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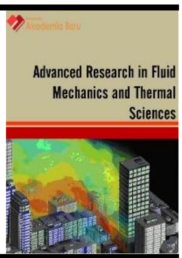

Optimum Tilt Angle for Solar Collectors used in Kano, Nigeria

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ABSTRACT

Solar intensity, collector design and its orientation are the key parameters that affect the performance of any solar collector. This work presents mathematical modelling of solar radiation for studying the effects of collector slope angle on the radiation falling on a solar collector and the determination of the collector optimum slope angle for Kano, Nigeria (12.05°N). To study such effects, two computer programs were developed for studying the effects of solar collector slope angle and optimization of the collection which was carried out using Engineering Equation Solver (ESS). Results showed that for maximum energy collection over the year, the collector should be tilted (in the order of priority); to the optimum angle of each month, to the seasonal tilt angles (i.e. horizontal from April to September and then set to Kano's latitude plus 15° for the other months) or fixed to the latitude of Kano. Sloping of solar collector to the monthly optimum tilt angle results in significant radiation gain throughout the year with 28.6 and 24.8% in December and January respectively. Also the maximum radiation obtainable in each month is received and there will be no radiation loss throughout the year. Also energy received by the collector for generating hot water or steam in solar thermal collector was found to be affected by the collector's orientation and slope angle.

1. Introduction

The use of renewable energy systems to harness solar radiation for different applications is getting more attention due to the problems of pollution and cost that are associated with the use of fossil fuel. In many countries, solar energy tends to be the most commonly used among all the renewable energy types. It is the most rapidly growing renewable source due to its advantages of flexibility, wide applications, maintenance free, versatility, etc. However, solar systems like other renewable systems are faced with the problems of low efficiency; high initial cost and lack of adequate awareness (in some locations) [1].

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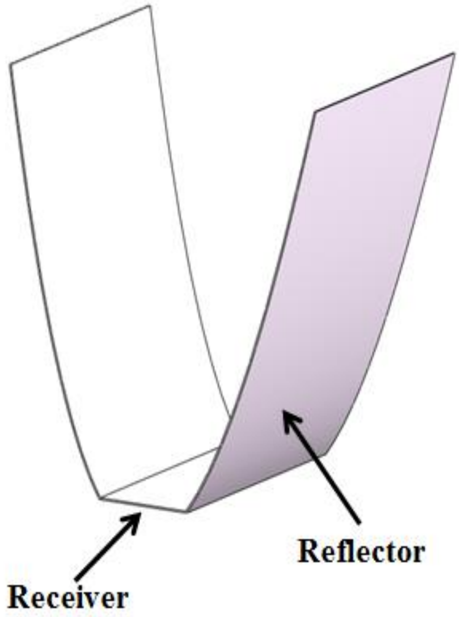
Kano, Nigeria (12.05°N, 8.52°E) enjoys high radiation falling on its surfaces almost throughout the year due to the rays of higher incidence angle striking its surface. On the other hand, the area is faced with serious energy problems ranging from regular power outage, non-access to the electricity by most rural dwellers, power losses, etc. Since the introduction of electricity in 1896 in Lagos, its development is slow while the demand is increasing with increase in the population [2]. With the total area of 9.23X1011m^2 and the population of over 170 million, the electricity supply of Nigeria is mostly below 4,000 MW. This situation led to low production, unemployment and crops wastage in agricultural states like Kano.

Studies have shown that only 10% of the rural households and 30% of the whole population have access to electricity [3] and this forced most households (70 - 80%) [4] rely on fuel wood for their energy requirements. The excessive use of fuel wood, reliance on personal power generators, coupled with about 79% of electricity generated from fossil fuel, Nigeria is put as 46th country in the world in carbon(IV)oxide emission with 73.69 metric tons released in 2011 [3]. Furthermore, the situation leads to continuous felling of trees that causes desert encroachment, erosion and loss soil fertility. Despite the availability of the solar radiation in Kano, only few solar systems are installed mostly for water pumping due to the cost of the photovoltaic cells, inadequate researches on the subject, economic status of the citizens and lack of proper awareness. It is believed that developing efficient and cost effective solar systems for domestic and industrial use can assist in addressing most of these problems. Among the ways to achieve this is having a proper design and orientation of the solar system for efficient operation throughout the day light hours. Solar thermal heat exchanger can provide most of the heating and cooling requirements of the region when properly harness while photovoltaic systems can provide the lightening and other low power requirements.

Solar radiation available in a location is the major parameter that determines the performance of any solar collector be it a photovoltaic cell (PV) or thermal collectors. PV systems convert solar radiation falling on its cells directly into electricity by photovoltaic effect as shown in Figure 1(a). Proper orientation and sloping of a solar panel enable it to capture most of the radiation falling on the surfaces. Similarly, correct orientation and tilting of a solar thermal collector enable it to capture most of the solar rays falling on its tubes for heating the water fluid (water or air) passing through it. Solar thermal collectors are heat exchangers that transform solar radiation into heat and transport the heat to a working fluid (which can be water, air, oil, etc.) flowing through it. They consist of different components such as glazing, receiver, receiver plate and concentrator (in case of concentrating systems). Figure 1(b) shows a typical solar thermal collector of concentrating type which concentrate all the radiation falling on its aperture if the rays are within its acceptance angle.

