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The Use of Factorial Design in the Analysis of Global Solar Radiation in Nigeria

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ABSTRACT

Factorial design is applied in the analysis of global solar radiation in eight selected stations in Nigeria. The analysis of coefficient of determination and adjusted coefficient of determination ranges between 0.9768(Ibadan) to 0.9965(Calabar) and 0.9361(Ibadan) to 0.9905(Calabar) respectively. The model equation using the 2^3*- factorial design could be used for prediction of global solar radiation on both short- and long –term bases. The values of mean absolute errors (MAE) and the root-mean –square errors (RMSE) calculated shows the applicability of the factorial design for the analysis of global solar radiation in Nigeria.*

INTRODUCTION

Renewed interest in renewable energy has developed since 1970 because of increasing costs of energy from conventional resources and the problems of importing and extracting fuels that are acceptable from environmental standpoint (Duffie and Beckman, 1991). Solar radiation is an enormous and virtually, inexhaustible source of energy. The power from the sun intercepted by the earth is approximately 1.8 x 10^5 MW. This energy is many thousands of times lager than the present global consumption rate of all commercial energy resources (REMP, 2005). In principle, solar energy could supply all the present and future commercial energy needs of the world on a continuous basis. This makes solar radiation one of the most promising of the unconventional energy sources (Sukhatme, 1984). Two – thirds of the population of Nigeria resides in rural areas. Integrated rural development will require increased access to energy services. Centralized energy forms, primarily grid electricity either may be too costly or may take a long time to reach most rural areas, especially as the sub-sector becomes market-driven (REMP, 2005). The use of solar energy as an alternative source of energy in the rural and remote areas of Nigeria will aid the growth of small-scale industries and stem the rural-urban drifts of the rural populace. The use of solar energy as an alternative source of energy in the rural and remote areas of Nigeria will aid the growth of small-scale industries and stem the rural urban drifts of the rural populace. It will also provide a cheap and abundant source of energy for about 90,000 communities whose connection to the national grid may not be economical due to their remoteness (Ojosu, 1990). A number of formulae and methods have been developed to estimate global solar radiation at instrumental sites where it is not measured based on other commonly measured meteorological variable or at non-instrumented sites. Three available methods include stochastic weather generators, satellite based, and empirically derived relationships. Stochastic weather generators may be used for risk analysis but not for model validation and simulation analysis for a particular period of times as the models may not generate the data to match the actual weather at a particular time of interest (Liu and Scott, 2001; Mavromatis and Hansen, 2001; Hayhoe, 2000). Satellite based methods (Garatuza-Payan *et al*., 2001) may provide appropriate coverage and Spatial resolution of data, but availability of these data on a real time basis is limited, nor can they be used for historical long-term studies. Empirical methods to estimate global solar radiation requires the development of a set of equation that relate it to other meteorological parameters (Donatelli *et al*., 2003). In developing country like Nigeria, the facility for global radiation measurement is available at a few places while bright sunshine hours, relative humidity and maximum ambient temperature are measured at many locations. Therefore, there is a need to develop models to predict global solar radiation from readily measured data (Sambo, 1988 and Fagbenle, 1990). The initial empirical formula normally applied in most part of the world is the Angstrom (1924) – Prescott (1940) – Page (1964).

Three climatological parameters namely relative sunshine duration, relative humidity and maximum ambient temperature will be used to develop a model for the prediction of global solar radiation in Nigeria using factorial design.

MATERIALS AND METHODS

Nigeria lies in the tropics between latitudes 4^o and 14^o N and longitudes 3^o and 15^o E. The stations coordinates are shown in table 1. The monthly mean values of the global solar radiation on horizontal surface, H, sunshine duration S, and maximum ambient temperature, T_m for a period of ten years (1994 – 2003) were obtained from Nigeria meteorological agency Oshodi, Lagos. The values of the extraterrestrial radiation, H_0 and the day length S_0 were calculated for the fifteenth day of the month (Klein, 1977). The data was subjected to quality checks before being used in the analysis. It was ensured only complete data was used. The values of H/Ho and S/So are all less than one. The solar radiation values obtained using Gunn – Bellani radiation integrators were converted to 1.216 MJ/m^2 – day (Ododo, 1994). The values of the sunshine duration were obtained using Campbell- Stokes sunshine recorder. Campbell-Stokes sunshine recorder, which is widely used to determine sunshine duration, does not give any indication of intensity as long as this exceeds the burning threshold values of about 140 – 280 Wm^{-2} (Ododo, 1995).Values of S_0 and H_0 have been calculated for the fifteenth day of each month using (Klein, 1977)

