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Comparative Study of Available Solar Potential for Six Stations of Sahel

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Abstract

Sahel is an African area with high solar potential. However, this potential is not uniform across the region. This paper examines the spatial distribution of the available solar potential by using six stations across the Sahel area. This comparative study was based on the analysis of in situ measurements in Dakar in Senegal, Niamey in Niger, Ouagadougou, Gaoua, Dori in Burkina Faso and N'Djamena in Chad. The results showed the presence of a good global solar potential with an average value of about 5.43 kWh/m^2/day. The maxima of global potential are noted in the northern part in Niamey with a value of 6.24 kWh/m^2/day while the minima are recorded in the south-eastern part in N'Djamena with an irradiation close to 4.71 kWh/m^2/day. Then, the monthly evolution of this potential shows similar trends for all stations. Indeed, two maximums are observed during the year in Spring (March) and Autumn (October). However, for most of these stations, the minima of global potential are recorded in Winter (November, February) and during the rainy season (July, October). Moreover, the direct normal potential also shows seasonal trends for the two stations (Dakar, Niamey) where it was measured. The maxima of direct normal irradiation (DNI) are observed between February and May with a value of 5.5 kWh/m^2/day in Dakar and in Niamey with a value around 5.32 kWh/m^2/day between February and November.

Keywords

Solar Potential, Pyranometer, Sahel, Comparative Study, Sunlight Analysis

1. Introduction

Sahel (10˚N and 18˚N; −17.5˚W and 20˚E) is a region where the climate system is very complex [1] [2]. This region also has a sunshine estimated at more than 2000 kWh per year [3] [4] [5] [6] amongst the highest in the world. Theoretically, the total solar reserves available in African are estimated at nearly 60 million TWh/year compared to 37.5 million TWh/year for Asia, including the Middle East (excluding Egypt) and only three million TWh/year for Europe [7] [8]. This makes this continent one of the largest solar deposits in the world with maximum sunshine around the large deserts, notably the Sahara in the north and its southern part (Kalahari) [9]. A study conducted by NASA between 1983 and 2005 in the Sahara ranks the Agadem region in Niger as the second sunniest region in the world [10] [11]. In addition, studies conducted in Dakar (Senegal) and Nouakchott (Mauritania) have shown high solar potential values with values between 7 and 8.25 kWh/m^2/day [12] [13] [14] [15]. Despite this high solar radiation, the installed capacity in Africa is quite low [16]. Nevertheless, it is constantly increasing in recent years with the installation of new solar plants throughout the continent. Indeed, it has quadrupled, for example, it was about 1330 MW in 2014 and increased by 2100 MW in one year (end of 2015) [17]. These solar plants totalled 4.15 GWp (gigawatt-peak) of generating capacity across Africa in 2017, more than half of which was in South Africa [18]. According to the 2018 report published by the International Renewable Energy Agency (IRENA) [4], Africa could potentially reach over 70 GW of PV capacity by 2030. For a better use of this renewable energy, a good knowledge of the solar potential is necessary. Indeed, most of the figures issued for the Sahel region are generally obtained from satellite data or empirical models which are often sources of uncertainties [19] [20]. Only a few rare in situ data have made it possible to characterize the solar potential at a few points in the Sahel [21] [22] [23]. Indeed, the AMMA (Multidisciplinary Analysis of the African Monsoon) campaign has allowed to collect data on solar radiation in this region [17] [24]. In addition, several instruments dedicated to the study of climate were installed, among which there were those dedicated to the measurement of solar radiation [12] [25].

The main objective of this paper is to perform a spatial characterization of the solar energy potential in this region. This will involve a comparative study of the solar potential using the data of these different stations. This work is divided into three parts. The first part presents the measurement stations, the types of data, and the instruments used. Then, the second part presents the results. Finally, the last part of this work's main conclusions.

2. Data and Method

2.1. Presentation of the Study Area

The area concerned by this study includes the Sahelian (−16˚W, 15˚E) region with six stations. **Figure 1** represents the study area (map) with the position of the six stations that concern our study framed in red from Senegal to Chad. From west to east, we have the stations of Dakar (14.4˚N, −16˚W) in Senegal, Ouagadougou (12.20˚N, −1.40˚W), Gaoua (10.29˚N, −3.15˚W) and Dori (14.03˚N, −0.02˚W) in Burkina Faso, Niamey (13.3˚N, −2.17˚W) in Niger and Ndjamena (12.1˚N, 15.04˚E) in Chad.