However, details of this important parameter (meteorological data) are often missing for many regions, which leads to the development of prediction models. Several studies have been conducted on the predictions of solar radiation of some regions like Moodaly [5], Al-Enezi *et al*., [6], Wong *et al*., [7] for Hong Kong Oliveira *et al.,* [8] for Sao Paulo, Sabziparvar *et al.,* [9] for East and West of Iran and Sabziparvar *et al.,* [10] for central Arid desert of Iran. Sambo [11] proposed 12 different correlations for estimating the global solar radiation of Kano, Nigeria using sunshine hours, average daily temperature and relative and specific humidity. Other correlations were developed for estimating the global radiation based on the percentage sunshine such as Sayigh [12] and Modi *et al.,* [13].

(a) Solar Photovoltaic



(b) Compound Parabolic Collector

Fig. 1. Types of Solar collector

Hashim and Sidik [14] studied the heat transfer in small size asphalt solar collector with water circulating through series of tubes embedded in the asphalt pavement to extract solar energy. Results have shown that the temperature of the ashalpt decreases when solar anergy is extracted from the circulating water. This leads to reduction in the heat island effects and power consumption of air conditioning systems. Ghaderian *et al*., [15] presented a numerical study using MATLAB on energy analysis of solar air heater considering the collector geometry, wind speed, solar radiation, collector area and ambient temperature. Results obtained shown that the energy losses can be minimized by altering the operating parameters. Also, the collector area was found to have the minimum effects compared to others.

Even with solar radiation available, there is need of knowledge on the orientation and correct tilt of solar collectors for it to receive most of the radiation available in any location of the world. Hence several attempts were made to determine optimum collector tilt angle for certain locations; China, Tang *et al*., [16], Syria, Skeiker [17] Jordan, Shariah *et al*., [18] and Egypt, Elimir *et al.,* [19] e.t.c. Although several attempts were made to determine the optimum slope angles for different locations in the world, there is little or no research conducted (to our knowledge) on the determination of its optimum value for Kano. Thus, creating a gap in enhancing the radiation collection in the area, which is addressed in this paper. The aim of the research is to determine the best orientation for solar photovoltaic and solar thermal collector (heat exchanger) for maximum output. To achieve this, a computer program was developed in excel spreadsheet® for studying the effects of tilt angle. Then Parametric study and optimization of the tilt angle were carried out using genetic algorithm in Engineering Equation Solver (ESS) by Golden Section Search (GSS) and quadratic approximation methods which led to the determination of optimum tilt angle for Kano.

2. Methodology

2.1 Prediction of Solar Radiation Components in Kano

Solar radiation available in a location and the collector orientation are the most important parameters for determining the performance of any solar collector. The climate of Nigeria is characterized by two seasons; the wet and dry seasons, but it is almost warm throughout the year with slight difference in temperatures between winter and summer. The summer (wet season) is usually between April and October while the winter (dry season) is between November and March.

As the first step of this work, daily average global solar radiation data for Kano, Nigeria [in MJ/(m^2.day)] on horizontal surfaces ($\overline{H}$) was obtained from Nigerian Meteorological Agency [20] and Figure 2 presents the monthly average of the data. Since the data are global radiation on horizontal surfaces, so correlations have to be used to predict the other components of the radiation which are needed in evaluating the performance solar collectors.

The monthly average daily extra-terrestrial radiation on a horizontal surface, ($\bar{H}_o$) at any location (with lat. +60 to -60) is obtained by using the day of the year (n) and solar declination (δ) for the mean day of the month as [21]:

$$\overline{H_o} = \frac{24X3600G_{sc}}{\pi}\left(1+0.033\cos\frac{360n}{365}\right)\left(\cos\phi\cos\delta\sin\omega_s + \frac{\pi\omega_s}{180}\sin\phi\sin\delta\right) \quad (1)$$

where, G_{sc} is the solar constant and ϕ is the latitude of the location. The mean day is the day having extraterrestrial value (H_o) closest to $\overline{H}_0$.

