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Analysis of the energetic dynamism between solar and wind energy available in the south of Brazil

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Based on the concept of sustainability, which covers the energy issue as well as its rational use from natural resources, conventional sources do not meet the real requirements of the current production methods. In that context the west region of Paraná state in Brazil presents a vocation for developing projects that involve energy production from alternate sources such as biomass, water, wind energy and solar. Thus, the aim of this research was to verify the behavior of solar and wind sources in the city of Cascavel, Paraná, under different time series of a weather station, subjecting them to quantitative and qualitative analyses of their available energy, by using a statistical approach with Spearman's correlation coefficients (CC). Solar radiation and wind speed were observed. The correlation coefficients used in the analyses of behavior among alternative sources showed weak correlation with independence between variables in all parameters. Solar energy availability was proportionally more representative than wind availability in all periods assessed, mainly between inter seasonal averages.

Key words: Energy availability, renewable sources, correlation coefficients, clean energy.

INTRODUCTION

The region within 30° North and 30° South from the Equator (Asia, Africa and Latin America) has plenty of one or more renewable and clean energy sources, as solar, wind, water, biomass, geothermal and tidal. The issue is how to proceed in combining these resources with human needs (Ramakumar and Bigger, 1993).

Brazil has a significant share of renewable sources in its energy matrix, reaching 74.60% in 2014, which is above the global average of 19.70% in 2010, according to the International Energy Agency (IEA). The Brazilian economy is two times less polluting than the American, 1.3 times less than the European and 4 times less than the Chinese (MME-Ministry of Mines and Energy (Brazil) and EPE- Empresa de Pesquisa Energética, 2015). Hydropower is the main production source in the Brazilian energy matrix with 76.90%. Hydroelectric power plants are great energy providers, but in general terms they are limiting for a number of conditions concerning

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environmental, logistical and financial issues, having to depend on other forms of renewable energy to meet the world's needs with the same efficiency and sustainability (MME-Ministry of Mines and Energy (Brazil) and EPE-Empresa de Pesquisa Energética, 2015). The Brazilian aptitude for renewable energy options is potentially favorable, mainly with water, solar, wind and biomass.

Studies by (Tiba et al., 2000) in a time span of 40 years showed that the average daily global solar radiation in Brazil ranges from 8 to 22 MJ/m².day^{-1}. In 10 years of studies (Pereira et al., 2006), found that the southern region of Brazil has an inter annual average between 17 and 22 MJ/m².day^{-1}. In Paraná the annual average of daily global solar radiation is 16 MJ/m².day^{-1} (Tiba et al., 2000). In 2014 the installed capacity for wind generation in the country increased by 122.0%. The northeast region presents the country's largest wind energy production with installed capacity of electrical generation of 3.9 MW. The advancement of Brazilian wind generation is noticeable; the difference between 2013 and 2014 represented an increase of 85.60% (MME-Ministry of Mines and Energy (Brazil) and EPE-Empresa de Pesquisa Energética, 2015).

Alternative sources of energy can be supplied together. The solar and wind energy sources can be regarded as complementary in time, space or both (Beluco et al., 2008). Li et al. (2009) examined the correlation of wind and solar power in Australia for a whole year. Studies of (De Jong et al., 2013) were based on statistical data variables that defined the solar and wind resource and its correlation with the load curve between levels of hydroelectric reservoirs. According to (Notton et al., 2011), it is possible to analyze weather data in order to check the available energy from wind and solar sources using a correlation coefficient (CC) for a given period. Correlation analysis is the definition of a numerical direct relationship between two variables and Spearman's correlation coefficient can be used for data that do not have a standard, as well as for nonparametric data using only ranks, also called Spearman's rank coefficients; this method makes no assumption about the frequency distribution of variables (Shimakura, 2005).

In this context, the aim of this study was to analyze the behavior of alternative sources from solar irradiance and wind speed and direction, turning the hourly data inherent to these variables into different time series in order to describe in more detail the energy availability provided by solar and wind sources in Cascavel, PR.