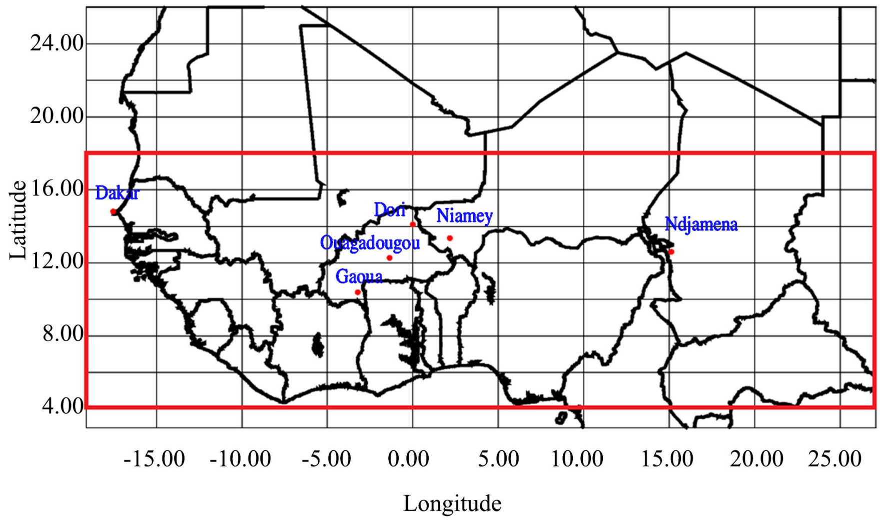

Figure 1. Spatial distribution of the six stations over Sahel region.

Indeed, this region is characterized by a short-wet season that lasts three months and a very long dry season of 8 to 9 months [26] [27] [28] [29].

Presentation of Instruments and Data

In this study, multiple categories of data were used.

First, instruments dedicated to the measurement of solar radiation have been installed in Dakar and Niamey as part of the AMMA project in 2006 [18] [30]. The data used in Dakar from a fluxmeter composed by a pyranometer, shadower, pyrheliometer and pyrgeometer [31] [32]. The pyrheliometer is intended for the measurement of direct-normal irradiation (DNI). The shortwave flux is measured in the spectral range of 200 - 3600 nm using the pyranometer with a time step of 2 minutes. To measure the diffuse irradiation, we have a disc (shadower) of 60 mm diameter occulting the sun direct radiation. The global radiation is obtained by the sum of the direct and diffuse flux. Measurements of global, direct, and diffuse DSSF are also available in Niamey from the Atmospheric Radiation Measurement (ARM) station [28] [33]. All components (diffuse, direct-normal, and global) are measured at a 15 min step and made available for scientific research.

Secondly, Ouagadougou, Gaoua, and Dori stations in Burkina Faso are also equipped with a small pyranometer measuring only global radiation since 2016 [34] [35]. These daily measurements were made at a time step of 15 minutes between 00h00 and 23h45.

Finally, a Vantage Pro2 type meteorological station including a pyranometer is installed at the National Research and Development Center (CNRD) in N'Djamena, Chad in 2017. This pyranometer provides daily global radiation data with a 30 min step [7] [21].

Table 1 summarizes the instruments and data available for each the six stations in the region.

Table 1. Instruments and data available for the six stations.

Stations	Instruments measurement	Measurement of irradiation	Time step of measured
Dakar	Fluxmeter (pyranometer, shadower, pyrheliometer and pyrgeometer)	Direct-normal, diffuse and global	2 min
Niamey			15 min
Ouagadougou			
Dori	Pyranometer	Global	15 min
Gaoua			
N'Djamena	Pyranomete	Global	30 min

2.2. Method of Calculating the Solar Energy Potential

2.2.1. Solar Energy Potential form Fluxmeter Data

From the measurements (direct and diffuse) made, the global solar radiation on a horizontal plane is calculated by the following formula [7]:

$$G = E_{dif} + E_{dir} + \sin(h) \quad (1)$$

G: Global solar radiation on horizontal plane (W/m^2)

