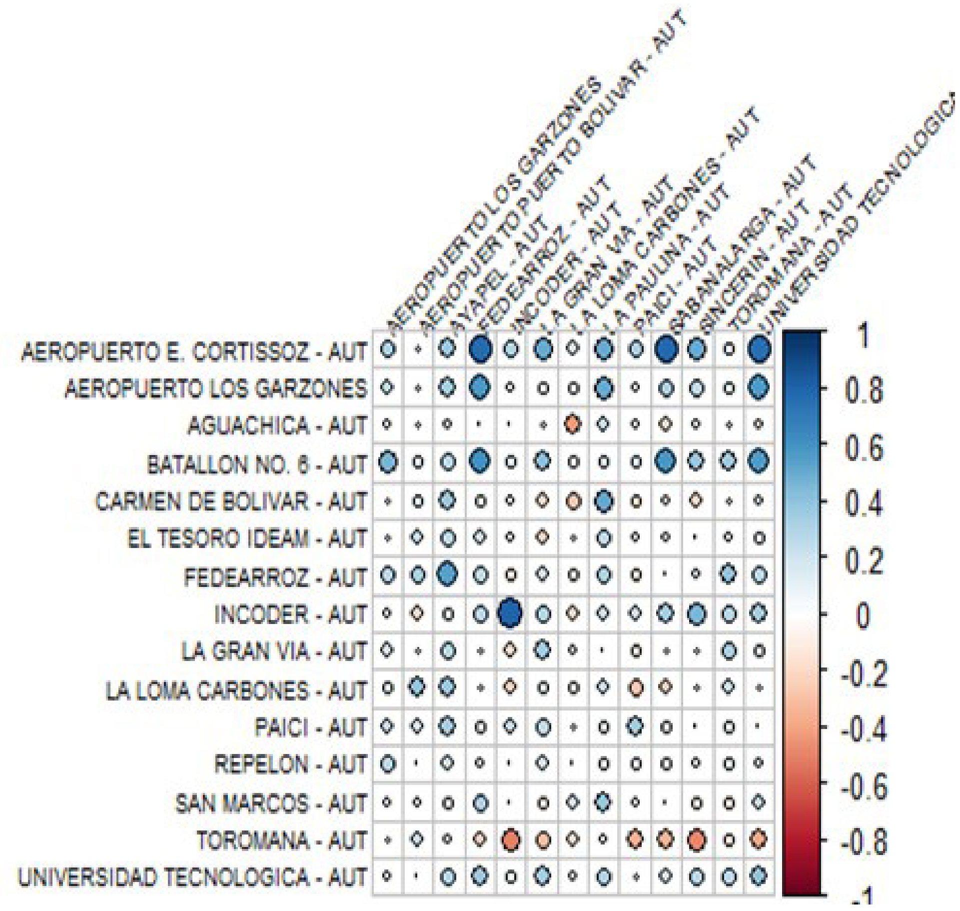

Fig. 19. Matrix of correlation coefficients for monthly averages of wind speed and global solar radiation at all measuring points in the Caribbean region.
Source: Author(s).

The diameters of the circles in Fig. 19, show the absolute value of the correlation coefficient between each pair evaluated, which indicates a low correlation, in which the Aeropuerto Ernesto Cortissoz solar measurement point stands out, has a good correlation with the Wind points in Fedearroz, La Gran Vía, Sabanalarga and Universidad Tecnológica, with values within the range 0.3 < r < 0.7. In the opposite case, the measurement of global solar radiation at the Toromana station shows inverse behaviors –0.24 < r < –0.5 with respect to wind measurement stations such as Incoder, Sincerin and Universidad Tecnológica.

