ESTIMATION OF GLOBAL SOLAR RADIATION ON HORIZONTAL SURFACES USING TEMPERATURE-BASED MODEL IN ILORIN, NIGERIA

Abstract

In this study, the Solar Irradiation received was estimated in Illorin, Kwara, Nigeria, using the maximum and minimum temperature measured by an Arduino-based solar power parameter measuring system. The Extraterrestrial, Global and Diffuse Solar Radiation were estimated monthly using the Hargreaves and Samani model. This model also required the daily temperature, clearness index, and extraterrestrial solar irradiation in its use alongside the maximum and minimum temperatures. In using this model, we resolved the graphs of the three types of Solar Irradiation over ten days. For the selected days, the estimated extraterrestrial solar irradiation varies from 10.41kWh/m2 to 10.47 kWh/m2, while the mean extraterrestrial solar irradiation is 10.44 kWh/m2. The estimated global solar irradiation varies from 4.42 kWh/m2 to 5.677kWh/m2, while the estimated mean global solar irradiation is 5.19kWh/m2 per day. The estimated diffuse solar irradiation varies from 3.46kWh/m2 to 5.48kWh/m2, while the mean diffuse solar irradiation is per day is 4.61kWh/m2.

Keywords: Solar Irradiation, Hargreaves and Samani, Temperature, Clearness Index

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1. Introduction

Global energy demand is increasing rapidly due to population and economic growth, especially in emerging economies such as Africa. It is also glaring that the current energy infrastructures in place cannot handle this demand. The number of people without access to electricity remains unacceptably high (Hannah Ritchie, 2019). Fossil fuels are residents' alternative to the epileptic power supply, leading to higher greenhouse gas emissions, especially carbon dioxide, contributing to global warming. Hence, there is a need for a shift from conventional energy systems towards a more affordable, , and cleaner energy system to combat these problems.

The abundance of solar energy in many countries contributes to why it is currently the world's most preferred and valued source of alternative energy. The design of a solar energy conversion system requires precise knowledge regarding the availability of global solar radiation at the location of interest. Since the global solar radiation reaching the Earth's surface depends upon the local meteorological conditions;, a study of solar radiation under local climatic conditions is essential (Alsamamra, 2015). However, for locations where measured values are not available, solar irradiance may be estimated using empirical models. Therefore, many researchers have explored various methods to estimate, with reasonable accuracy, the solar radiation from other available meteorological data.

Environmental parameters most frequently investigated are sunshine, cloud cover, temperature, and precipitation variables. Solar radiation can be easily estimated from sunshine duration using the Angstrom-Prescott models. The models are sunshine-based and have widely applied to estimate global solar radiation (Angstrom, 1924) (Prescott, 1940). However, data for sunshine and cloud observations are usually not available at most meteorological stations. Global solar radiation estimation models based on measured air temperature are attractive and a viable option in this context. It is necessary to develop a precise solar radiation model which utilizes commonly available parameters such as maximum and minimum temperatures of the geographical location (Hargreaves GL, 1985). Several methods have been reported using empirical relationships to estimate global solar radiation from commonly measured meteorological variables. Daily solar extraterrestrial radiation, Ho is often included in the relationships. Ho values are calculated in this project using standard geometric procedures.

2. Basic Solar Components

2.1 Declination angle (δ)

The declination angle of the Sun is defined as the angle between the Equator and the line drawn between the centers of the Earth and the Sun. The declination angle (δ) varies every season due to the Earth's rotation around the Sun and the Earth's movement on its axis of rotation. It should have an angle of zero but for the Earth's tilt on its axis of rotation. Earth's Equator is tilted 23.45 degrees with respect to the plane of the Earth's orbit around the Sun, so at various times during the year, as the Earth orbits the Sun, declination varies from 23.45 degrees north to 23.45 degrees south. (Abood, 2015)

This declination gives rise to the different seasons. At around 21st December, the Earth's northern hemisphere is tilted 23.45 degrees away from the Sun, thus, the winter solstice for the northern hemisphere and the summer solstice for the southern hemisphere. In the periods around 21st June, the southern hemisphere is tilted 23.45 degrees away from the Sun, which results in the summer solstice for the northern hemisphere and the winter solstice for the southern hemisphere. 21st March and 21st September are the fall and spring equinoxes when the Sun is directly overhead the Equator. Note that the Tropics of Cancer and Capricorn mark the maximum declination of the Sun in each hemisphere (Abood, 2015).