E_{dif}: Measured diffuse solar radiation (W/m^2)

E_{dir}: Measured direct normal solar radiation measured (W/m^2)

h: Solar height (˚) calculated by the following expression

$$\sin(h) = \sin(\psi)\sin(\delta) + \cos(\psi)\cos(\delta)\cos(\omega) \quad (2)$$

ψ: Latitude of the place (˚)

δ: Solar declination (˚) given by the following formula:

$$\delta = 23.45 + \sin\left[360/365 \times (284 + j)\right] \quad (3)$$

d: Number of the Julian day

ω: Hourly angle given by the equation below:

$$\omega = 15 \times (T_s - 12) \quad (4)$$

T_s: Real solar time

2.2.2. Calculation of the Solar Energy Potential from the Measured Radiation

From the radiation, we calculate the solar energy potential on the horizontal plane by the following formula [7]:

$$E_g = \int_{L_s}^{C_s} G(t)\,\mathrm{d}t \quad (5)$$

E_g: Global potential on horizontal plane (kWh/m^2/day)

C_s: Time of sunrise

L_s: Time of sunset

3. Results and Discussions

3.1. Characterization of the Solar Potential in Dakar, Senegal

Data collected at Dakar station from January to November 2017 were used to calculate direct normal, diffuse, and global solar irradiation. Figure 2 represents the monthly evolution of global (red), direct normal (blue) and diffuse (black) solar potential.

The analysis shows that, the global (red) and direct-normal (blue) solar potentials follow similar trends. Their maxima are observed between February and May. The global potential varies from 4 to 6.7 kWh/m²/day and the direct from 4 to 5.5 kWh/m²/day. From June, these values begin to decrease until September. The peak of the global solar potential is recorded in April (7 kWh/m²/day) while that of the direct normal in February (5.5 kWh/m²/day). The minimum of the global is noted in August (5.10 kWh/m²/day) and that of the direct in July (2.90 kWh/m²/day). However, the diffuse radiation remains quite low throughout the year. Thus, the month of June is characterized by a maximum of diffuse radiation (3.53 kWh/m²/day) while the minimum is observed in November (1.45 kWh/m²/day). Seasonal fluctuations in solar potential are probably due to the scattering and absorption properties of atmospheric elements, such as clouds, aerosols, gases, and water vapor [36] [37].

Table 2 summarizes the annual and seasonal (dry season and rainy season) results of global, direct normal and diffuse solar potentials in Dakar in 2017.

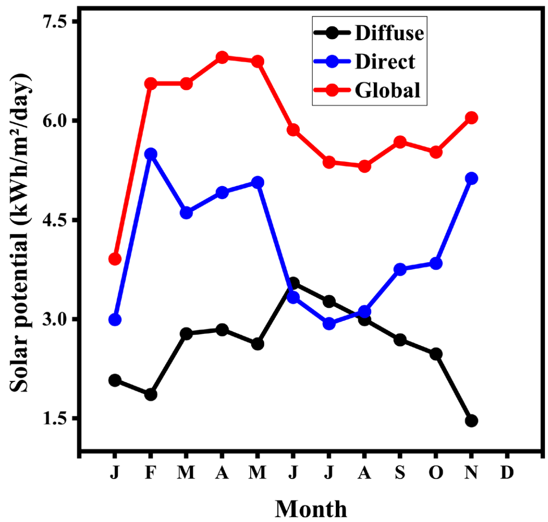

Figure 2. Monthly evolution of global, direct normal and diffuse solar potential in Dakar in 2017.

Table 2. Seasonal variation and annual average of diffuse, direct normal and global potential in 2017 in Dakar.

	Solar potential (kWh/m²/day)		
Seasons	Diffuse	Direct-normal	Global
Dry season (October-May)	2.46	4.42	6.04
Wet season (June-September)	2.98	3.27	5.53
Annual average	2.61	4.11	5.94

The value of the direct normal potential is about of 4.42 kWh/m²/day in dry season and 3.27 kWh/m²/day in wet season. The global solar potential is about of 6.04 kWh/m²/day in the dry season and 5.53 kWh/m²/day during the wet season. Also, the diffuse potential varies between 2.46 kWh/m²/d in the dry season and 2.98 kWh/m²/day in the wet season. The annual average shows that the direct normal and global solar potential are higher during the dry season. However, the diffuse potential reaches its maximum during the wet season (2.98 kWh/m²/day). This is often because of aerosols and clouds that can increase the diffusion especially during the rainy season [38] [39].

