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Empirical Modelling and Estimation of Solar Radiation from Tilted Surfaces Relative to Angular Solar Relations

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Abstract

Interest in solar energy has prompted the accurate measurement and mapping of solar energy resources of the globe. Solar radiation data are available in several forms. Most radiation data available for horizontal surfaces include both direct and diffuse radiation. This is normally done by using solar-meters. Most solar-meters measurements are recorded simply as total energy (global radiation) incident on the horizontal surface; other measurements separate the direct (beam) and the scattered (diffuse) radiation. Radiation data are the best source of information for estimating average incident radiation and for the proper designing of a solar water heating system. A precise analysis and design of a solar water heating system requires knowledge of the solar energy obtained from the sun and the availability of global solar radiation and its components at the location of project site. Since the solar radiation reaching the earth's surface depends upon climatic conditions of the place, a study of solar radiation under local climatic conditions is essential. Solar radiation data were obtained through the use of an empirical model to predict and estimate solar radiation seems inevitable. The highest value of solar radiation was obtained in April, 2018 and the average horizontal radiation on a surface and radiation on a tilted surface was found to be 966.12W/m^2 and 1055.99W/m^2 respectively.

1. Introduction

Energy and its different forms is fundamental to human existence and the economic development of any country, Nigeria inclusive. Nigeria with its increasing population needs energy, alternative source of energy is needed to support the growing population. Currently there is a lot of over dependence on fossil fuel and environmental pollution caused by fossil fuel combustion, Chlorofluorocarbons, other chemicals and organic materials has been of global concern, Nigeria inclusive [1]. Researches are being conducted towards addressing this problem, these includes the use of solar energy through collectors, followed by optical, thermal and thermodynamic analysis of these collectors, coupled with the use of optimum tilt angle for maximum insolation across different locations. Solar radiation from the sun that keeps our planet warm exceeds by far the current primary energy supply used by mankind for its comfort, leisure and economic activities. It also exceeds vastly other energy sources at ground level such as geothermic or tidal energy, nuclear power and fossil fuel burning. Sunrays also drive hydraulics, wind, wave power and biomass growth. The global warming crisis as a result of the depletion of the ozone layer caused by the emissions of CFC'S (chlorinated and brominates organic compounds) and NOx has led to many researches on alternative renewable sources of energy like the sun, hydro, wind and geothermal. Most countries in the world have realized the need for reduction of gas emissions to contrast the adverse global climatic change, encouraging the use of renewable and fully sustainable sources of energy [2].

The solar radiation from the sun coming through the atmosphere to the earth can be anticipated with a high accuracy. The amount of solar energy depends basically on the astronomical geometric parameter such as the actual distance from sun to earth, since the earth moves around the sun on an elliptical orbit, the sun-earth distance is a function of the day. With regard to the mean value of the earth-sun distance, the sum of the energy per unit area obtained from the sun exterior of the earth's atmosphere, known as the solar constant, is approximately 1367W/m^2 [3]. The earth's cross-sectional area is estimated to be 127400000km^2 and the total power released to the earth by the sun is estimated to be 1.75 × 1014 kW [3]. The solar radiation reaching the earth's surface is sometimes difficult to estimate because of the interaction with the atmosphere and the different soil surfaces in contact. The mean solar radiation is a function of various statistical data which cannot be predicted with a high precision. While passing through the atmosphere a major part of the incident energy from the sun is suppressed by reflection, scattering or absorption by air molecules, clouds and particulate matter also called aerosols. Due to this only 60% (approximately 1.05×10^{14} kW) of sunlight from the sun to the earth's atmosphere reaches the earth's surface [4]. Notwithstanding, the total annual solar radiation falling on the earth's surface is approximately more than 7500 times the world's total annual primary energy consumption of 450 EJ [5].

The energy generated within the inner core of the suns solar sphere having temperatures of approximately many millions of degrees must be transferred out to the surface and then be radiated into space. A combination of radiative and convective processes occur with successive emission, absorption and radiation. The radiation in the sun's core is in the x-ray and gamma-ray parts of the spectrum, with the wavelengths of the radiation increasing the temperature drops at larger radial distances [3]. The surface of the sun consists of granules (irregular convection cells), with a measurement of between 1000 to 3000 km and having a lifetime cell of a few minutes. Other features of the sun's solar surface are small dark areas called pores which are of the same size in magnitude as the convective cells and the larger dark areas called sunspots which vary in size. The convective zone has an outer layer called the photosphere. It is essentially opaque and also consist of gases that are composed of strongly ionized particles that are able to absorb and emit a continuous spectrum of radiation. The source of most solar radiation is the photosphere [6].