MATERIALS AND METHODS

Availability of solar and wind energies

Solar energy

Several devices are used for measuring solar radiation and its components; the Campbell-Stokes heliograph measures the number of hours of sunshine or heat; the actinographer measures the total or diffuse solar radiation; the pyrheliometer measures the flow of direct solar radiation, and the pyranometer measures global radiation (Tiba et al., 2000). These measuring devices, according to (Martinazzo, 2004), meet the technical recommendations of the World Meteorological Organization (WMO) in what concerns to their installation and calibration, what makes them reliable and accurate, since each device requires specific care according to their purpose and limitations. The Angstrom relationship is the one existent between the daily global insolation and radiation. This method was established in 1924 and was modified by Prescott in 1940, and is currently known as the Angström-Prescott equation, defined by Equation 1, in accordance with (Suehrcke et al., 2013), in which the rate of daily global solar radiation H [$MJ.m^{-2}$] by the daily global radiation at the top of the atmosphere $_{H0}$ [$MJ.m^{-2}$] is equivalent to the sum of the linear regression coefficients $a + b$ [$dimensionless$], being multiplied by the ratio between daily insolation n [$hours$] and daytime duration n [$hours$]. The pyranometer was used to measure global solar radiation in a horizontal surface.

$$\frac{H}{H_0} = a + b\left(\frac{n}{N}\right) \tag{1}$$

Wind energy

According to (Masseran, 2015; Pinto, 2013), when the flow of air in motion is variable through time, it turns into potential wind energy P [$W.m^{-2}$] (Equation 2). It is used in order to better describe the flow of wind power available, which in this situation is directly proportional to wind speed cubed v [$m.s^{-1}$], the area of the airstream that has been measured at a perpendicular plane to wind speed direction A [m^2] and air density [$kg.m^{-2}$].

$$P = \left(\frac{1}{2}\right).\rho.A.v^3 \tag{2}$$

Air density ρ is established according to local altitude z [m], atmospheric pressure in relation to sea level P_0 [$kg.m^{-3}$] and temperature T [K] with the air specific constant R [$\frac{J}{K}mol$] and gravity acceleration g [$m.s^{-2}$], as shown in Equation 3 (Pinto, 2013).

$$\rho\,(z) = \frac{P_0}{RT}e^{-\frac{gz}{RT}} \tag{3}$$

Characterization of the area and obtainment of meteorological data

The obtainment of solar and wind energy data was provided by a meteorological station model Hobo U30, located at 18 meters high, at coordinates - 24° 59' 19" (S) and - 53° 26' 52" (W), 763 m above sea level, as shown in Figure 1. Data acquisition was performed automatically for a period of two years by means of a Datalogger.

Time series

The several types of weather variations are highly relevant for the use of solar and wind energy, considering daily, annual, seasonal and short-term variations, the latter in the case of wind speed (Macêdo and Pinho, 2002). After automatic data collection by the

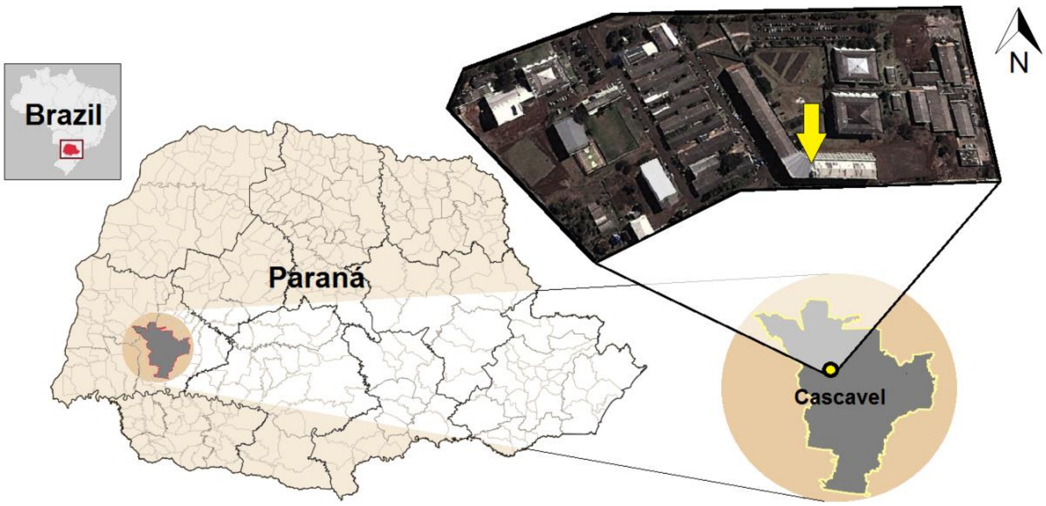

Figure 1. Map with the location of the meteorological station with automatic acquisition of solar radiation and wind speed data in UNIOESTE. Source: author.

Table 1. Spearman's rank coefficients.