$$S_0 = \frac{2}{15}\cos^{-1}(-\tan L \tan\delta) \qquad \ldots (3.1)$$

$$H_0 = \frac{24}{\pi} I_{0n}\left(1 + 0.033\cos\frac{360}{365}n\right)\left(\cos L\, Cos\,\delta\, Sin\,\omega_s + \frac{2\pi}{360}\omega_s\, Sin\, L\, Sin\,\delta\right) \ldots (3.2)$$

where $\omega_s = \cos^{-1}(-\tan L \tan\delta)$

$$\delta = 23.45\, \mathrm{Sin}\left(\frac{360}{365}(284+n)\right)$$

where n is the day of the year, L is the latitude of the location, δ is angle of declination and ω_s is the sunrise hour angle. I_{on} is a solar constant, having a value of 1367 W/m^2. The relative humidity is the average values of the measured data for 09:00 and 15:00 local time. The value of the relative humidity of a sample of atmosphere represents the degree of saturation of the water vapour present in the atmosphere. It will be 0.00 if there is no vapour present, and 1.00 if the vapour is saturated.

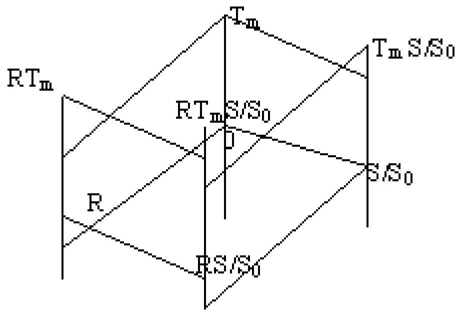

Fig.1: Pictorial diagram of factorial design

The pictorial representation of the factorial design is shown in figure 1 showing the interactions between various parameters

Table 1: Stations Coordinates

S/No.	STATION	LAT (^{0} N)	LONG (^{0} E)	ALTITUDE (m) (Above sea level)
1.	Jos	9.867	8.900	1286
2.	Makurdi	7.730	8.530	113
3.	Sokoto	13.017	5.250	351
4.	Maiduguri	11.850	13.080	354
5.	Enugu	6.470	7.550	142
6.	Ibadan	7.433	3.900	227
7.	Calabar	4.970	8.350	6.3
8.	P/Harcourt	4.850	7.020	20

The maximum and minimum monthly mean values of S/S_0, T_m and R are in Table 2. Normalization was used for the coding so that the values lie between -1 and 1 using

$$x = \frac{y - \frac{1}{2}(\max + \min)}{\frac{1}{2}(\max - \min)}$$

The monthly mean values for H/Ho, and the monthly mean coded values of S/So, R and T_m(^{0}C) are shown in Table 3.

Table2: Maximum and minimum mean monthly values of S/S_0, T_m (^{0}C) and R

Station	S/S_0		T_m		R	
	max	min	max	min	max	min
Jos	0.8518	0.3285	32.0	24.2	0.8433	0.1298
Makurdi	0.6065	0.2743	37.8	30.1	0.7706	0.3565
Sokoto	0.8185	0.5414	40.8	31.3	0.7270	0.1553
Maiduguri	0.8566	0.4948	40.9	31.2	0.7086	0.1201
Enugu	0.6470	0.2318	35.4	29.5	0.7875	0.4553

Ibadan	0.6386	0.2737	35.0	28.7	0.8208	0.4867
Calabar	0.5537	0.1480	33.9	28.1	0.8709	0.6423
Port Harcourt	0.5183	0.3840	33.9	28.8	0.8521	0.6131