Apart from the photosphere, a less transparent solar atmosphere can be observed during total solar eclipse or by an instrument known as the solar disk. The photosphere is immediately below a layer of gases that are cooler and several hundred kilometers deep called the reversing layer. Chromosphere is another layer that is close to the photosphere having a depth of about 10,000 km and this is a gaseous layer with temperatures higher than that of the photosphere but with lower density [7]. Also, there is a layer called corona, which is far from the photosphere and it is a zone of very low density with a very high temperature of about 10^6 K. The sun showing its physical structure, temperature and density gradients will serve as a basis for acknowledging that the sun does not in fact function as a blackbody radiator at a fixed temperature [8].

The radiation aspect from the sun that is not reflected or scattered and reaches a specific surface directly from the sun is known as the direct or beam radiation. The scattered radiation which reaches a specific surface from all directions is known as diffuse sky radiation. The total radiation incident on a horizontal surface consist of diffuse sky and direct radiation and is known as the global or total horizontal radiation. The total radiation incident on a non-horizontal or tilted surface is a combination of the direct radiation, diffuse sky radiation, and another form of radiation that is reflected from the ground surface and is known as the global tilted radiation [9].

Some factors that determines the availability of the solar radiation in specific locations are climate conditions formed by geographical factors including latitude, size of lands and seas, sea tides, height above sea level and land formation. The latitude is of great importance since the angle of the incidence of the solar radiation causes the lower irradiance at higher latitudes. According to solar radiation travels through a distance in the atmosphere before reaching the earth and at higher latitudes the distance is longer resulting in the increased absorption and reflection of the solar radiation before reaching the earth. The other one is that the higher angle of incidence results in the lower irradiance on the horizontal ground surface [10].

Solar energy is a form of energy obtained from the sun and it is a type of renewable energy. The energy from the sun can be used to generate thermal energy or heat energy for use in our residential homes and industry respectively. Solar radiation varies with location and it is important to known the quantity of solar energy that can be obtained in a particular location, this can be measured and also estimated for. Due to the issues of faulty equipment and maintenance of research centers that can store this information, it is important to also obtain this solar radiation data by empirical and angular solar relations.
The aim of this work is to determine theoretically reliable solar radiation data that can be used for research purpose and the design and fabrication of solar machines and equipment.

2.0 Methodology

This study compares its obtained data with that measured from National Centre for Energy and Environment, University of Benin, Benin City, Edo State, Nigeria (longitude and latitude of 6.33°N, 5.61°E) for the project location. Data obtained from the energy center was from the period of 2012 to 2017. Solar radiation data available at the agency is only global radiation (a combination of both the direct and diffuse radiation).
In order to properly estimate the total solar radiation on a tilted surface, angular solar relation like the incident angle, hour angle, altitude angle, zenith angle, azimuth angle and the declination angle were calculated respectively.
Collectors were installed horizontally at an angle to increase the amount of radiation intercepted by the surface of the collector. In order to obtain the radiation on a tilted surface, angular relations of solar radiation were estimated for. The surface absorbs beam, diffuse and ground reflected solar radiation. Also, the amount of solar radiation received per unit area by a surface held perpendicular to the sun rays comes in straight line from the direction of the sun at its current position in the sky and this was determined with the aid of Equation (1).

$$\mathrm{I_n} = \mathrm{A}\exp\left(-\frac{B}{cos\theta_Z}\right) \tag{1}$$

Where I_n is the normal solar radiation intensity in W/m^2, A and B are constants (1230 and 0.142 were obtained from [11]).

$$\mathrm{I_b} = \mathrm{I_n}\cos\theta_Z \tag{2}$$

$$\mathrm{I_d} = \mathrm{I_n}C \tag{3}$$

Where $\mathrm{I_b}$ is the beam radiation, $\cos\theta_Z$ is the zenith angle, $\mathrm{I_d}$ is diffuse radiation and C is a constant (0.058 was obtained from [11]).

$$\theta_z = 90 - \alpha \tag{4}$$

Where α is the altitude angle.

$$\mathrm{Sin}\alpha = \mathrm{cosL}\cos\omega\cos\delta + \mathrm{sinL}\sin\delta \tag{5}$$