Negative	Level	Positive
[-1]	Perfect	[1]
[-0.9 to -1]	Very Strong	[0.9 to 1]
[-0.6 to -0.9]	Strong	[0.6 to 0.9]
[-0.3 to -0.6]	Regular	[0.3 a 0.6]
[0 to -0.3]	Weak	[0 to 0,3]
[0]	Absent	[0]

Source: adapted from (Masseran, 2015).

weather station, the five-minute intervals were changed to hourly intervals. The variables of barometric pressure, ambient temperature, solar irradiance, wind speed and direction were processed into a spreadsheet. Mean and/or cumulative values were discussed in order to analyze the solar and wind energy availabilities occurring in these different variations of time, for a daily, monthly, yearly and hourly stationary discussion. Discussions related to the behavior of the time series, wind and solar availability and analysis of correlation coefficients are put separately to assess the variations observed in each series.

Energy availability data analysis

Posterior to obtaining the solar irradiation meteorological data, the available solar energy (ASE) $[Wh]$ was calculated with the nth average of the data group n $[unit]$ by multiplying the described average global radiation $l_h\,[Wh]$ described by Equation 4. The 5 min intervals were changed to hourly intervals by multiplying them by the coefficient demonstrated in Equation 5.

$$\mathrm{ASE} = \sum_{i=1}^{n} l_h \ x\, t \quad (4)$$

$$t = \frac{1}{12}\ \text{hours} \quad (5)$$

For the available wind energy (AWE) $[Wh]$, the nth average of the data group n $[unit]$ was calculated by multiplying the average wind power described in Equation 6. The 5 min intervals were changed to hourly intervals by means of multiplying them by the coefficient demonstrated in Equation 7. The same was done to solar energy.

$$\mathrm{AWE} = \sum_{i=1}^{n} P \ x\, t \quad (6)$$

$$t = \frac{1}{12}\ \text{hours} \quad (7)$$

Analysis of available energy correlation

Spearman's rank correlation coefficient ρ $[dimensionless]$, expressed in Equation 8 (Andriotti, 2010) was used for verifying the correlation rank among variables, in which the differences among ranks with correspondent x and y $[numeral]$ values and pair numbers of the n $[unit]$ values are inserted. The correlation ranks of this coefficient's classification range from - 1 to 1, as shown in Table 1.

$$\rho = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n\,(n^d - 1)} \quad (08)$$

RESULTS AND DISCUSSION

Interannual energy availabilities

The peak hours for solar and wind energy availability were concentrated at 10 and 12 o'clock, as shown in

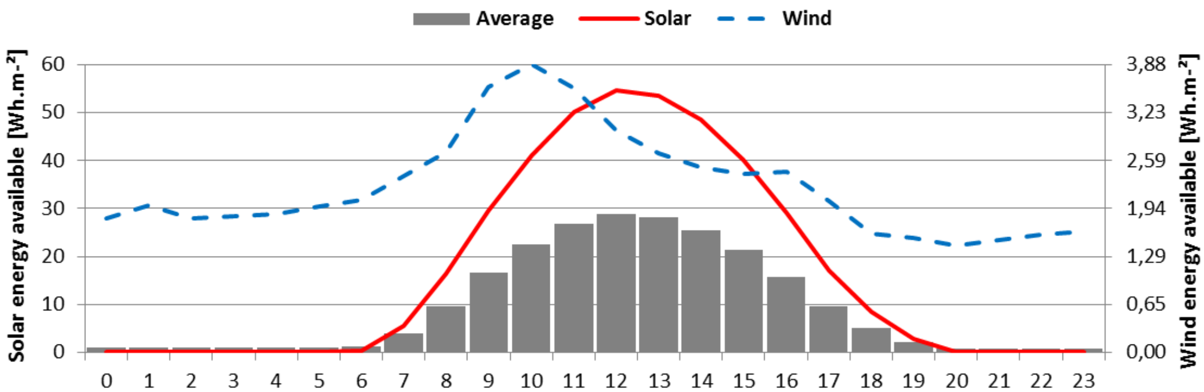

Figure 2. Availabilities energetic (solar and wind) hourly during a typical year.