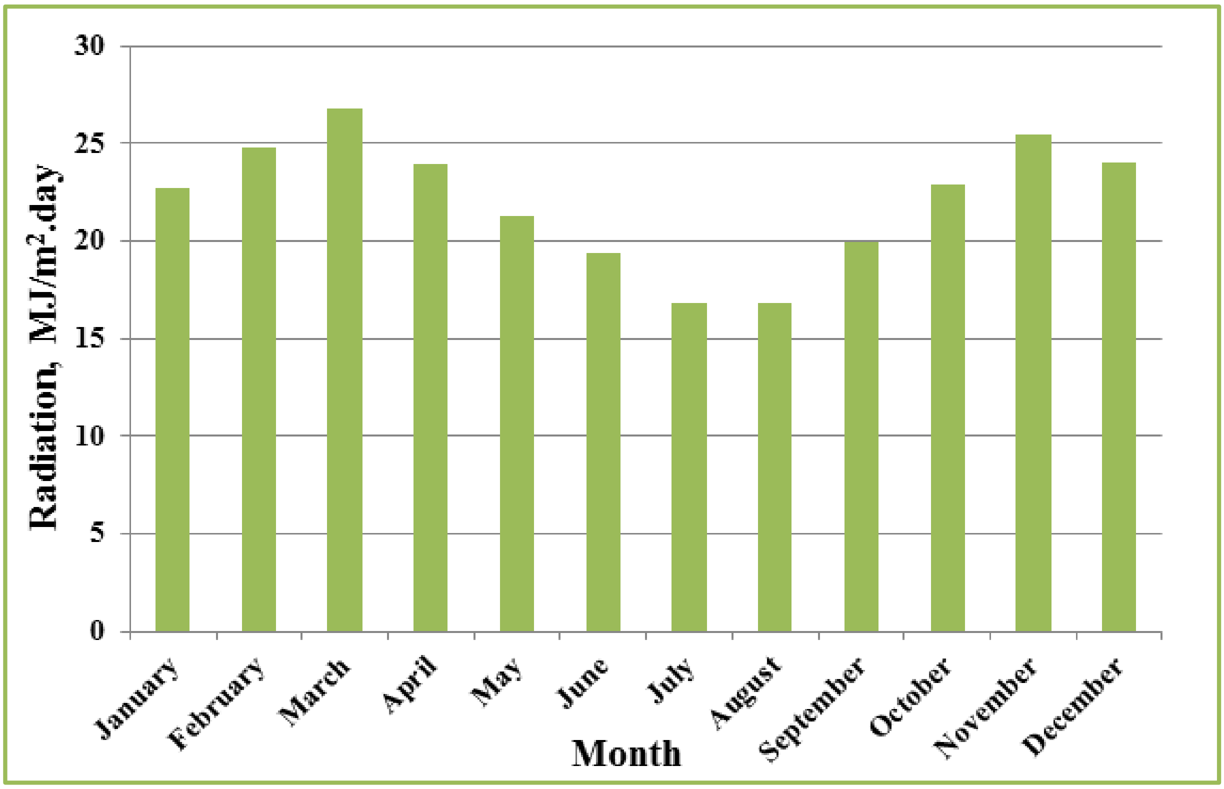


Fig. 2. Monthly average global solar radiation on horizontal surface of Kano, Nigeria

Details explanations on the modelling of radiation and the effects of the slope angle of the collector is given in [22]. This paper is only concern with the optimization of the radiation collection by a solar system through the determination of its optimum monthly, seasonal and annual slope angles so as the output (light, hot water or steam) will be enhanced.

2.2 Prediction of Radiation Components on A Sloped Surface

Solar collectors are usually tilted to maximize energy collection especially the beam component and the gain depends on the angle, latitude and the time of the year [23]. The total global radiation on a tilted solar collected is given by [21]:

$$\overline{H_T} = \overline{H}\left(1-\frac{\overline{H_d}}{\overline{H}}\right)\overline{R_b} + \overline{H_d}\left(\frac{1+Cos\beta}{2}\right) + \overline{H}\rho_g\left(\frac{1-Cos\beta}{2}\right) \tag{2}$$

where, $\overline{H_T}$, is the monthly average total radiation on a slope surface, $\overline{H\left(1-\frac{\overline{H_d}}{\overline{H}}\right)\overline{R_b}}$ is the monthly average beam radiation on sloped surface. While $\overline{H_d}\left(\frac{1+Cos\beta}{2}\right)$ and $\overline{H}\rho_g\left(\frac{1-Cos\beta}{2}\right)$ are the monthly average diffuse and ground reflection respectively.

where, $\overline{R_b}$ is the tilt factor which is the ratio of the beam on tilted surfaces to that on horizontal surfaces and it is given (for a surface in northern hemisphere) as [21]:

$$\overline{R_b} = \frac{Cos(\phi-\beta)Cos\delta Sin\omega' + \left(\pi/180\right)\omega'_s Sin(\phi-\beta)Sin\delta}{Cos\phi Cos\delta Sin\omega'_s + \left(\pi/180\right)\omega'_s Sin\phi Sin\delta} \tag{3}$$

where, w'_s is the sunset hour angle for the tilted surface for the mean day of the month, given by [21]:

$$\omega'_s = \min\begin{bmatrix} Cos^{-1}(-\tan\phi\tan\delta) \\ Cos^{-1}(-\tan(\phi-\beta)\tan\delta) \end{bmatrix} \tag{4}$$

The reflectivity of the material in front of the collector (ρ_g), can be taken as 0.7 and 0.2 with and without snow respectively [24] if it is not known. The solar declination depends on the day of the year, *n* (with *n* = 1 for 1st January) given by [21,25]:

$$\delta = (23.45^o)\sin[360^o(284+n)/365] \tag{5}$$

3. Results

3.1 Prediction of Beam and Diffuse Radiation on Horizontal surface of Kano

Using equations described in Section 2, a mathematical radiation model was developed and used in studying the effects of solar collector slope angles on the radiation collector. Using the developed model, monthly average beam and diffuse radiation were predicted from the measured global radiation on horizontal surface (Figure 3). It can be seen from the figure that in some months of the year, Kano recorded a significant amount of diffuse. This will help in the selection of the best solar collector for capturing such amount of radiation. Compound parabolic collector (CPC) will be a good option, since it captures significant amount of diffuse component without tracking the sun.