3.2. Characterization of the Solar Potential in Niamey, Niger

Figure 3 represents the monthly evolution of direct-normal (blue), diffuse (black) and global (red) irradiance in 2017 in Niamey, Niger.

The results also show that the global and direct normal potential follow similar trends. The maximums are observed in April and November for the direct-normal and global solar potentials. For example, the global solar potential is about 6.87 kWh/m²/day in April and 5.52 kWh/m²/day in November. The minimums in global and direct potential are noted in summer and winter with values about of 5.32 kWh/m²/day and 4.01 kWh/m²/day respectively. The diffuse potential is quite low during the year. The maximum diffuse potential is recorded in May (2.95 kWh/m²/day) and the minimum in December (1.95 kWh/m²/day).

Table 3 summarizes the seasonal and annual averages of diffuse, direct normal and global solar potential in Niamey (Niger).

The global and direct irradiation evolve during the year with maxima observed during the dry season. The direct normal potential varies from 4.87 kWh/m²/day in the dry season to 4.43 kWh/m²/day in the wet season. Also, the

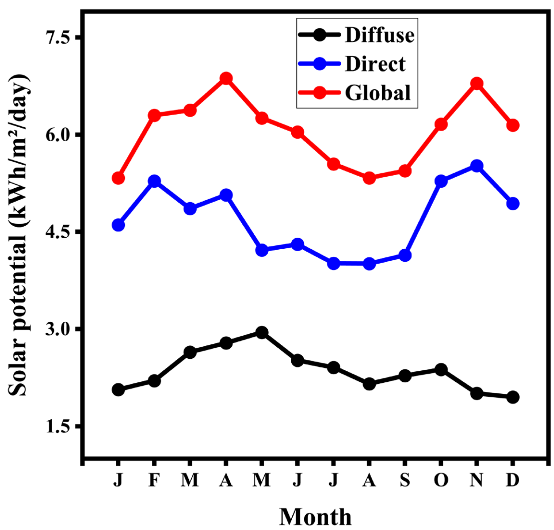

Figure 3. Monthly evolution of global, normal direct and diffuse solar potential in Niamey in 2017.

Table 3. Seasonal and annual assessment of diffuse, direct normal and global potential in Niamey in 2017.

Solar potential (kWh/m²/day)			
Seasons	Diffuse	Direct-normal	Global
Dry season (October-May)	2.29	4.87	6.29
Wet season (June-September)	2.37	4.43	6.18
Annual average	2.33	4.65	6.24

global potential ranges from 6.29 kWh/m^2/day in dry season and 6.18 kWh/m^2/day in wet season. The diffuse irradiation varies between 2.29 kWh/m^2/day in dry season and 2.37 kWh/m^2/day in wet season. Unlike the diffuse potential, the direct normal and the global potential are higher during the dry season. The annual amount of diffuse, direct-normal and global irradiation is 2.33, 4.65 and 6.24 kWh/m^2/day respectively.

3.3. Characterization of the Global Solar Potential in Ouagadougou, Dori and Gaoua

The in-situ data obtained at Ouagadougou (green), Dori (red) and Gaoua (black) stations in 2017 were used to calculate the global solar potential in Burkina Faso. Figure 4 represents the monthly evolution of the global potential on these three stations in Burkina Faso.

Figure 4 shows similar seasonal variability for these three stations. However, the potential is greater in the north. Consequently, this potential increases from Dori (14.03˚N, −0.02˚W) in the northern part to Gaoua (10.29˚N, −3.15˚W) in the south. The maxima are observed in Spring (March) and Autumn (October). While, the minima are observed in Summer (August) probably due to the cloud cover and aerosol in Winter (December) [38] [39]. The monthly average of the global potential varies from 5.05 kWh/m^2/day to 6.82 kWh/m^2/day in Dori; from 4.51 kWh/m^2/day to 6.03 kWh/m^2/day in Gaoua; and from 4.47 kWh/m^2/day to 5.52 kW h/m^2/day in Ouagadougou.