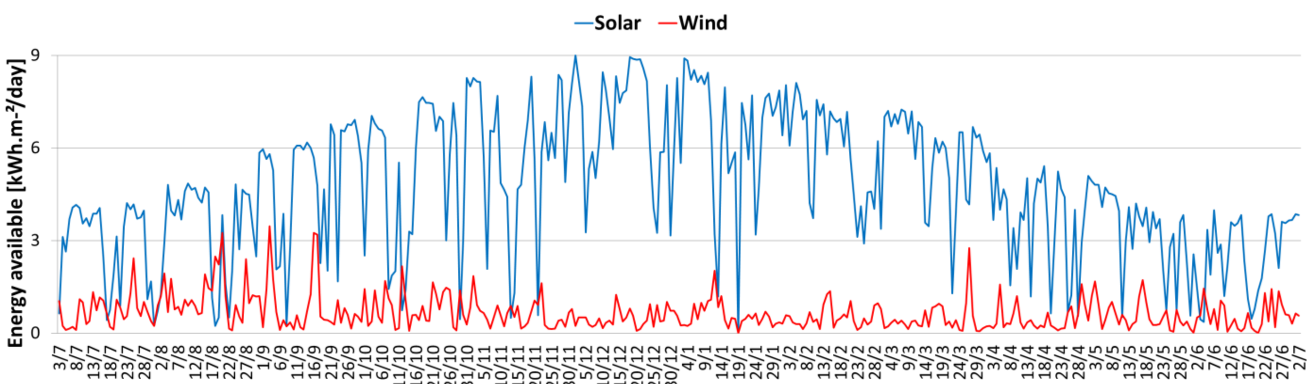

Figure 3. Availabilities energetic (solar and wind) during a typical year.

Figure 2. The daily temperature cycle, according to (Tubelis and Nascimento, 1986), reflects the solar irradiation variation throughout the day. The daily variations of radiation balance occur due to the sun daily path above the horizon, and during this moment of the day, the uneven warming of soil surface induces the ascending hot air to replace colder air masses, occasioning a thermal and gradient difference of pressure and generating a bigger flow of air masses. The hourly averages of energy availabilities always had solar energy with the highest potential during the year typical. The solar energy was 7.39 times superior to wind energy. The highest hourly averages of solar energy availabilities obtained were 54.67 $Wh.m^{-2}$ (Solar) and 3.88 $Wh.m^{-2}$ (wind).

The lowest daily average of solar energy availabilities during a typical year was 0.24 $Wh.m^{-2}$, and the highest 9.00 $Wh.m^{-2}$. The lowest daily average of wind energy availabilities was 0.00 $Wh.m^{-2}$and the highest 3.46 $Wh.m^{-2}$. The solar energy availability presented a typical behavior of the Sun's seasonal trajectory (Figure 3).

Interseasonal energy availabilities

The main characteristic related to the natural resources observed concern their diluted energetic nature, verified on seasonal periods (Nogueira, 2004). This peculiarity was noticed on the solar and wind energy availability verified between the seasons of the period observed, showing a higher solar potential during summer. A higher wind potential was verified during fall, showing a typically stochastic wind peculiarity, as seen in Figure 4. During winter the solar energy was 10.38 times superior to wind energy; in spring, 23.60 times superior; in summer, 11.92 times superior and in fall 5.53 times superior.

Minimum and maximum values were assessed for daily average availabilities among seasons. The lowest solar energy availabilities were 0.74, 1.81, 2.89 and 0.42 $kWh.m^{-2}$ and the highest were 6.43, 8.87, 8.60 and 6.43 0.42 $kWh.m^{-2}$ for winter, spring, summer and fall, respectively. The lowest wind energy availabilities were 0.00, 0.04, 0.03 and 0.03 $kWh.m^{-2}$ and the highest were 2.10, 1.08, 6.51 and 7.87 $kWh.m^{-2}$ for winter, spring,