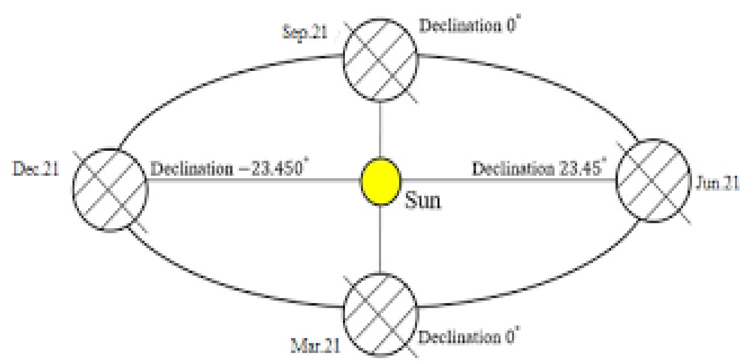

Figure 1: Maximum and minimum value of declination angle

Declination is calculated with the following formula:

$$\delta = 23.45 \times \sin\left(\frac{360}{365}\right) \times (284 + N)$$

Where, δ = declination angle, N = day number, January 1 = day 1

2.2 Hour Angle (*w*)

The angle between two planes is the hour angle of a point: one containing the Earth's axis and the zenith (the meridian plane), and the other containing the Earth's axis and the given point. The angle is negative east of the meridian plane and positive west of the meridian plane, or it can be positive westward zero to 360 degrees. The angle may be measured in degrees or in time, with 24 hours which equals 360 degrees exactly (Bhatia, 2014)**.**

The hour angle is paired with the declination to fully specify the position of a point on the celestial sphere. Again, this is the way we represent the apparent displacement of the Sun away from solar noon. An hour angle of zero degrees indicates that the Sun is directly above, and the sign of the hour angle is determined by occurring either before noon (negative) **or** afternoon (positive) (Bhatia, 2014)**.**

$$\omega = cos^{-1}(-\tan\delta \tan\phi) \quad \tan\delta \tan\phi \leq 1$$

$$\omega = \pi \qquad \tan\delta\tan\phi > 1$$

Where, ω = hour angle, ϕ = latitude, δ = declination angle

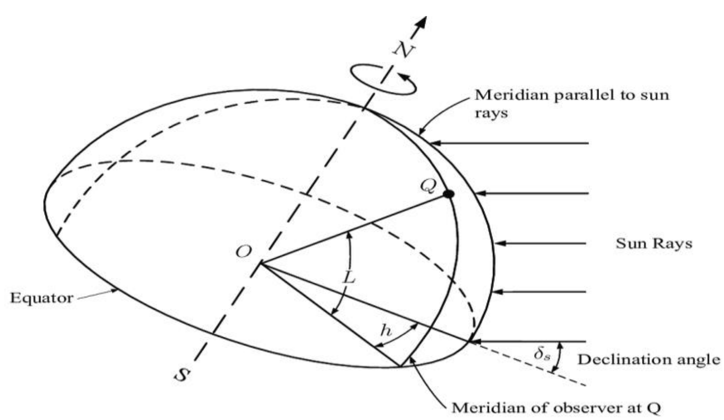

Figure 2: Hour angle (ω) for point Q

2.3 Latitude (ϕ)

Latitude is an angle that ranges from 0° at the Equator to 90° (North or South) at the poles. Lines of latitude refer to arcs or circles that span huge distances. Lines of constant latitude, or parallels, run east-west as circles parallel to the Equator. Latitude is used together with longitude to specify the precise location of features on Earth's surface.