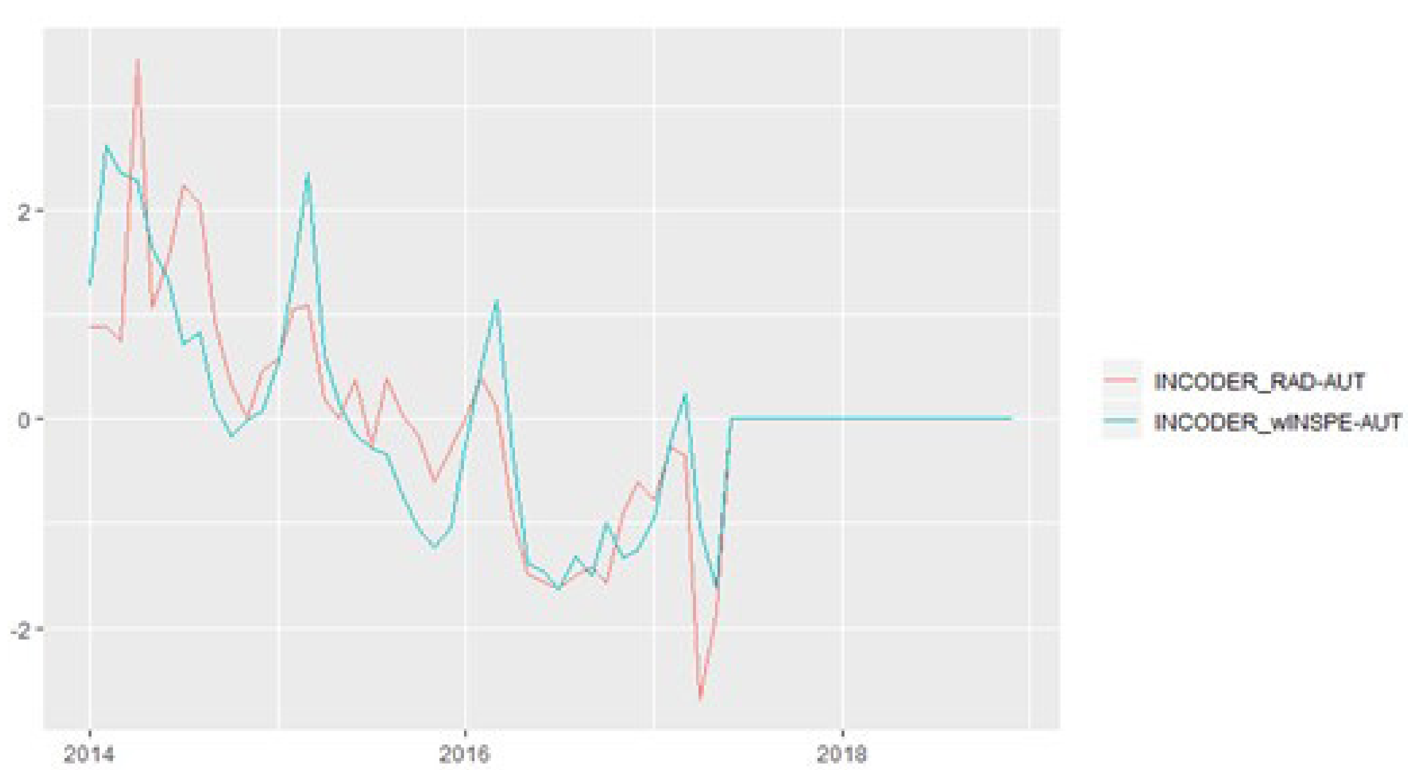

Fig. 20. Scaled time series of monthly averages of wind speed and global solar radiation for the stations with the best correlated behavior (0 < r < 1).
Source: Author (s).

According to the previous analysis, the pairs of stations that correlate positively and negatively with each other are identified, which allows us to better observe their behavior, in both Fig. 20 and Fig. 21. The correlated behavior is obtained at the same station, Incoder, which measures the two variables under study, while the pair of stations with an inverse behavior occurs between Toromana (measuring global solar radiation) and Incoder (measuring wind speed).