Table 3: Monthly mean values of H/Ho, S/So, T_m (^{0}C) and R

STATION	MONTHS	H/Ho	S/So	T_m (^{0}C)	R
JOS	Jan	0.7377	0.8739	0.1026	-1.0000
	Feb	0.7255	0.7195	0.4872	-0.9125
	Mar	0.6853	0.4068	1.0000	-0.4826
	Apr	0.5714	-0.1412	0.6923	0.1919
	May	0.5302	-0.2540	0.1538	0.6992
	Jun	0.5163	-0.4068	-0.4359	0.7976
	Jul	0.4642	-0.7229	-0.8974	0.9784
	Aug	0.4475	-1.0000	-1.0000	1.0000
	Sep	0.5219	-0.5746	-0.5641	0.7945
	Oct	0.5820	0.1779	-0.1538	0.2961
	Nov	0.7507	1.0000	0.0000	-0.6662
	Dec	0.7778	0.9144	-0.0513	-0.7191
MAKURDI	Jan	0.5641	0.5238	0.3766	-0.9614
	Feb	0.5736	0.2553	0.8442	-1.0000
	Mar	0.5258	0.2661	1.0000	-0.4905
	Apr	0.4914	0.1957	0.4026	0.1616
	May	0.5227	0.4624	-0.1429	0.5117
	Jun	0.4809	0.0102	-0.6883	0.8112
	Jul	0.4252	-0.6737	-0.8961	0.9029
	Aug	0.3945	-1.0000	-1.0000	1.0000
	Sep	0.4474	-0.6159	-0.8701	0.9633
	Oct	0.5212	0.2721	-0.5325	0.7387
	Nov	0.6115	1.0000	-0.0649	0.0070
	Dec	0.6228	0.9964	0.2466	-0.8599
SOKOTO	Jan	0.6344	0.9957	-0.7053	-0.8580
	Feb	0.6416	0.1223	-0.3263	-0.9699
	Mar	0.6368	0.1649	0.6000	-1.0000
	Apr	0.6047	-0.3093	1.0000	-0.5116
	May	0.5869	-0.3252	0.7474	-0.1219
	Jun	0.5553	-0.5352	0.0737	0.2720
	Jul	0.5041	-0.7589	-0.6211	0.7030
	Aug	0.4517	-1.0000	-1.0000	1.0000
	Sep	0.5412	-0.5424	-0.7895	0.7782
	Oct	0.6087	0.3172	0.0105	0.1205
	Nov	0.6699	0.9538	0.0737	-0.7898
	Dec	0.6583	1.0000	-0.5158	-0.7929
MAIDUGURI	Jan	0.5401	0.7971	-0.8557	-0.7998
	Feb	0.5640	0.6650	-0.4227	-0.9252
	Mar	0.5836	0.3179	0.5052	-1.0000
	Apr	0.5706	-0.1310	1.0000	-0.7121
	May	0.5238	0.0967	0.9381	-0.3510
	Jun	0.4707	-0.5119	0.1753	0.1780
	Jul	0.4085	-0.7021	-0.5464	0.6767

