Statistical Assessment of Average Global and Diffuse Solar Radiation on Horizontal Surfaces in Tropical Climate

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Abstract-The hourly and monthly average global and diffuse solar radiation on horizontal surfaces in Nsukka, a tropical climate on Lat. 6^0 52' N, Long. 7^0 24' E and 397 metres above sea level, were critically evaluated for each month of the year, starting from November 2009 to October 2010. For each month, the hourly average global and diffuse irradiance obtained were correlated with local time of the day, using second degree polynomials, while the monthly average values were correlated with the months of the year, using third degree polynomials. These correlations were performed to facilitate easy prediction of global and diffuse irradiance at any time and month of the year in Nsukka. The maximum hourly average global irradiance of 773 W/m^2 was observed at 12.00 noon for the month of January 2010, while the minimum hourly average value of 426 W/m^2 was observed at 2.00 pm for the month of August 2010. The monthly average global radiation varied from 243 W/m^2 for the month of August 2010 to 427 W/m^2 for the month of January 2010, while the monthly average diffuse irradiance varied from 28.83 W/m^2 in June 2010 to 42.84 W/m^2 in January 2010.

KeywordsStatistical Assessment, Global and Diffuse Solar radiation, Horizontal Surfaces, Tropical Climate

1. Introduction

Solar radiation is an electromagnetic radiation of varying wavelengths ranging from 10^{-6}μm (γ-rays) to 10^8μm (radio waves) [1]. The terrestrial solar spectrum deviates from the extra-terrestrial spectrum because of various absorptions in the earth's atmosphere. The composition of this terrestrial sunlight is further complicated by the fact that atmospheric scattering gives rise to a significant indirect or diffuse component. Even in clear and cloudless skies, the diffuse component can account for 10 to 20% of the total radiation received by a horizontal surface during the day. For less sunny days, the percentage of radiation on a horizontal surface that is diffuse generally increases. Infact, for days on which there is a notable lack of sunshine, most of the radiation will be diffuse [2]. The most important parameter that is sought is the average global irradiation (H). In most cases, measurements of this parameter with reliable and calibrated pyranometers are not available in most parts of the world, and the values of H have to be estimated from measurements of nearby stations with similar geographical characteristics. Many meteorological stations have for several years been measuring related parameters like the sunshine duration (S) with instruments such as the Campbell Scientific sunshine recorder. The unavailability of irradiation data for many places led to the development of various methods of estimating this parameter theoretically. Sayigh [3] and the International Energy Agency [4] gave examples of the various relations that use meteorological data to estimate the solar irradiation. The most convenient and most widely used relationship is given by [5]

$$H = H_0 (a + b \times S/S_0) \quad (1)$$

where H_0 is the extraterrestrial radiation and S_0 is the day length ($S_0 = (2/15) \cos^{-1}(-\tan\Phi\tan\delta)$ and Φ and δ are the latitude and declination.

The spectral distribution of light emitted by the sun extends from a wavelength of less than 0.3 μm to 4.0 μm [6]. This is attenuated by at least 30% during its passage through the earth's atmosphere. The monthly average values of these ambient parameters were correlated with the months of the year, using third-degree polynomials. The correlation equation

$$H = a + bM + cM^2 + dM^3 \quad (2)$$

was fitted into the observed data using NLReg data analysis software, version 6.3 developed by Philip H. Sherrod [7] where a, b, c and d are constants and M is the month of the year. The annual hourly average values were correlated with local time of the day, using second-degree polynomials and the correlation equation

$$H = a + bT + cT^2 \quad (3)$$

was also fitted into the observed data.