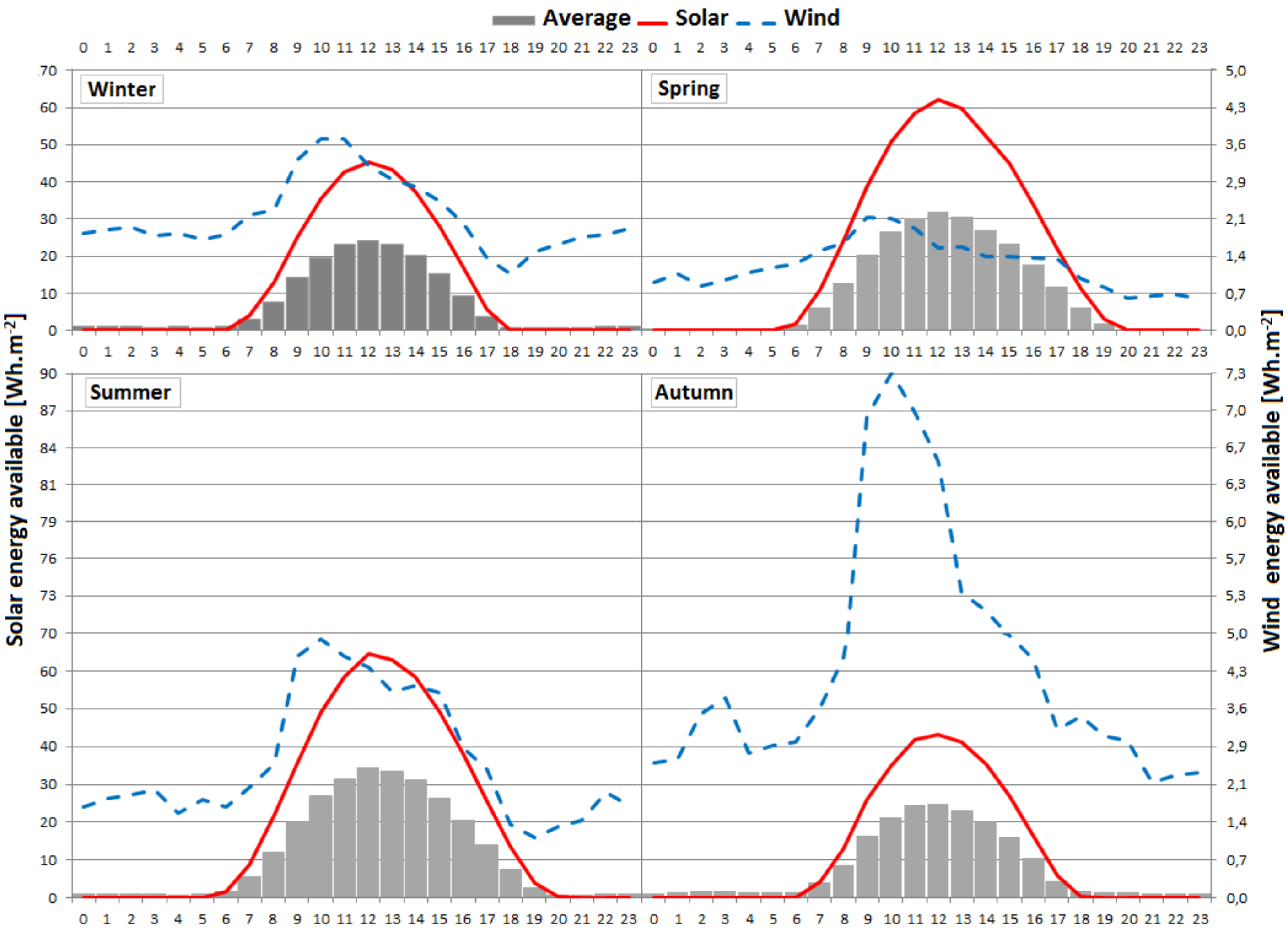

Figure 4. Daily averages of solar and wind energy availabilities between seasons.

summer and fall, respectively. The solar availability presented its highest values in the transition between spring and summer. According to Nobel (1983), wind regimes are seasonal, once the direction and speed are set accordingly to the intensity of radiation changes during seasons. However, the wind energy presented higher availability values in the end of summer and beginning of fall with the decrease of stationary radiation. The average availabilities among alternative sources were 0.58, 4.50, 5.57 and 0.49 kWh.m^{-2} in winter, spring, summer and fall, respectively, as seen in Figure 5.

Correlation coefficient (CC) analysis

The CC among energy availabilities for year 1 was negative and weak (- 0.07), in which independence among variables prevailed due to the existing variability between solar and wind amplitudes. In year 2, the correlation coefficient was negative and regular (- 0.32), mainly because of the sharp increase of wind variables in relation to solar variables, as shown in Figure 6, on the second part of this interval. The highest positive (0.32) correlation coefficient for the solar variable was found in year 1. In year 2 the lowest negative correlation coefficient found between wind and solar variables was (- 0.32). 40.00% of the coefficients on the matrix presented weak correlation levels and 20% presented regular levels (Table 2). The correlations between wind and solar variables among the seasons were positive and weak (0.17) in spring and (0.08) fall, and negative and weak (- 0.07) in winter and (- 0.05) summer. These coefficients show that energy availabilities have correlation independency between solar and wind variables during the seasons, as shown in Figure 7.