Where L is the latitude of the site, ω is the hour angle and δ is the declination angle respectively.

$$\omega = (\mathrm{ST} - 12)15 \tag{6}$$

Where ST is the solar time and it is from 1 to 24 hours.

$$\delta = 23.45 \sin\left(360 \frac{284+n}{365}\right) \quad (7)$$

Where n is for the number of days.

$$R_b = \frac{\cos\theta_Z}{\text{Cos}\theta} \quad (8)$$

where θ is the anle of incidence.

$$\text{Cos}\theta = \cos\theta_Z \cos\beta + \sin\theta_Z \sin\beta \quad (9)$$

where α is the altitude angle, γ is azimuth angle and β is the tilt angle respectively.

$$\beta = \text{lattitude} + 5^o \quad (10)$$

$$\gamma_s = \text{sign}(\omega) \left|\cos^{-1}\left(\frac{\cos\theta_z \sin L - \sin\delta}{\sin\theta_z \cos L}\right)\right| \quad (11)$$

Where γ is the azimuth angle.

$$I_T = I_b R_b + I_d\left(\frac{1+cos\beta}{2}\right) + I_b R_b \rho_g\left(\frac{1-cos\beta}{2}\right) \quad (12)$$

Where I_T is the total solar radiation on a tilted surface and ρ_g is ground reflectance.

Data source was generated using Equations (1) to (12), this is to ensure that at any point in time of a particular day and time, when the tilt angle is altered, horizontal radiation and radiation on a tilted surface is obtained for that location and time. This data sheet could be readily available for solar energy research and for the purpose of weather forecast.

3.0 Results and Discussion

The amount of solar energy obtained in a particular location depends on the angular solar relations, analysis of the solar flat plate collector considering the location, tilt angle and ambient conditions of the site under study.

3.1 Angular relations of solar radiation

Solar energy availability was determined considering some conditions, these conditions are ambient conditions, tilt angle, the location (longitude and latitude) of study and the mid-month in each month. The mid-months (nth) are recommended average days of various months. A particular day in each month was chosen (mid-month), this day has approximately the average solar radiation which is equal to the monthly mean value for that particular month as shown in Table 1, with this the total radiation on a horizontal and tilted surface were obtained respectively as shown in Table 2 and 3 using Equations 1 to 12.

Table 1: Angles of solar relations from January to December 2018 in Benin City, Edo State.

Mid-Month	No of Days(n)	Declination (d)	Altitude angle	Zenith angle	Azimuth angle	Incident angle
17 Jan 2018	17	-20.92	49.86	40.13	46.44	29.13
16 Feb 2018	47	-13.61	54.14	35.85	56.06	24.85
16 Mar 2018	75	-2.42	58.79	31.21	74.61	20.21
15 April 2018	105	9.42	60.15	29.87	97.88	18.87
15 May 2018	135	18.79	58.26	31.74	115.88	20.74
11 June 2018	162	23.09	56.62	33.37	123.26	22.37
17 July 2018	198	21.21	57.40	32.60	120.08	21.60
16 Aug 2018	228	13.46	59.63	30.37	105.87	19.37
15 Sept 2018	258	2.221	59.80	30.19	83.48	19.19
15 Oct 2018	288	-9.60	56.13	33.87	62.19	22.87
14 Nov 2018	318	-18.92	51.12	38.88	48.90	27.88
10 Dec 2018	344	-23.05	48.48	41.51	43.96	30.52

Table 1 shows the obtained solar declination angle, altitude angle, zenith angle, azimuth angle and incident angle respectively from January to December 2018 for Benin City, Edo State, the mid-month, latitude, number of days and hour angle were considered during the analysis. This analysis enabled the estimation of the radiation on a horizontal surface and the radiation on a titled surface respectively.

Table 2: Radiation on a Horizontal surface from January to December 2018 of Benin City, Edo State

Months	I_b(W/m^2)	I_d(W/m^2)	I_{TH}(W/m^2)
January	781.04	59.25	840.29
February	836.73	59.87	896.60
March	891.09	60.43	951.52
April	905.55	60.57	966.12
May	885.16	60.40	945.56
June	866.56	60.19	926.75
July	875.51	60.27	935.78
August	900.20	60.51	960.71
September	902.09	60.53	962.62
October	860.68	60.13	920.81
November	797.87	59.45	857.32
December	761.90	59.02	820.92

Table 2 shows the direct solar radiation, diffuse solar radiation and the total solar radiation on a horizontal surface for a period of one year for Benin City, Edo State, Nigeria considering the location and site of study. This obtained data will enable researchers estimate the total radiation on a tilted surface and also enhance solar energy researches due to the fact that parameters/data for solar energy are scarce.