2. Research Methodology

The global and diffuse radiation data considered were from 8.00am to 6.00pm each day continuously for a period of one year, spanning from November 2009 to October 2010 at the National Centre for Energy Research and Development, University of Nigeria, Nsukka (Latitude 6^0 52' N, Longitude 7^0 24' E and Altitude 397 metres). The global solar radiation was monitored using a solar radiation sensor (SENSOL-MONOKRISTALLIN), with calibration of 60.6 mV/1000 Wm^{-2} while the diffuse radiation was monitored using a shadow-band Eppley Radiometer with calibration 9.6 x 10^{-6} V/Wm^{-2}. Data collection was performed using a CR10X software-based data logging system. For each month, the hourly global and diffuse irradiance measurement, at say 8.00 a.m., were averaged over the days of the month to give the average values at 8.00 a.m. for the month, called the hourly average value for the month. The monthly average global and diffuse irradiance were computed by obtaining the daily hourly values from 8.00 am to 6.00 pm and averaging over the month. The annual average values, which represent the averages of these monthly values over a period of one year, are presented in table 2. The predicted values were obtained using a non-linear regression analysis (NLReg) software to develop statistical models in third degree polynomials (as shown in figures 1 and 2) and second degree polynomials (as shown in figures 3 and 4). These models were fitted to the measured data to generate the predicted values. The non-linear regression analysis software, version 6.3 was developed by Philip Sherrod.

3. Results and Discussion

The monthly average global solar radiation varied from 243 W/m^2 for the month of August 2010 to 427 W/m^2 for the month of January 2010, while the monthly average diffuse radiation varied from 28.83 W/m^2 in June 2010 to 42.84 W/m^2 in January 2010. The results of correlation of average values of the ambient parameters with months of the year are presented in figures 1 and 2. The results of the correlation of annual hourly average value of these parameters with local time are presented in figures 3 and 4. A slight attenuation of global and diffuse radiation during the mid November and December 2009 was observed while a substantial attenuation during the entire months of June to August 2010 was also observed as could be seen in figures 6 and 7 respectively. In addition to the attenuation of solar radiation by the effect of solstices (times of the year when the sun is farthest north or south of equator) during these months, the attenuation in November and December 2009 could be attributed to the significant increase in the turbidity of the lower atmosphere due to dust particles during the harmattan season (i.e. period of North-east trade wind in Nigeria between November and March, usually associated with too much dust particles and aerosols coming from Sahara desert). The variations of monthly average global and diffuse radiations shown in figures 6 and 7 indicated that the global irradiance was as high as 427 W/m^2 and 423 W/m^2 in January 2010 and March 2010 respectively, but dropped appreciably to 243 W/m^2 in August 2010. The diffuse irradiance was observed to be at its peak in January and July 2010. Studies of the extinction of the solar radiation by aerosols have been earlier conducted by Cerf [8], Carlson and Caverly [9], Oluwafemi [10], Brinkman and McGregor [11], Fouquart et al [12], Tanre et al [13], Adeyefa and Adedokun [14], Adeyefa et al [15] and Maduekwe and Chendo [16] among others. The attenuation in July and August could be attributed to the high amount of cloud cover and precipitable water molecules in the atmosphere, which absorb and scatter substantially some amount of solar radiation, thereby attenuating the effective terrestrial solar spectrum. A correlation between the diffuse ratio Kd (defined as the ratio of diffuse irradiance to the global irradiance), and the clearness index KT for the period of this investigation is shown in figure 5. The equation for the best line of fit is obtained as

$$K_d = 0.137 - 0.114K_T \quad (4)$$

compared with the equation

$$K_d = 1.13 - 1.48K_T \quad (5)$$

recommended by Ezekwe and Ezeilo [17] which they considered for only the dry season period from January to May. The variations of average global irradiance as a function of local time of the day is presented in table 3. The maximum hourly average global irradiance at 1200hrs varied from 773 W/m^2 in January 2010 to 319.33 W/m^2 in August 2010.