The highest correlation coefficient between wind and solar variables for stationary periods observed between

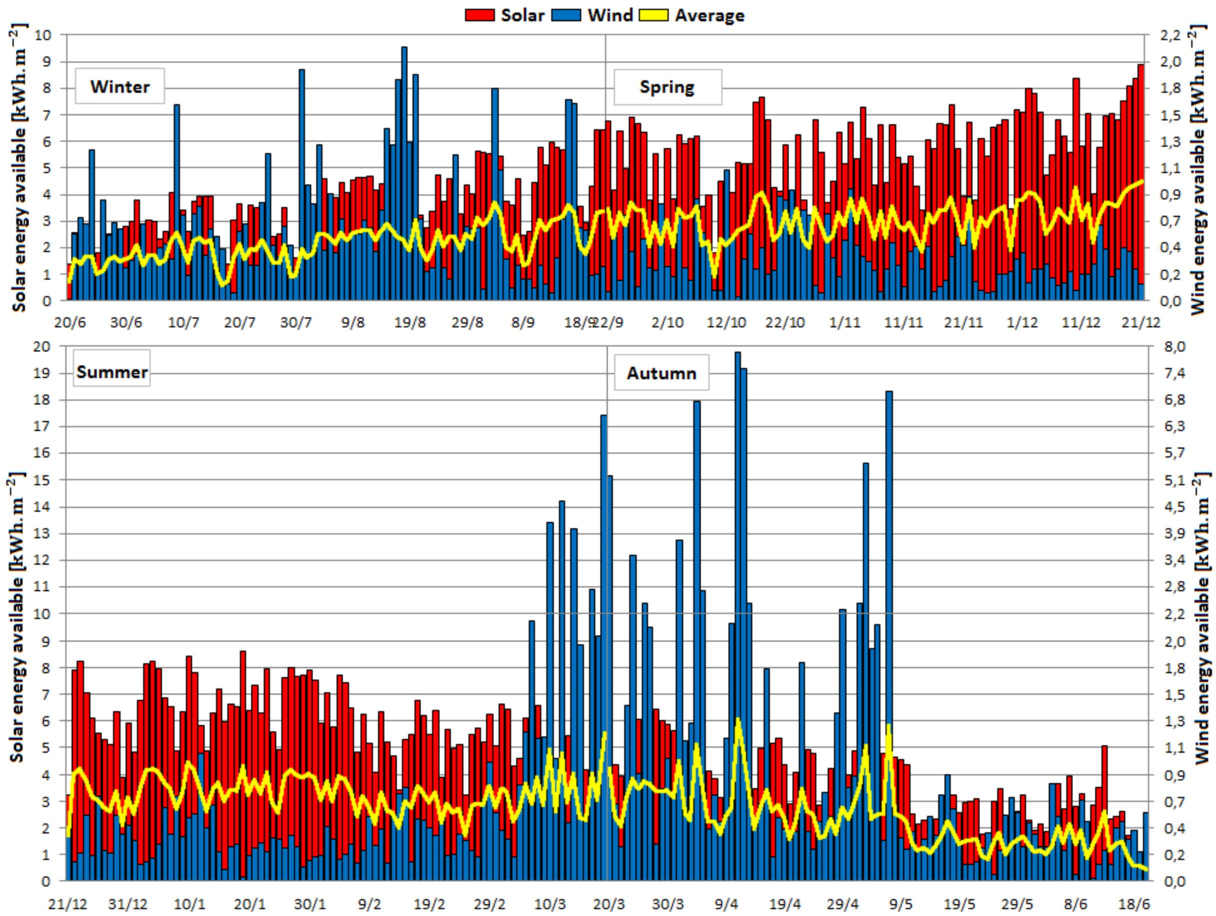

Figure 5. Daily averages of solar and wind energy availabilities among seasons.