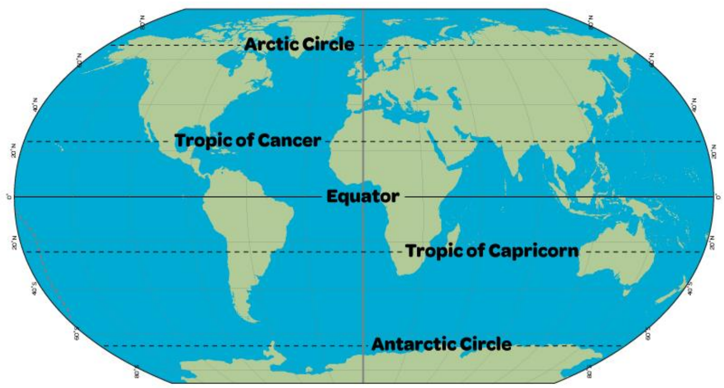

Figure 3: Lines of latitude

2.4 Global Solar Irradiation (H_g)

Solar irradiation is the amount of electromagnetic radiation from the Sun per unit area (usually square meters). In other words, it's the amount of solar power detected by a measuring instrument. When these data are integrated over time, the information is called solar irradiation, insolation, or solar exposure (Garner, 2018).

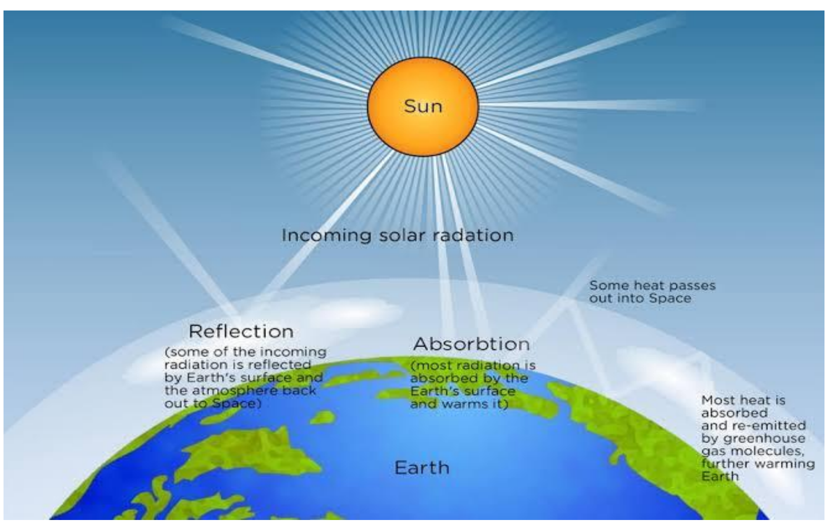

Figure 4 Solar Radiation System

The total radiation is composed of the following three components (Garner, 2018):

1. *Direct radiation*" is also sometimes called "beam radiation" or "direct beam radiation". It is used to describe solar radiation travelling on a straight line from the Sun down to the surface of the Earth.

2. *Diffuse radiation*", on the other hand, describes the sunlight that molecules and particles have scattered in the atmosphere but that has still made it down to the surface of the Earth.

3. *Reflected radiation* (the radiation reflected back by the lake, seas, and other water bodies). The total ground reflection is a sum of all the above three.