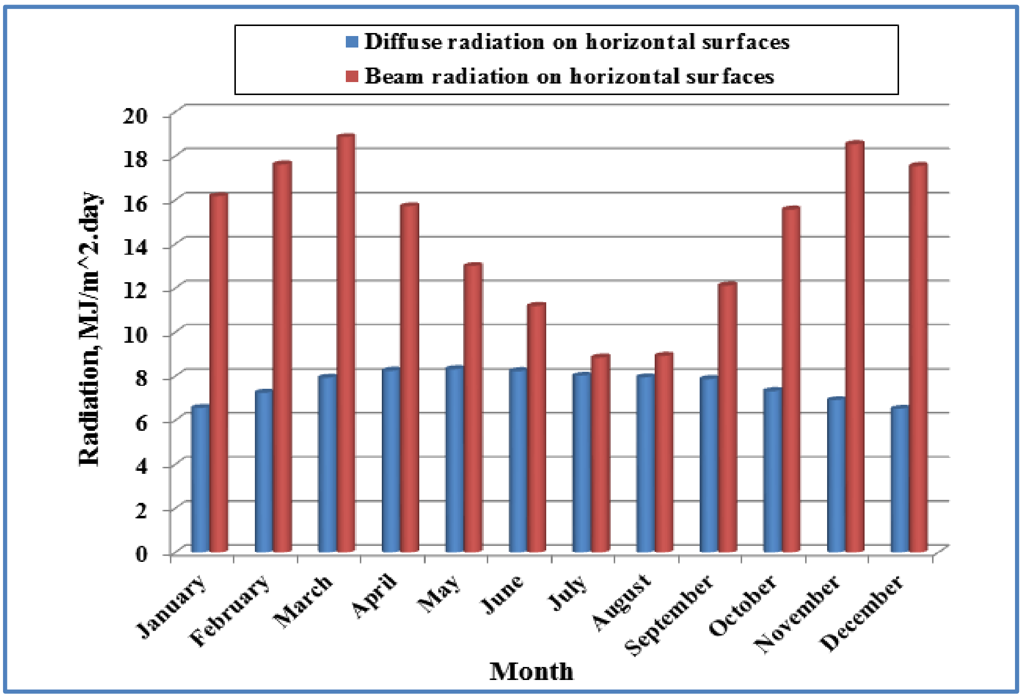


Fig. 3. Predicted beam and diffuse radiation on horizontal surfaces of Kano

3.1.1 Prediction of beam and diffuse radiation on a sloped solar collector in Kano

Figures 4 and 5 show the predicted beam and diffuse radiation when a solar collector is sloped at an angle equals to the latitude of Kano (12.05° N). Comparing Figures 4 and 5, it can be seen that the amount of beam radiation in the month of January has increased when the collector is tilted to the angle of 12.05° (Figure 4) compared to horizontal (Figure 3).