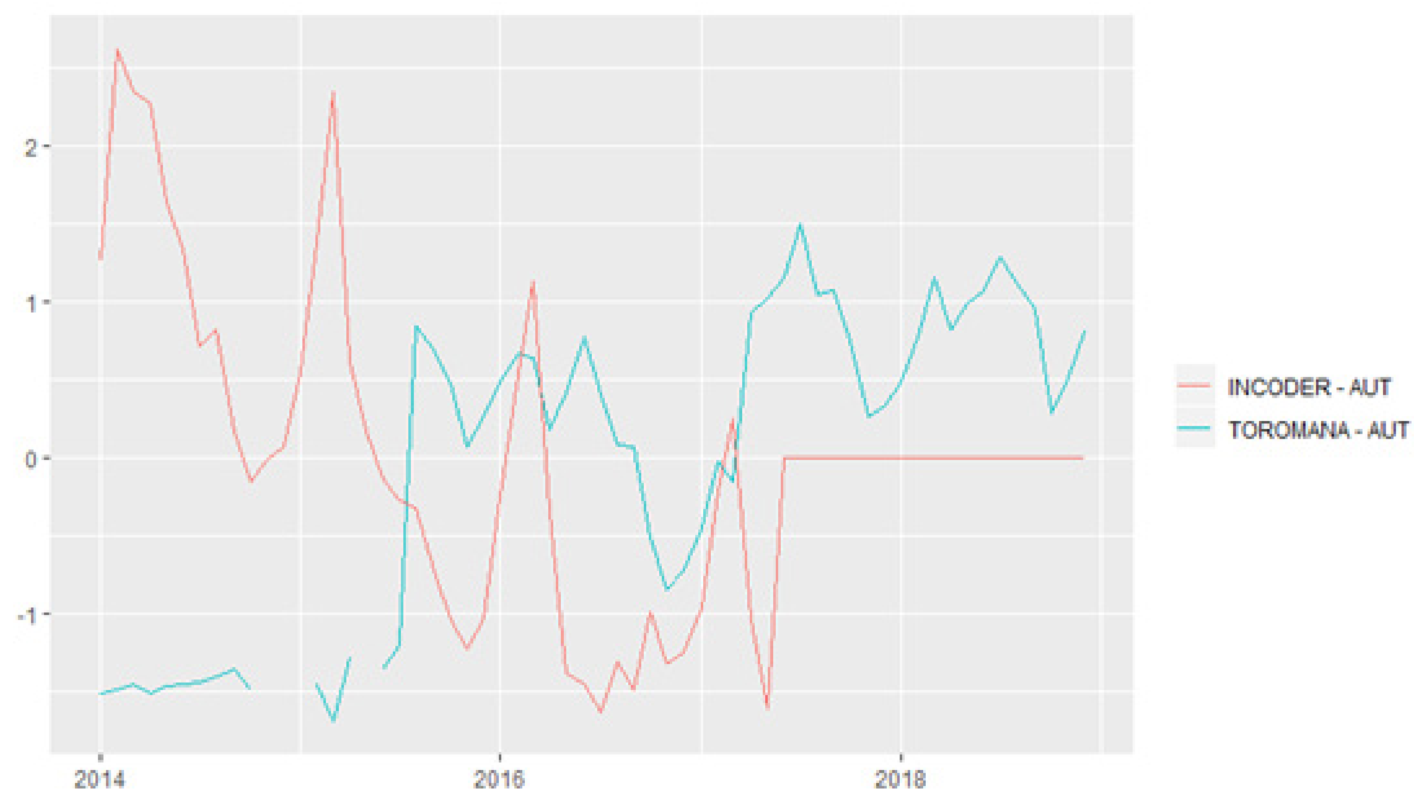

Fig. 21. Scaled time series of monthly averages of wind speed and global solar radiation for the stations with more complementary behavior (0 < r < –1).
Source: Author (s).

A more noticeable variability in the time series of normalized solar radiation with respect to wind speed can be observed in Fig. 20, in addition to an almost similar behavior of the two resources, with 4 peaks during the time horizon analyzed in both series that are observed at the beginning of each year, obeying a marked seasonality that reaches its maximum at the beginning of each year and then with a tendency to reduce the averages during the rest of the year, for the two energy resources.

This seasonality is due to the oscillation of the ITCZ, that occurs as a result of the annual cycle of surface temperatures due to insolation. For this reason, the peak at the beginning of each year —observed in Fig 19— results from the position of the ITCZ, because during the December-May season, it moves towards the north of the country, seeking its southernmost position during the month of July (summer of the northern hemisphere). The position of the ITCZ is associated with the intensity of the eastern trade winds from the opposite hemisphere [48].