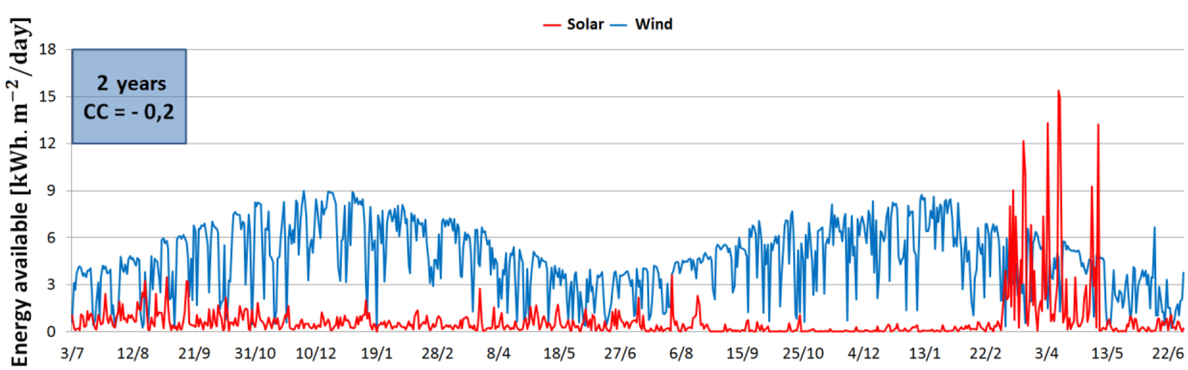

Figure 6. Solar and wind energy availability and CC for 2 year period.

winter and spring was regular (0.37) (Table 3), in which the value concerns to the most stable averages of wind availability. The lowest correlation coefficient considered weak (-0.24) was observed between summer and fall, in which the variability of the wind variable is inversely proportional. 69.44% of the coefficients on the matrix

Table 2. CC of the period averages 2 years of energy availability

Months	Variables	Jul S	Jul W	Aug S	Aug W	Sep S	Sep W	Oct S	Oct W	Nov S	Nov W	Dec S	Dec W	Jan S	Jan W	Feb S	Feb W	Mar S	Mar W	Apr S	Apr W	May S	May W	Jun S	Jun W
Jul	*S	1																							
	**W	0,16	1																						
Aug	S	0,05	-0,21	1																					
	W	-0,02	0,02	-0,21	1																				
Sep	S	-0,10	0,14	0,15	0,00	1																			
	W	-0,03	0,17	-0,28	0,51	0,06	1																		
Oct	S	0,10	-0,04	-0,14	0,33	-0,29	0,25	1																	
	W	0,14	0,32	-0,24	0,45	0,17	0,39	-0,04	1																
Nov	S	-0,17	-0,06	-0,19	0,18	0,09	0,23	0,14	0,01	1															
	W	0,11	0,31	-0,32	0,54	0,10	0,50	0,10	0,57	0,15	1														
Dec	S	-0,18	0,23	-0,23	0,27	0,17	0,26	0,00	0,18	0,03	0,29	1													
	W	0,00	0,28	-0,14	0,37	0,26	0,50	0,03	0,52	0,09	0,57	0,17	1												
Jan	S	0,14	-0,23	0,17	-0,16	-0,11	-0,13	-0,02	-0,14	0,08	0,02	-0,17	0,01	1											
	W	0,18	0,46	-0,12	0,35	0,15	0,43	0,04	0,44	-0,06	0,61	0,16	0,52	-0,15	1										
Feb	S	-0,06	0,11	-0,13	0,48	0,02	0,39	-0,05	0,36	-0,04	0,33	0,30	0,32	-0,19	0,32	1									
	W	-0,18	0,14	-0,21	0,54	0,21	0,38	0,08	0,31	0,07	0,53	0,36	0,32	-0,21	0,39	0,37	1								
Mar	S	0,14	0,04	-0,09	0,29	-0,01	0,24	-0,04	0,46	-0,04	0,41	-0,07	0,24	0,06	0,31	0,27	0,08	1							
	W	-0,03	-0,25	0,28	-0,28	-0,03	-0,26	0,12	-0,56	0,12	-0,60	-0,01	-0,33	0,09	-0,43	-0,24	-0,33	-0,53	1						
Apr	S	-0,05	-0,21	-0,06	0,09	0,01	-0,02	0,24	-0,05	0,22	-0,07	0,12	-0,03	-0,04	-0,18	0,21	0,05	-0,29	0,19	1					
	W	-0,06	-0,10	0,11	-0,25	0,04	-0,36	-0,25	-0,46	0,02	-0,34	-0,28	-0,34	0,08	-0,41	-0,17	-0,13	-0,06	0,18	-0,12	1				
May	S	0,11	0,10	-0,17	0,10	-0,24	0,19	-0,17	0,20	-0,03	0,18	0,18	-0,01	0,06	0,12	0,33	0,12	0,33	-0,08	-0,17	-0,05	1			
	W	-0,23	0,30	-0,30	0,13	-0,23	0,20	0,16	0,04	0,08	0,15	0,10	0,06	0,03	0,16	0,12	-0,07	0,22	-0,28	-0,09	-0,17	0,15	1		
Jun	S	0,13	0,48	-0,12	0,03	0,18	0,06	-0,28	0,10	0,08	0,11	-0,11	0,06	-0,19	0,32	0,05	0,05	-0,04	-0,20	-0,25	0,21	0,04	0,08	1	
	W	0,08	-0,08	0,06	0,17	0,25	0,24	0,24	0,27	0,20	0,25	-0,03	0,25	-0,01	0,22	-0,04	0,11	0,25	-0,16	0,27	-0,02	-0,27	-0,11	-0,04	1