4. Conclusion

The results of the measured and predicted global and diffuse radiation at Nsukka showed higher irradiance levels during the months of January to March 2010. The measured and predicted values compared closely. From the measured values, the monthly average global radiation varied from 427 W/m^2 in January to 243 W/m^2 in August 2010, while the diffuse values showed a variation from 42.84 W/m^2 in January to 29.00 W/m^2 in June 2010. The predicted monthly average global irradiance varied from 420 W/m^2 in January to 285 W/m^2 in August 2010, while the predicted diffuse values also showed a variation from 41.60 W/m^2 in January to 31.00 W/m^2 in June 2010. The results also showed clear sky for most periods of the investigation except for few times of cloudy and dusty atmosphere and associated atmospheric turbidity. These results show that the region of this study has substantial amount of solar energy potentials to be harnessed for various solar energy applications.

Table 1. Monthly Average Values of the global and diffuse irradiance.

Month	Diffuse Irradiance H_d	Global Irradiance H_g
November 2009	29.76	339.07
December 200	29.54	368.07
January 2010	42.84	427.37
February 2010	36.57	390.66
March 2010	33.04	423.14
April 2010	36.20	364.39
May 2010	34.20	367.99
June 2010	28.83	320.86
July 2010	37.25	309.34
August 2010	29.40	243.70
September 2010	30.65	288.24
October 2010	30.90	310.07

Table 2. Annual Hourly global and diffuse irradiance.

Time	Diffuse Irradiance (W/m^2)	Global Irradiance (W/m^2)
	H_d	H
800	17.68	116.26
900	31.15	259.23
1000	37.54	402.65
1100	42.41	479.37
1200	46.81	521.02
1300	45.50	542.33
1400	43.03	502.51
1500	38.38	438.20
1600	33.47	318.44
1700	23.75	170.68
1800	9.62	52.30

Table 3a. Hourly Average Diffuse and Global Irradiance for each month of the year(November 2009- April 2010)

Time	Nov 2009		Dec 2009		Jan 2010		Feb 2010		Mar 2010		Apr 2010	
	H_dW /m^2	H_gW/ m^2	H_dW/ m^2	H_gW/ m^2	H_dW/ m^2	H_gW/ m^2	H_dW/ m^2	H_gW/ m^2	H_dW/ m^2	H_gW/ m^2	H_dW/ m^2	H_gW/ m^2
800	23.9	124.9	29.7	145.6	27.9	126.0	18.2	157.7	14.4	131.3	15.9	133.3
900	28.5	303.4	-	380.4	60.4	311.9	36.7	260.7	33.0	339.4	31.1	285.2
1000	38.9	453.1	45.1	566.4	62.9	477.9	47.7	473.9	37.9	473.9	42.6	456.9
1100	43.4	591.0	48.2	739.0	64.6	660.7	49.4	554.5	42.4	620.4	46.0	462.1
1200	44.1	629.3	43.4	770.0	58.3	773.6	50.1	584.5	43.5	695.8	51.1	521.9
1300	40.9	511.9	36.4	542.9	54.1	744.8	45.8	675.8	42.9	658.5	51.2	590.8
1400	37.4	448.5	34.1	420.4	47.6	649.7	46.3	569.4	45.0	618.7	43.2	519.2
1500	32.3	356.3	29.7	311.9	40.4	483.5	42.1	487.2	42.4	577.0	41.7	500.1
1600	21.1	194.2	13.2	103.2	31.4	299.2	36.3	325.0	32.1	318.8	39.3	322.0
1700	13.8	98.2	12.2	54.1	18.7	145.3	24.0	165.3	22.3	160.8	29.3	167.7
1800	3.3	19.1	3.5	15.1	5.1	28.5	5.9	60.0	7.7	60.1	6.9	49.3
Mont Av.	29.8	339.1	29.6	368.1	42.8	427.4	36.6	390.7	33.0	423.1	36.2	364.4

Table 3b. Hourly Average Diffuse and Global Irradiance for each month of the year(May 2010- October 2010)