	Aug	0.3701	-1.0000	-1.0000	1.0000
	Sep	0.4506	-0.3339	-0.5876	0.7892
	Oct	0.5190	0.2941	-0.0309	0.1032
	Nov	0.5638	1.0000	-0.1134	-0.6682
	Dec	0.5196	0.8933	-0.7113	-0.7722
ENUGU	Jan	0.4680	0.4623	0.4576	-1.0000
	Feb	0.4863	0.3197	1.0000	-0.9699
	Mar	0.4353	0.2064	0.9661	-0.2560
	Apr	0.4178	0.2686	0.4915	0.3283
	May	0.4530	0.3490	-0.0169	0.6265
	Jun	0.4224	-0.1371	-0.4915	0.8163
	Jul	0.3468	-0.6436	-0.8305	0.9157
	Aug	0.3074	-1.0000	-1.0000	1.0000
	Sep	0.3817	-0.5450	-0.7627	0.9548
	Oct	0.4500	0.0513	-0.4576	0.7771
	Nov	0.5389	0.8449	0.2542	-0.0121
	Dec	0.5232	1.0000	0.3898	-0.9277
IBADAN	Jan	0.4771	0.1768	0.4921	-0.6444
	Feb	0.5292	0.2869	0.6825	-1.0000
	Mar	0.5073	0.3204	1.0000	-0.2721
	Apr	0.4835	0.2239	0.4286	0.2386
	May	0.4962	0.3423	-0.0794	0.4451
	Jun	0.4648	0.1192	-0.4286	0.6736
	Jul	0.3412	-0.9123	-0.9048	0.9773
	Aug	0.317	-1.0000	-1.0000	1.0000
	Sep	0.3707	-0.5747	-0.8730	0.8527
	Oct	0.4636	-0.1466	-0.4603	0.5762
	Nov	0.5595	1.0000	0.3968	-0.0775
	Dec	0.5257	0.8635	0.4921	-0.5834
CALABAR	Jan	0.4437	1.0000	0.4828	-0.7909
	Feb	0.4469	-0.1891	1.0000	-1.0000
	Mar	0.4257	0.2058	0.6207	-0.2496
	Apr	0.4355	0.6110	0.3448	0.1081
	May	0.4328	0.5479	0.1724	0.1626
	Jun	0.3809	-0.6865	-0.2759	0.4596
	Jul	0.3024	-0.7042	-0.6897	0.8656
	Aug	0.2713	-1.0000	-1.0000	1.0000
	Sept	0.3215	-0.9305	-0.6552	0.7548
	Oct	0.3704	-0.2162	-0.3448	0.5352
	Nov	0.4294	0.1969	0.0690	0.2408
	Dec	0.4543	0.9645	0.3448	-0.4139
P/HARCOURT	Jan	0.5100	-0.5915	0.6470	-0.7799
	Feb	0.5307	-0.4094	1.0000	-1.0000
	Mar	0.4718	-0.9781	0.8431	-0.1297
	Apr	0.4819	-0.9044	0.5294	0.1682
	May	0.4828	0.6627	0.2157	0.5289
	Jun	0.4273	1.0000	-0.4118	0.5222
	Jul	0.3489	-0.6414	-0.8431	0.9607
	Aug	0.3299	-1.0000	-1.0000	1.0000
	Sep	0.3540	-0.7315	-0.7255	0.9515

Oct	0.4158	-0.3169	-0.4902	0.6427
Nov	0.4946	-0.1823	0.0588	0.1941
Dec	0.5411	-0.5690	0.4118	-0.5590

4.0 Data Analysis

In order to know the utility of the model the following goodness-of-fit test were carried-out. The values of the data analysis are in table 4.

i) the coefficient of determination, R^2

$$R^2 = 1 - \frac{\left(H_i - \hat{H}\right)^2}{\left(H_i - \bar{H}_i\right)^2}$$

ii) the adjusted coefficient of determination, R_a^2

$$R_a^2 = \frac{(n-1)R^2 - (k-1)}{n-k}$$

iii) the root mean square error, RMSE

$$\text{RMSE} = \left\{ \frac{\left(H_i - \hat{H}_i\right)^2}{n} \right\}^{1/2}$$

RESULTS AND DISCUSSION

The values of coefficient of determination R^2, adjusted coefficient of determination, root mean square error RMSE and mean absolute error are shown in Table 4. The Durbin-Watson (DW) statistic tests the residuals to determine if there is any significant correlation based on the order in which the parameters occur in the data. For all the stations, there is no any serious autocorrelation in the residuals as shown in Table 4; therefore all the parameters are important in the model. The minimum values of relative sunshine duration and ambient temperatures were observed in the month of August in all the stations which correspond to month with maximum values of relative humidity. This month corresponds to the month with highest record of rainfall in most Nigerian stations. The values of coefficient of determination range between 0.9361 at Ibadan to 0.9905 at Calabar. The minimum value of root-mean-square error is obtained at Calabar with a value of 0.0036 and the highest is at Jos with 0.0150. These values show the applicability of the model for short-term analysis of global solar radiation in Nigeria (Sambo, 1986). The values of mean absolute error ranges between 0.0062 at Calabar and 0.0250 at Jos. The analyses of the adjusted mean square error showed the values ranges between 0.9524 at Jos to 0.9905 at Calabar. These values have shown that all the parameters and the interaction terms used contribute to the global solar radiation.