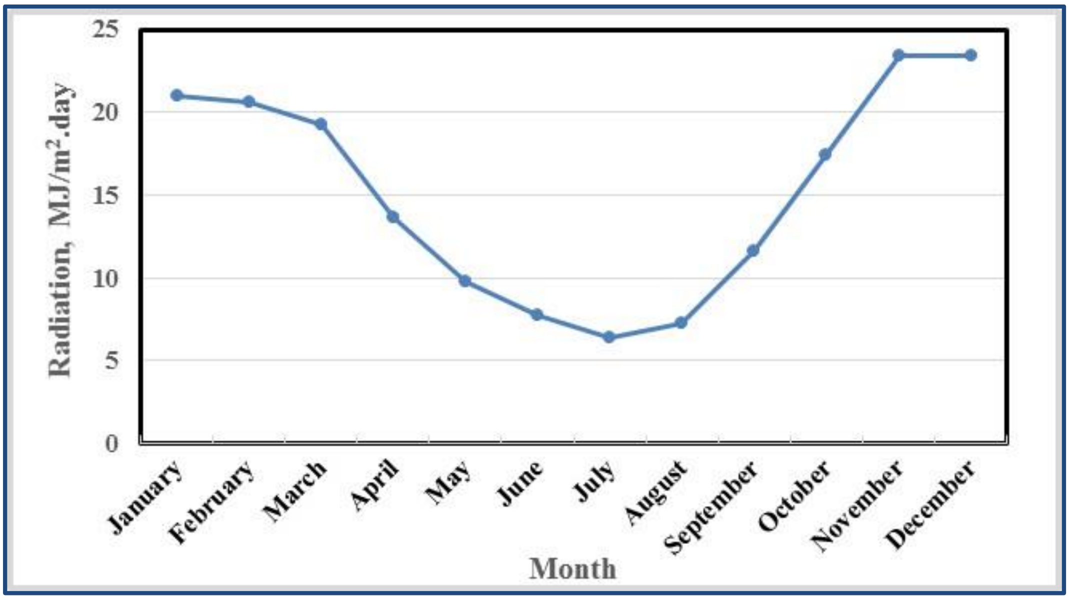


Fig. 4a. Monthly average beam radiation at 12.05° tilt angle

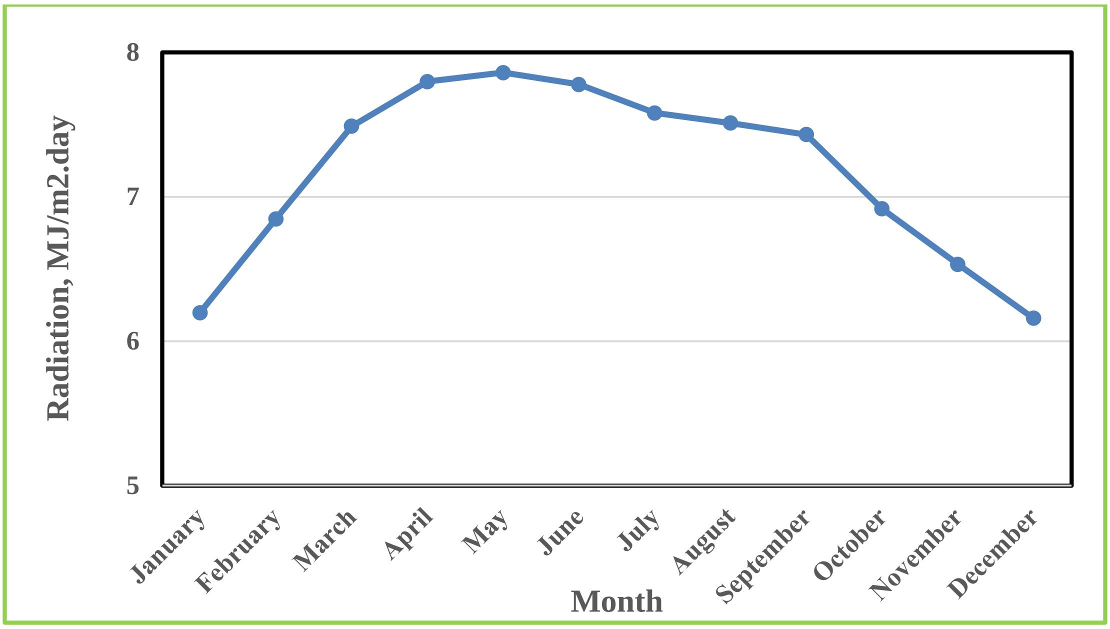


Fig. 4b. Monthly average diffuse radiation at 12.05° tilt angle

3.2 Optimum Solar Collector Tilt Angles

To study the effect of the tilt angle on the global solar radiation in details, eight different slope angles relative to the latitude of Kano (Table 1) were simulated and the result is presented in Figure 5. It can be deduced from such figure that there is general increase in the global radiation received at slope angles compared to the horizontal orientation from October to March as the tilt angle increases up to $\beta = \phi + 15^o$. But for the month of March, the amount starts decreasing when $\beta > \phi$, which shows that the optimum tilt for such month lies between $\beta = \phi$ and $\beta = \phi + 10^o$. However, when the tilt angle is greater than $\beta = \phi + 15^o$, there is increase in November, December and January up to $\beta = \phi + 30^o$ but decrease when it reaches $\beta = \phi + 45^o$. This shows that the optimum tilt for these months lies between these extremes (i.e. $\beta = \phi + 30^o$ and $\beta = \phi + 45^o$).

On the other hand, there is decrease in the global radiation as the tilt angle increases in the months of April to August, with the highest loss of 45.23% in June when $\beta = \phi + 45^o$. Hence horizontal orientation is the best for these months and this is because they have significant amount of diffuse radiation component (Figure 3) and the best orientation for capturing it is horizontal alignment. Due to the trends of these results, more investigations are required for the determination of optimum collector tilt angle for Kano. Parametric studies was first carried out for all the months and the global radiation was determined from 0° to 90° tilt angles using the measured radiation on horizontal surface, mean day and solar declination of each month using codes developed in Engineering Equation Solver (EES).