Level		%
Perfect		8,00
Very strong		0,00
Strong		0,33
Regular		18,00
Weak		73,00
Absent		0,66
Total		100,00

*Solar **Wind.

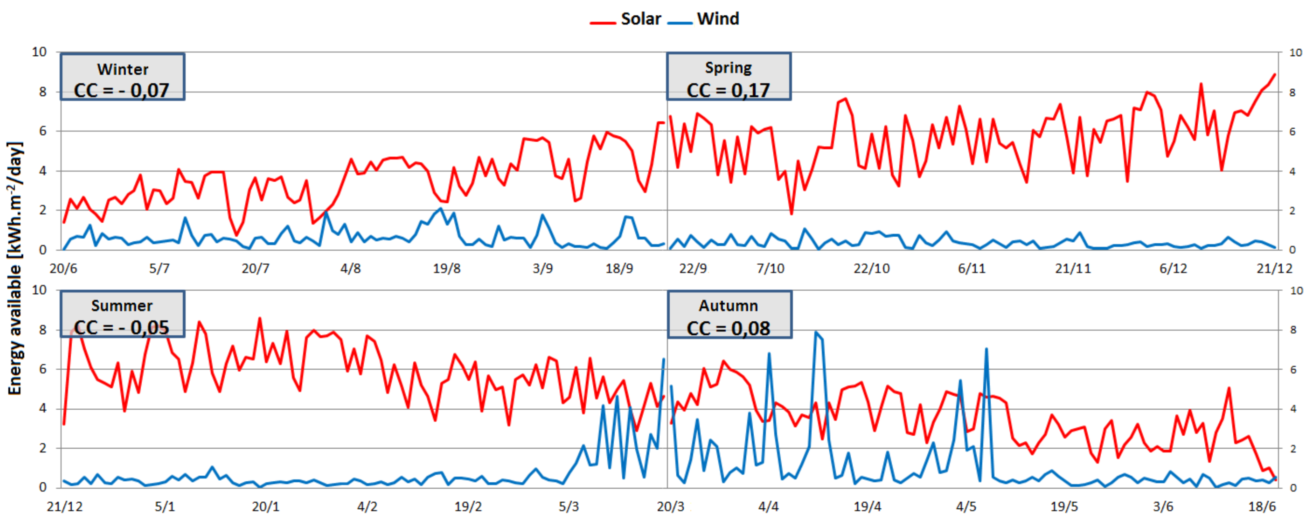

Figure 7. Solar and wind energy availabilities and CC during seasons.

Table 3. CC among stationary averages of energy availabilities.

Seasons	Variables	Winter Solar	Winter Wind	Spring Solar	Spring Wind	Summer Solar	Summer Wind	Autumn Solar	Autumn Wind
Winter	Solar	1							
	Wind	-0,07	1						
Spring	Solar	0,13	-0,03	1					
	Wind	-0,10	0,37	0,17	1				
Summer	Solar	-0,03	0,14	-0,04	0,25	1			
	Wind	0,22	0,11	0,13	0,36	-0,05	1		
Autumn	Solar	-0,23	0,12	-0,05	0,13	0,28	0,00	1	
	Wind	-0,12	0,12	-0,14	-0,03	0,21	-0,24	0,08	1

Level		%
Perfect		22,22
Very Strong		0,00
Strong		0,00
Regular		5,55
Weak		69,44
Absent		2,77
Total		100,00

present weak correlation levels and 5.55% regular levels.

Conclusion

Wind availability is relatively low, does not present satisfactory energy complementarity, safeguarded the magnitudes among the alternative sources studied, such as the height observed of anemometer. Solar energy availability was proportionally more representative than wind availability in all periods assessed, mainly between interseasonal averages. The highest accumulated energy between seasons was observed in summer. The correlation coefficients used in the analyses of behavior among alternative sources showed weak correlation with independence between variables in all parameters.

Conflict of interests

The authors have not declared any conflict of interest

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