Table 4 summarizes the seasonal variation of global potential in Ouagadougou, Dori and Gaoua.

The table shows that irradiation is highest during the dry season with a value of 5.04 kWh/m^2/day in Ouagadougou, 5.92 kWh/m^2/day in Gaoua and 5.98 kWh/m^2/day in Dori. Thus, this high potential is clearly illustrated by annual average values between 4.96 and 5.89 kWh/m^2/day. In the wet season, the global potential values are 4.80, 4.87 and 5.73 kWh/m^2/day in Ouagadougou, Gaoua and Dori respectively. The maximum recorded is equivalent to 5.98 kWh/m^2/day in dry season in Dori and the minimum 4.80 kWh/m^2/day in Ouagadougou in rainy season. However, the minimum is observed in the rainy season is certainly due to the cloud cover [33].

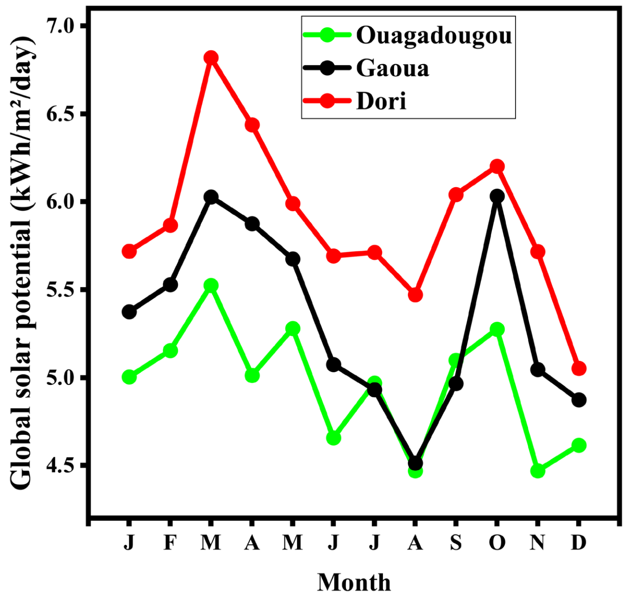

Figure 4. Monthly evolution of global solar potential in Ouagadougou, Dori and Gaoua in 2017.

Table 4. Seasonal and annual assessment of global potential in Dori, Ouagadougou and Gaoua in 2017.

Global potential (kWh/m²/day)			
Season	Dori	Gaoua	Ouagadougou
Dry season (October-May)	5.98	5.92	5.04
Wet season (June-September)	5.73	4.87	4.80
Annual average	5.89	5.33	4.96

3.4. Monthly Characterization of Available Solar Potential in N'Djamena, Chad

Figure 5 represents the monthly average global irradiance in 2017 in N'Djamena (Chad).

The results show the presence of a good solar potential with an annual value around 4.71 kWh/m²/day. On a seasonal scale, there are two maximums in terms of global solar potential. The first one is recorded in May (spring) with a value of 5.25 kWh/m²/day and the second in October (fall) with an amount of 5.18 kWh/m²/day. However, the minimum of the global potential is recorded in Winter (from December to February) with values close to 3.86 kWh/m²/day. The seasonal variations of the global solar potential at N'Djamena could be due to the absorption properties of atmospheric elements such as aerosols, clouds, gases, and water vapor as well as the activity of the sun (insolation and sun height) [21].

Table 5 summarizes the seasonal and annual variation of global solar potential in N'Djamena in 2017.

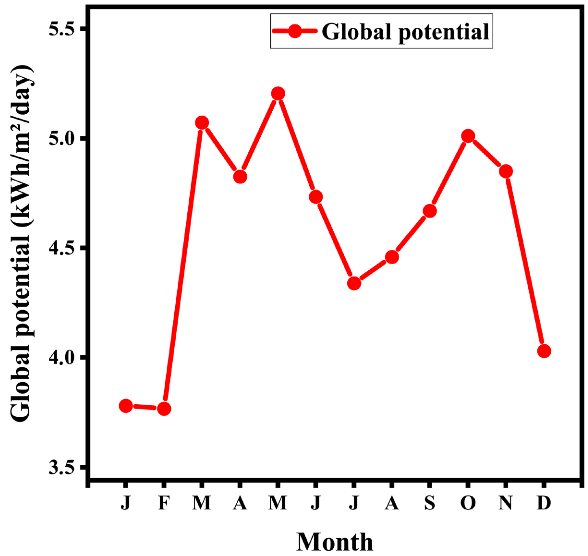

Figure 5. Monthly average of the global potential in N'Djamena in 2017.