Table 1
Solar Collector tilt angles simulated and their relationship to the latitude of Kano

S/N	Tilt angle, β /°	Relation to the latitude
1	0	β = ϕ - 12.05°
2	2.05	β = ϕ - 10°
3	10	β = ϕ - 2.05°
4	12.05	β = ϕ
5	22.05	β = ϕ + 10°
6	27.05	β = ϕ + 15°
7	42.05	β = ϕ + 30°
8	57.05	β = ϕ + 45°

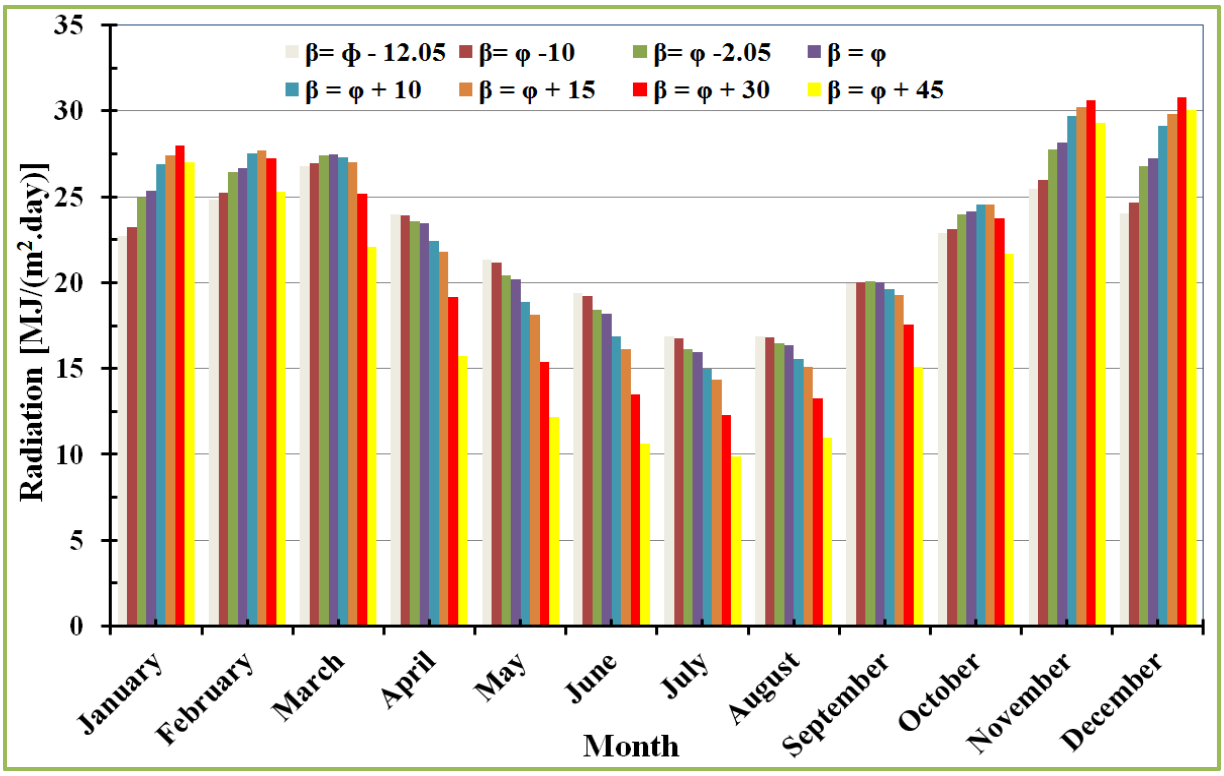


Fig. 5. Monthly average global radiation at different tilt angles

For the parametric study, the program was ran for wide range of angles (ie from 0° to 90°) and monthly average global radiation is obtained for each angle. Figure 6 shows the results obtained from the parametric study. It can be seen from such figure that the global radiation reach peak value for each month, after which it starts decreasing and the results are the same as the other model (Figure 5), hence the two models show a good agreement. But the advantage of EES model is that it simulates wider range of angles with less computational times.

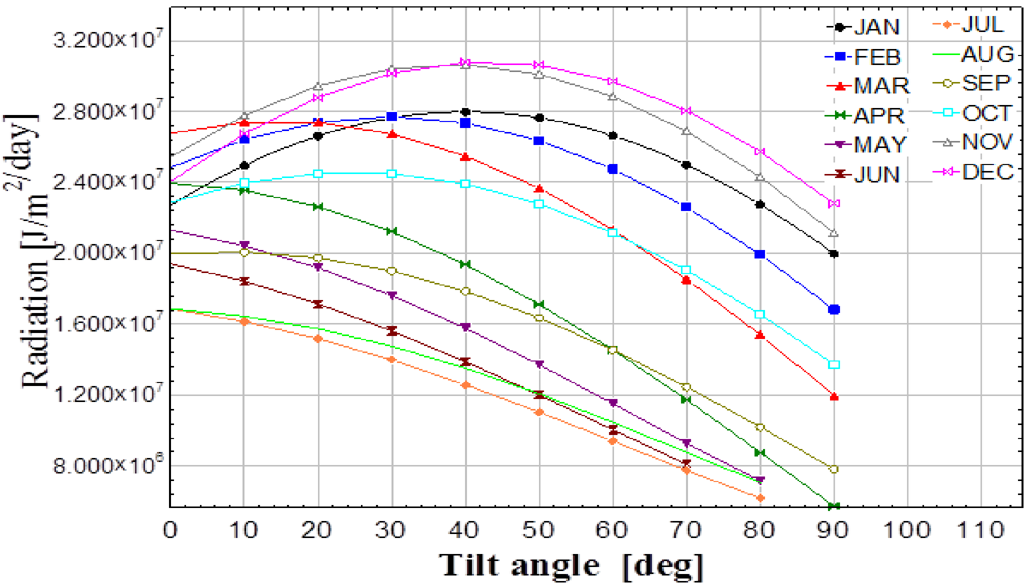


Fig. 6. Monthly average global radiation at different tilt angles using ESS model