Table 4: Values for model parameters,

Stations	Jos	Makurdi	Maiduguri	Sokoto	Enugu	Ibadan	Calabar	P/Harcourt
α_0	0.5857	0.4782	0.5128	0.6011	0.3753	0.4635	0.4576	0.5196
α_1	0.1271	0.1205	0.0430	0.0556	0.2297	0.0783	0.0087	0.0265
α_2	0.0229	0.0456	-0.0257	-0.0137	0.0360	0.0063	-0.0663	0.0371
α_3	-0.0347	-0.0082	-0.0790	-0.0349	0.0323	-0.0138	-0.1466	-0.1101
α_{12}	-0.0544	-0.2554	0.0169	-0.0172	-0.2277	0.0259	-0.0084	0.0627
α_{13}	-0.0306	-0.0962	0.0770	0.0261	-0.0426	0.0690	0.0443	-0.0433
α_{23}	-0.0407	-0.0941	-0.0339	-0.0199	-0.1584	-0.0264	0.1136	0.0568
α_{123}	0.0294	0.1630	-0.0232	-0.0497	0.1964	-0.0301	0.0695	-0.0665
R^2	0.9827	0.9927	0.9828	0.9877	0.9911	0.9768	0.9965	0.9950
$\bar{R}^2$	0.9524	0.9800	0.9526	0.9663	0.9755	0.9361	0.9905	0.9863
MAE	0.0116	0.0046	0.0075	0.0064	0.0106	0.0092	0.0030	0.0035
RMSE	0.0150	0.0058	0.0086	0.0070	0.0061	0.0113	0.0036	0.0049
DW	1.8945	3.2396	2.7509	2.4421	3.0418	2.6296	3.0595	1.5551
SEE	0.0250	0.0101	0.0148	0.0122	0.0106	0.0196	0.0062	0.0086

Table 5: Predicted values of the global solar radiation

Months	Jos	Makurdi	Maiduguri	Sokoto	Enugu	Ibadan	Calabar	P/Harcourt
Jan	0.7573	0.5675	0.5358	0.6438	0.4682	0.4938	0.4413	0.5213
Feb	0.7297	0.5694	0.5539	0.6356	0.4866	0.5133	0.4458	0.5285
Mar	0.6748	0.5293	0.5915	0.6479	0.4353	0.5107	0.4317	0.4687
Apr	0.5771	0.4916	0.5646	0.5999	0.4145	0.4832	0.4312	0.4837
May	0.5350	0.5187	0.5314	0.5826	0.4681	0.4948	0.4345	0.4822
Jun	0.5149	0.4940	0.4630	0.5578	0.4164	0.4738	0.3786	0.4270
Jul	0.4800	0.4181	0.4197	0.5130	0.3473	0.3319	0.3007	0.3455
Aug	0.4472	0.4019	0.3672	0.4511	0.3118	0.3184	0.2718	0.3284
Sep	0.4943	0.4397	0.4464	0.5318	0.3745	0.3873	0.3219	0.3590
Oct	0.5960	0.5179	0.5204	0.6152	0.4522	0.4430	0.3762	0.4162
Nov	0.7563	0.6115	0.5538	0.6638	0.5297	0.5520	0.4236	0.4972
Dec	0.7479	0.6216	0.5366	0.6511	0.5262	0.5336	0.4576	0.5311

The standard error of estimate indicates the applicability of the factorial design as the values ranges between 0.0062 at Calabar and 0.0250 at Jos. The factorial design as applied to the analysis of global solar radiation in Nigeria gives a better predictive result than Angstrom-Prescott-Page equation. It also supports the use of relative sunshine duration, relative humidity and maximum ambient temperature for the prediction of global solar radiation in Nigeria (Swartmann and Ogunlade, 1967, Ododo, 1995 and 1997, Burari and Sambo, 2001 and Abdulazeez *et al.,* 2005). The predicted values for the global solar radiation using the factorial design is shown in table 5. Therefore, this method could be applied to areas without meteorological stations as the global solar radiation equipment is very expensive.

CONCLUSION

Factorial design is applied in the analysis of global solar radiation in eight selected stations in Nigeria. The analysis of coefficient of determination and adjusted coefficient of determination ranges between 0.9768(Ibadan) to 0.9965(Calabar) and 0.9361(Ibadan) to 0.9905(Calabar) respectively. The model equation using the factorial design could be used for prediction of global solar radiation on both short- and long –term bases. The values of mean absolute errors (MAE) and the root-mean –square errors (RMSE) calculated shows the applicability of the factorial design for the analysis of global solar radiation in Nigeria.

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