Time	May 2010		Jun 2010		Jul 2010		Aug 2010		Sep 2010		Oct 2010	
	H_d W/m^2	H_g W/m^2	H_d W/m^2	H_g W/m^2	H_d W/m^2	H_g W/m^2	H_d W/m^2	H_g W/m^2	H_d W/m^2	H_g W/m^2	H_d W/m^2	H_g W/m^2
800	20.0	147.2	10.4	81.0	28.5	93.1	16.5	70.3	17.2	86.6	18.1	104.3
900	32.2	295.9	27.2	275.2	34.2	213.2	23.7	145.1	21.2	202.3	28.5	226.4
1000	40.3	528.9	34.0	363.0	30.6	309.9	29.7	212.2	32.0	281.6	32.7	339.9
1100	40.0	590.2	34.1	394.1	49.3	392.1	35.6	342.2	41.2	370.9	38.6	443.0
1200	46.1	522.0	43.3	554.3	55.2	449.2	38.4	319.3	42.6	415.5	44.7	488.6
1300	46.1	475.4	40.0	517.7	47.9	511.1	44.6	367.2	51.1	512.8	45.3	480.8
1400	43.2	514.1	35.0	410.1	39.7	460.1	48.9	426.1	39.7	461.6	40.8	476.6
1500	38.6	440.9	29.0	357.2	41.9	398.0	33.1	307.0	39.7	434.7	43.9	400.7
1600	32.1	302.3	28.9	328.7	36.6	363.4	28.9	268.8	27.2	236.0	29.0	285.1
1700	26.7	186.8	25.9	180.3	26.6	171.7	16.5	162.4	15.8	126.5	15.4	142.3
1800	11.1	44.3	9.3	67.8	19.1	41.1	7.4	60.1	9.7	40.3	3.0	23.1
Mont Av.	34.2	368.0	28.8	320.9	37.3	309.3	29.4	243.7	30.7	288.2	30.9	310.1

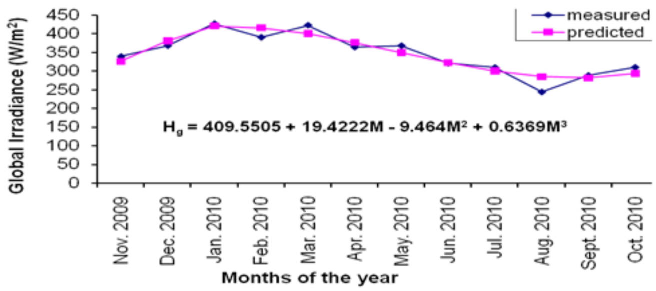

Fig. 1. Measured and predicted monthly average global irradiance

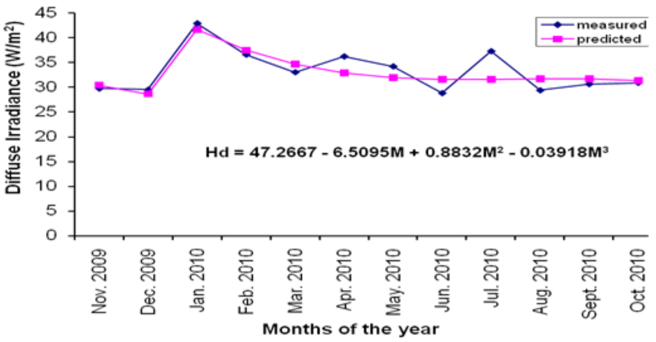

Fig. 2. Measured and predicted monthly average diffuse irradiance

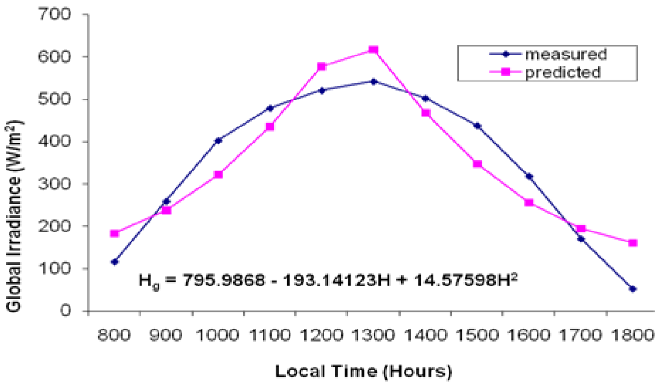

Fig. 3. Annual hourly average global irradiance (measured and predicted)