Table 5. Seasonal and annual variation in global solar potential in N'Djamena in 2017.

	Global potential (kWh/m²/day)
Season	4.74
Dry season (October-May)	4.39
Wet season (June-September)	4.56
Annual average	4.74

In N'Djamena, the maximum of global potential is recorded during the dry season with a value of 4.74 kWh/m²/day. In addition, the wet season is characterized by a minimum of the global potential with a value of about 4.39 kWh/m²/day, mainly due to the cloud cover [21]. The annual seasonal average is about 4.56 kWh/m²/day in N'Djamena in 2017.

3.5. Intercomparison of Global Solar Potential between the Six Stations of Sahel

In this section, we perform a comparative study using data from all stations. On Figure 6, we superpose the evolution of the monthly global potential for the six stations such as Dakar (black line), Niamey (black dashed line), Dori (black dotted line), Gaoua (blue line), Ouagadougou (blue dashed line) and N'Djamena (blue dotted line).

The analysis shows that for all stations, the global potential follows the same seasonal dynamics. Indeed, the maxima are noted in Spring (March, April) and Autumn (October, November) with values between 5.07 and 6.96 kWh/m²/day. The minima are observed in Summer (July, August) and Winter (December, January) with a potential ranging from 3.76 to 5.33 kWh/m²/day. The observed maxima are probably related to high solar activity during the dry season with clear sky [35] [37]. However, the minima observed in the wet season are probably due to the presence of aerosols and especially clouds [12] [15].

The monthly average of the overall potential for the six stations is shown in Figure 7 representing the region.

The analysis shows that the global solar potential varies between 4.85 and 6.07 kWh/m²/day. There is significant seasonal variability for the global solar potential of the region. The maxima are observed Spring in March with a value of

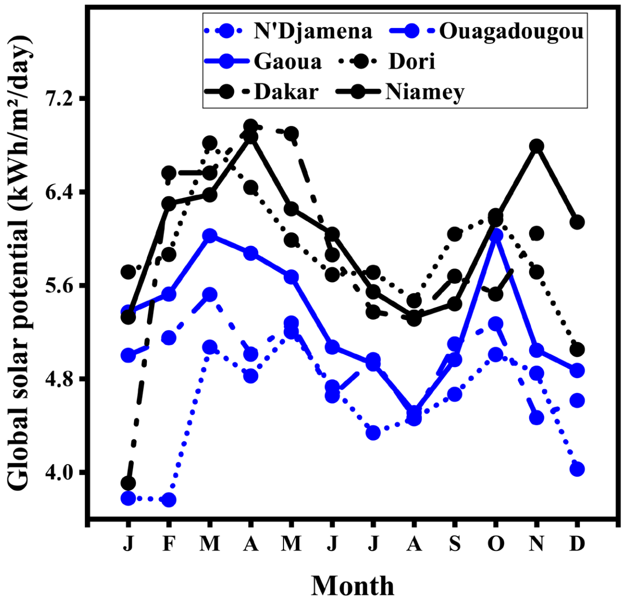

Figure 6. Intercomparison of global potential in Dakar (black line), Niamey (black dotted line), Dori (black dotted line), Gaoua (blue line), Ouagadougou (blue dotted line) and N'Djamena (blue dotted line) monthly over the six stations in 2017.