This seasonal behavior, marked by the annual cycle of the latitudinal movement of the ITCZ, in accordance with the IDEAM reports for the behavior of the weather in the horizon under study, during the first quarter of the years under study, the ITCZ was found fluctuating in latitudes approximately between 2°N and 8°N, with an average position close to 5°N. In addition, in such period, dry conditions were observed, favoring insolation and without the occurrence of rains. For the second semester of each year, there were increases in precipitation levels for the region, where the ITCZ was oscillating in the south of the region, however, there were dry conditions in the upper Guajira. In July and the rest of the third quarter of each year, the ITCZ helped to cause the rains on the southwestern Caribbean. For the last semester of each year of the study horizon, it is highlighted that in the second week of October, rainy weather prevailed, due to the transit of tropical waves interacting with the ITCZ, while in November, the conditions between partial to mostly cloudy prevailed, showing low levels of solar radiation ending each annual period. At the beginning of December, for the center and south of the Caribbean Region, there were some high volumes of precipitation, then dry conditions were maintained [49], [46], [50], [51], [52].

As for the correlation maintained by resources at this same measurement point (Fig. 20), a coefficient with a value of 0.8 was obtained, i.e., in the same weather station, the global solar radiation and wind speed have a high correlation, very similar in terms of its behavior during one year and throughout the analysis under study. Given the above, between the months of December-April appear these peaks of solar radiation and strong winds, propitious for the use of these resources in the generation of electricity, contributing its production to the electrical system, becoming a backup for the season of drought that affects water resources, this being the main source with the greatest contribution in the generation of the National Interconnected System (SIN in spanish).

Regarding the measurement points or EMAS that present an inverse correlation behavior, it is presented between the Incoder stations (as a point of measurement of the wind) and Toromana (measuring solar radiation) with a coefficient of –0.50, which represents a mean negative correlation, but compared to the absolute value of the daily coefficient, we have a higher value, as can be seen in the graph in Fig. 21.

In Fig. 21, it can be seen how the time series have a different seasonality, given that these two points are geographically more dispersed, the Toromana station being located towards the northernmost point of the region —over 12°— while the Incoder station is located in the department of Córdoba, one of the stations located in the extreme south of the region on latitude 8°, so it is inferred that the movement of the ITCZ does not affect the two stations at the same time, unlike the stations that present a correlated behavior, and also with respect to the stations with greater complementarity in their daily averages, which are located in the same department of La Guajira. With the seasonal displacement of the ITCZ, according to the weather reports for Colombia, it is identified that while the ITCZ moves towards the extreme north location, it oscillates between latitudes 9°–12°N [50], while when it moves towards the extreme south of the region, it fluctuates reaching latitude 2°N [46], so it is evident that the fluctuations do not affect the two stations at the same time. Furthermore, the inverse correlation is more noticeable in the period between mid-2015 and mid-2017.

In the daily and monthly correlation analyses, it should be noted that the Toromana station presents inverse behaviors with respect to other stations; with Paici, for the inverse correlation with the daily averages, and with the Incoder station for the monthly averages. In other words, this geographical point can offer an inverse behavior or can replace the low levels of wind speed measured in other points located in the Caribbean Region of Colombia, that is, provide support to other possible generation plants, when these do not have a high availability of the resource.

IV. Conclusions

This article examines the correlations and possible behaviors with negative or anti-correlated correlations, between the availability of wind and solar resources in the continental Caribbean Region of Colombia, on daily and monthly scales. The results indicate that when the analysis of the resources is carried out individually on the daily scale, it leads to the determination that the smaller the distance between the measurement points, the greater the correlation between them, while the points located at a greater distance between them, exhibit supplementary or inverse behaviors. Otherwise, when the resources are analyzed together, the points have a mostly inverse behavior or with a negative correlation by measuring the radiation and wind that are at a shorter distance. In the event that the EMAS are at a greater distance, they are more correlated. Regarding the same analysis for the monthly scale, it does not occur in the same way, since the distance is not related to the behaviors between the EMAS; it is observed that both the two points with the best correlation, and the two most anti-correlated points, are geographically distant.