Using Golden Section Search (GSS) and Quadratic approximation methods in EES, the optimization of tilt angles was carried out for all the months. The global radiation at tilt was set as the objective function (to be maximized) while the tilt angle was selected as the independent variable. Figures 7 and 8 show the monthly optimum angles and corresponding radiation values for the winter and summer months respectively. From April to August zero degrees is shown to be the optimum (Figure 8) while for October to February, their optimum angles ranging between 24.72° and 43° (Figure 7) with December having the largest optimum angle (43°). March and September have 14.86° and 7.41° as optimum respectively.

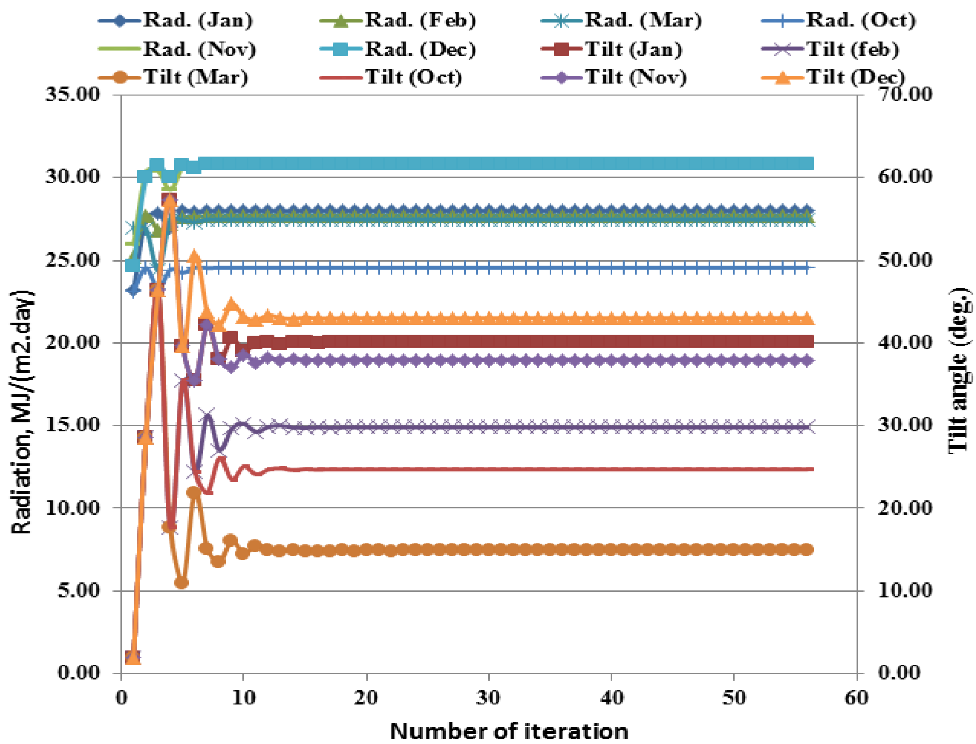


Fig. 7. Monthly optimum tilt angles and corresponding radiation values against the number of iterations (winter)