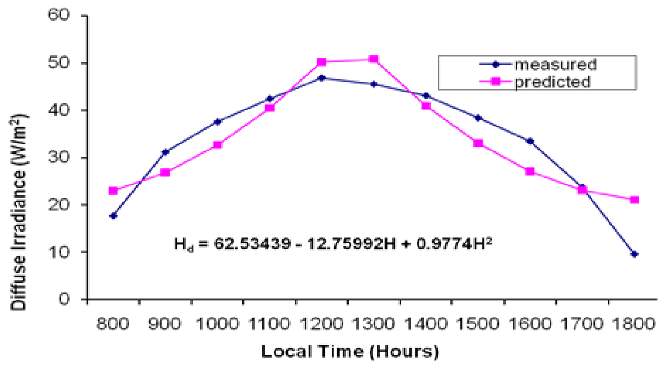

Fig. 4. Annual hourly averagediffuse irradiance(measured and predicted)

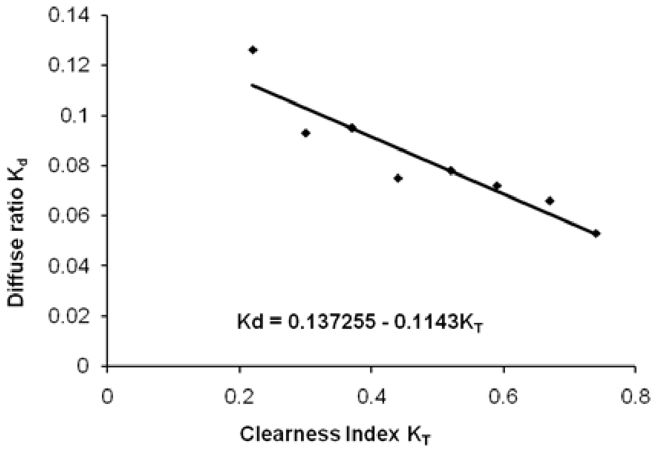

Fig. 5. Correlation of diffuse ratio K_d with clearness index K_T for the period of investigation

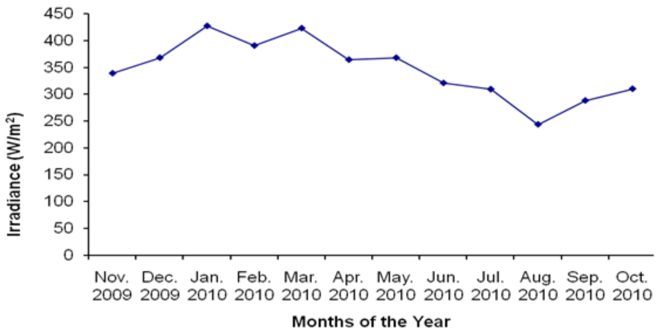

Fig. 6. Variation of monthly average solar irradiance for the year

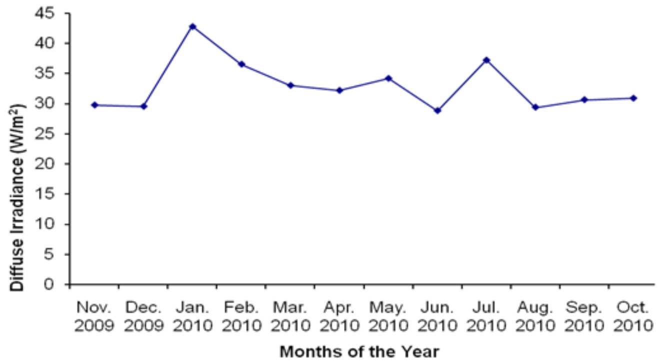

Fig. 7. Variation of averagediffuse irradiance at different months of the year

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