When calculating the daily and monthly correlation coefficients for each resource separately, fewer negatively correlated pairs were obtained, a result that is different when the coefficients were calculated with the resources together. From the graphical representation of the matrices of correlation coefficients of the resources both separately and together, the largest number of negative pairs can be determined, which indicates that the resources are better supplied. When analyzing the results, it is observed that the resources as a whole, are those that present this behavior. However, it was perceived in the analyzes that although there is a degree of inverse correlation, it cannot be assumed constant, on the other hand, its strength or magnitude varies throughout the year and due to climatological effects, such as ENSO in its warm phase.

Observing the results for each time scale, it has been shown that when the variables are analyzed together, negative coefficients are presented, increasing their absolute value or strength when the daily values move to monthly and their respective calculation, use found in a study carried out on wind and solar installations in Sweden [16].

The daily and monthly correlation coefficients evaluated for each resource individually show positive correlations for the entire Caribbean Region. Given that the inverse correlation between the two resources is greater, a joint use of wind and solar resources should be considered, selecting geographically dispersed points for the construction of possible generation plants, managing the typical variability presented by intermittent renewable resources, and smooth the production of electrical energy. Thus, in addition to the use of inexhaustible sources for energy production, the use of sources can be optimized by identifying key areas in which inverse behaviors are obtained between sources.

The latitudinal migration of the ITCZ in the Colombian territory and more specifically in the Caribbean Region, directly affects the behavior of the resources under study, exhibiting seasonal patterns in the availability of the resources. Given the points that are under the area of influence of the ITCZ, these increase both the magnitudes and the availability of resources that can complement the points with low levels and that are not under the presence of the ITCZ. That is why the analysis of global and local climatic dynamics on interannual scales in the case of ENSO and annual scales such as the ITCZ displacement, is a key factor to understand the behavior of stochastic variables that are the main source for energy uses in a more efficient and environmentally friendly way.

The results of the study can serve as an input for the planners of the national electricity system and, in general, for the development and implementation of the NCRES, since they indicate possible points where wind and solar power plant projects can be located and developed, not only taking advantage of high availability, but also optimizing their location at strategic points where high inverse correlations are present, also making renewable sources more attractive for implementation. Additionally, planners can be based on this study for their analyses of expansion plans, a base of projections for the construction of projects on transmission lines and substations, that allow the injection of this type of energy into the electric system, in order to bring energy to consumption centers.

V. Observations and Recommendations

Within the analysis of the wind resource and its correlation with the solar resource, only the EMAS measurements of the land wind resource, located in the continental Caribbean, were taken into account. However, observing the Atlas de Velocidad del Viento maps and other studies, which highlight the high speeds of the air masses over the sea, so it is advisable to pay attention to future studies taking into account the offshore wind resource, as well as the location of on-site wind measurement points, present in the Caribbean Sea.

It should be noted that no validation process was applied to the time series of wind speed measured by the EMAS for the study, raw data were taken for the calculation of daily and monthly averages, as in the subsequent study of the wind potential and calculation of the correlation coefficients, considering that these data or results may present erroneous information or may affect the precision of the study.

The measurements made by EMAS should be subject to quality control, where it should be ensured that the data satisfy the necessary conditions (in terms of uncertainty, resolution, continuity, homogeneity, representativeness, timeliness, format, etc.) for the desired application, at a minimum feasible cost. To do this, firstly, a continuous operation and maintenance of EMAS should be performed to avoid faults both in sensors and measuring devices, as it is preferable to prevent errors rather than correct them, and of course, it is a much cheaper option. Followed by the application of a validation process to the dataset, to verify the data validity, check the required data amount, data fit process, to achieve the desired quality or reject the data.

For future studies, the authors consider it convenient to expand the analysis window, according to the norm and climatic anomaly, it is recommended to carry out the analyses with a minimum time horizon of 30 years, to show and analyze the climatic variables, their availabilities, and behaviors, along with the presence of climatic events on global scales such as ENSO and the Pacific Decadal Oscillation.

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