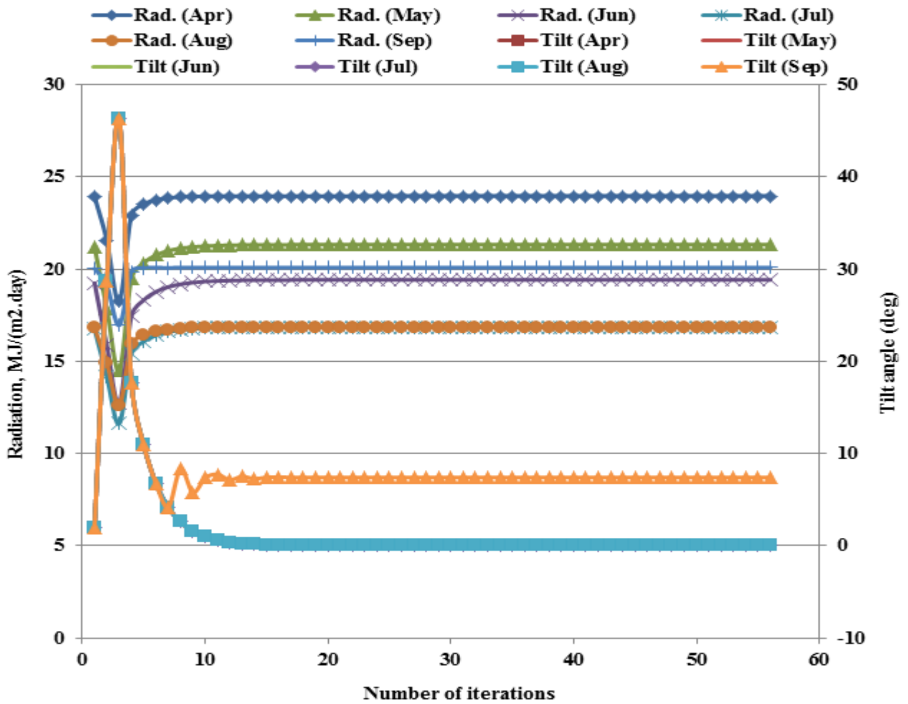


Fig. 8. Monthly optimum tilt angles and corresponding radiation values against the number of iterations (summer)

3.3 Effect of Tilt Angle on The Solar Energy Received in Kano

The solar energy to be received by a surface in Kano when it is horizontal, sloped to the latitude and to the optimum tilt angles of every month for an average of eleven daylight hours is shown in Figure 9. Comparing β = βopt and β = 0°, gives 28.6% and 24.8% increase in average energy received in December and January respectively. For β = βopt and β = ϕ, January and December will still have the highest increase of 11% and 13.2% respectively. While 13.7% and 12.4% increase in energy receive in December and January will be achieved when comparing β = ϕ and β = 0° but with loss in performance from April to August; highest in June (5.2%).

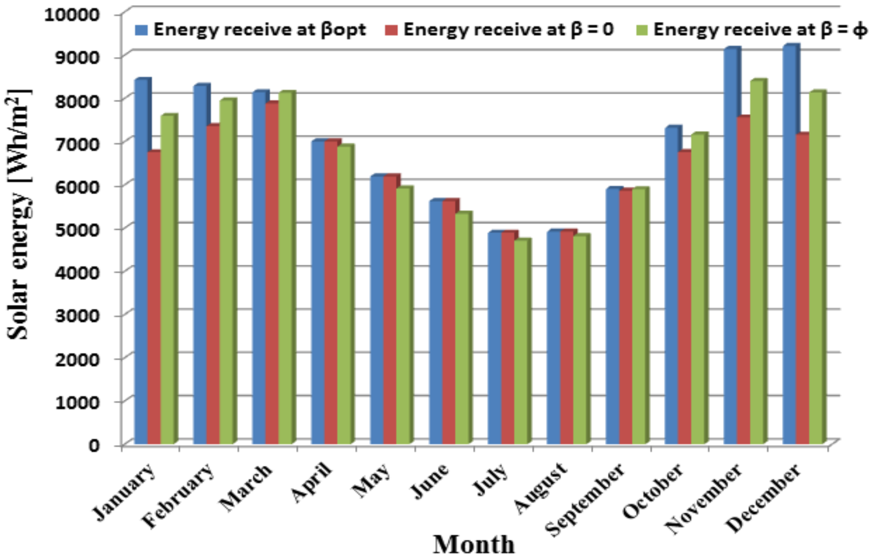


Fig. 9. Daily average solar energy receives at different tilt angles for each month

4. Conclusions

Two computer programs were developed for studying the effects of solar collector slope angle on the solar radiation acceptance and determination of the monthly and seasonal optimum slope angles for Kano, Nigeria. Global, beam and diffuse radiation on both horizontal and sloped surfaces were predicted and optimum slope angle for each month was determined. The choice of the best tilt angle for Kano depends on whether the collector will be fixed or adjusted (monthly or seasonally). The following recommendations are put forward for Kano:

i) Fixed collector: For the collector to be fixed at an angle throughout the year without adjustment, the best tilt is to the latitude of Kano ($\beta = \phi = 12.05^o$) because of uniformity and having radiation gain in seven month (highest of 13.2% in December) and annual average of 7.3%.
ii) Monthly adjustment: The optimum angle for each month has been determined and the collector can be tilted to such angles shown in Figures 7 and 8 to maximize the radiation collected. This is best option because there will be significant radiation gain throughout the year with 28.6 and 24.8% in December and January respectively. Also, the maximum radiation obtainable in each month is received and there will be no radiation loss throughout the year.
iii) For seasonal tilt:

- $\beta = 27.05^o$ ($\phi + 15^o$) is the best angle for the months between October and March, with the highest increase in December (24%) and seasonal average of 14%.
- $\beta = 0$ ($\phi - 12.05^o$) is the best angle for the months between April and September. This is due to the significant amount of diffuse component in these months and the best angle for capturing it is horizontal orientation, because it is distributed randomly in the sky. Also, in these months (especially June to September), the northern hemisphere is tilted towards the sun, thus sun rays hit normal to the surface.

Finally, the study has shown that correct tilt angle for PV solar system and solar thermal heat exchanger enables the systems to receive the maximum solar radiation falling on their surfaces which lead to high outputs.

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