Table 3: Radiation on a tilted surface from January to December 2018 of Benin City, Edo State

Months	I_{bt}(W/m^2)	I_{dt}(W/m^2)	I_g(W/m^2)	I_{TH}(W/m^2)
January	892.31	67.69	1.54	961.54
February	936.72	67.03	1.65	1005.40
March	977.72	66.30	1.75	1045.77
April	988.12	66.09	1.78	1055.99
May	973.38	66.39	1.73	1041.51
June	959.55	66.64	1.70	1027.89
July	966.25	66.52	1.72	1034.49
August	984.30	66.17	1.77	1052.24
September	985.66	66.14	1.77	1053.57
October	955.12	66.72	1.69	1023.53
November	905.96	67.50	1.58	975.03
December	876.59	67.90	1.51	945.99

Table 3 shows the direct solar radiation, diffuse radiation, ground reflected radiation and the total solar radiation on a tilted surface for a period of one year for Benin City, Edo State, Nigeria considering the location and site of study. This data was obtained considering a tilt angle of 11^{o} (11 degree), the computation was done so as to allow for varying climatic condition for optimum performance of the solar system under study. The solar radiation obtained was compared to the solar radiation data obtained from National Centre for Energy and Environment, University of Benin, Benin City, Edo State, Nigeria as shown in Figure 1 for 2017.

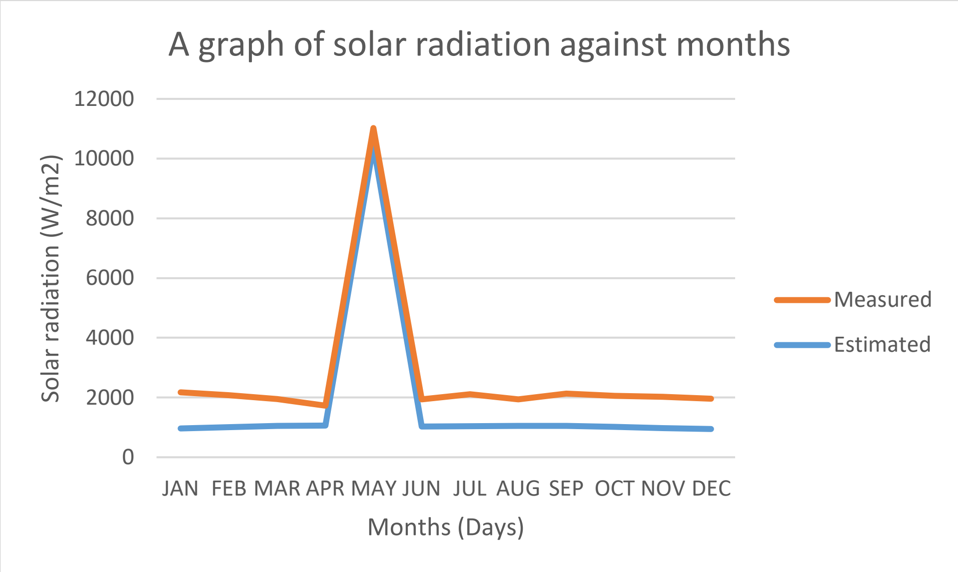

Figure 1: A graph of measured and estimated solar radiation against months.

The graph shows the interaction between the estimated and measured solar radiation of 2017 (obtained from the National Centre for Energy and Environment) with the number of days, from the above it shows there is a good agreement between the measured and estimated solar radiation. Therefore, proving that the accuracy of the estimated solar radiation obtained by empirical equations could be relied on.

4.0 Conclusion

A procedure was developed to determine the solar radiation on a horizontal surface and on a tilted surface. A solar radiation data of Benin City, Edo State was generated with respect to various input parameters (time, day, hour angle, latitude and longitude, tilt angle and angular solar relations respectively) so that when the input parameters are altered or varied, output parameters like solar radiation on a horizontal surface and on a tilted surface can be obtained. The highest form of solar radiation obtained were 966.12W/m^2 and 1055.99W/m^2 respectively for the month of April, 2018.

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