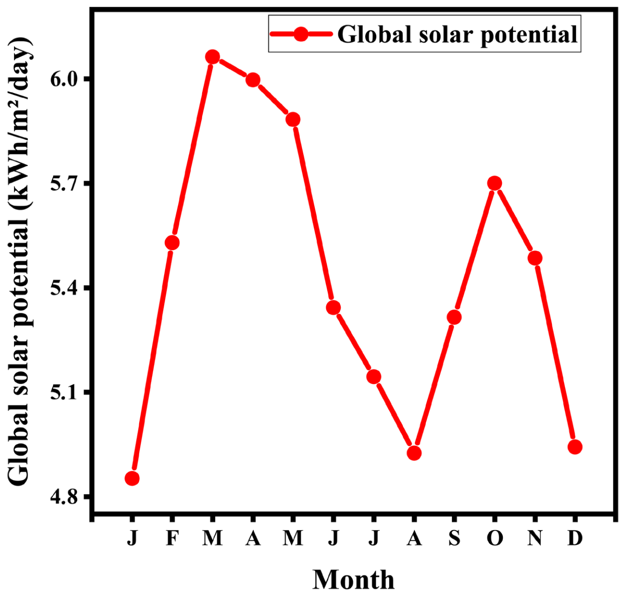

Figure 7. Monthly distribution of the global potential for Sahelian region.

6.07 kWh/m²/day and in Autumn in October with an irradiation of 5.07 kWh/m²/day. The minima of the global potential are noted during the rainy season (August) with a value of 4.93 kWh/m²/day and in winter (December to January) with a value close to 4.8 kWh/m²/day. On average, the region monthly value of global potential is about 5.43 kWh/m²/day

Table 6 summarizes the annual averages of diffuse, direct-normal, and global potentials at each station and the regional average.

The results show that the maximum of global potential is observed in Niamey with a value of 6.24 kWh/m²/day. The minimum global potential is noted in N'Djamena with a value of 4.71 kWh/m²/day. The regional annual of diffuse, direct normal and global potentials are 2.47, 4.38 and 5.43 kWh/m²/day respectively.

Table 7 shows the seasonal average of solar potential (direct, diffuse, and global) for the Sahel region.

It indicates that the seasonal average of the global potential and the direct-normal potential are 5.46 kWh/m²/day and 4.25 kWh/m²/day respectively. The wet season is characterized by values of 5.25 kWh/m²/day for the global and 3.85 kWh/m²/day for the normal direct potential. The maximum of diffuse potential is noted during the wet season with a value of 2.68 kWh/m²/day.

Table 6. Annual balance of the solar potential for the six stations.

Stations	Years	Solar potential (kWh/m²/day)		
		Diffuse	Direct-normal	Global
Dakar	2017	2.61	4.11	5.94
Niamey	2017	2.33	4.65	6.24
Dori	2017	×	×	5.91
Gaoua	2017	×	×	5.33
Ouagadougou	2017	×	×	4.96
Ndjamena	2017	×	×	4.71
Annual average of the region		2.47	4.38	543

×. Direct and diffuse radiation measurements are not available for these different stations.

Table 7. Seasonal average of the region's diffuse, direct-normal, and global potential.

Season	Solar potential (kWh/m²/day)		
	Diffuse	Direct-normal	Global
Dry season (October-May)	2.38	4.65	5.67
Wet season (June-September)	2.68	3.85	5.25
Annual average	2.53	4.25	5.46

4. Conclusion

The spatial distribution of solar potential is studied by using in situ measurements at six stations in Sahel region. The results obtained indicate the presence of a good global potential in this region with an average value around 5.43 kWh/m^2/day. The maxima of global potential are noted in the north at Niamey station with a value of 6.24 kWh/m^2/day and the minima in the southeast part at N'Djamena station with an irradiation close to 4.71 kWh/m^2/day. Also, the global irradiation seasonality shows similar trends for all stations. Indeed, two maximums are observed during the year in Spring (March) and in Autumn in October. However, for most of these stations, the minimums in global potential are recorded in Winter (between November and February) and during the rainy season (between July and October). Similarly, the direct normal potential confirms the seasonality of the global potential. Indeed, the maximum of direct potential is observed between February and May with a value of 5.5 kWh/m^2/day in Dakar and between February and November in Niamey with a value around 5.32 kWh/m^2/day. Contrary to the global and direct potential, the diffuse potential remains quite low during the year. The maximum in diffuse potential is observed in May (2.95 kWh/m^2/day) in Dakar and in June (3.53 kWh/m^2/day) in Niamey (Niger). The comparative study of the solar potential in this area showed great spatial and temporal variability, especially during the rainy season.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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