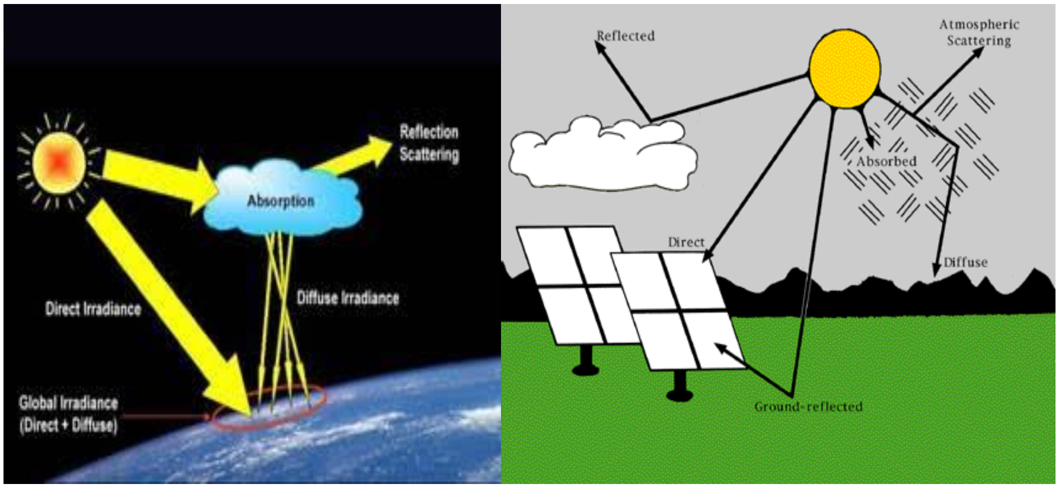

Figure 5 Solar Radiation Components

2.5 Hourly Extraterrestrial solar radiation on the horizontal surface (Ho)

Extraterrestrial solar irradiation is the irradiance available outside the Earth's atmosphere. Measurement of extraterrestrial solar radiation intensity is difficult because it varies with the distance between the Earth and Sun. The following arithmetical relationship gives the monthly average of daily extraterrestrial radiation (Duffie, Beckman, & Worek, 2003).

$$Ho = \frac{12}{\pi} s \left(1 + 0.033 \cos\left(\frac{360d}{365}\right)\right) [cos\varphi \cos\delta \sin\omega + \omega \sin\varphi \sin\delta]$$

Where 's' is the solar constant, and its value is 1.367 KW/m2, 'd' is the day of the year, 'ω' is the sunshine hour angle, 'φ' is the latitude angle and 'δ' is the declination angle.

$$\omega = cos^{-1}(-\tan\delta \tan\phi) \ /\tan\delta \tan\phi/ \leq 1$$

$$\omega = \pi \ \ \tan\delta \tan\phi > \ 1$$

Solar declination angle (Rani, 1982) is given as

$\delta = 23.45\sin\,[2\pi\,(284 + d)\ 365]$

2.6 Daily Extraterrestrial Solar Radiation on the horizontal surface (Ho)

Extraterrestrial solar irradiation is the irradiance available outside the Earth’s atmosphere. Measurement of extraterrestrial solar radiation intensity is difficult because it varies with the distance between the Earth and Sun. The following arithmetical relationship gives the monthly average of daily extraterrestrial radiation (Duffie, Beckman, & Worek, 2003).

$$Ho = \frac{24}{\pi} s \left(1 + 0.033 \cos\left(\frac{360d}{365}\right)\right) [cos\varphi\cos\delta\sin\omega + \omega\sin\varphi\sin\delta]$$

Where ‘s’ is the solar constant and its value is 1.367 KW/m2, ‘d’ is the day of the year, ‘ω’ is the sunshine hour angle, ‘φ’ is the latitude and ‘δ’ is the declination angle.

$$\omega = cos^{-1}(-\tan\delta\,\tan\phi)\ /\tan\delta\,\tan\phi/\leq 1$$

$$\omega = \pi\ \ \tan\delta\tan\phi > \ 1$$

Solar declination angle (Rani, 1982) is given as

$\delta = 23.45\sin\ [2\pi\ (284 + d)\ 365]$

Extraterrestrial irradiation can be used to find the value of the clearness index, KT, which is the ratio of global solar irradiation and extraterrestrial solar radiation.

$$KT = \frac{Hg}{Ho}$$

Where Hg is the global solar irradiation and Ho is the extraterrestrial radiation.

If $\omega < 81.4°$ and $0.3 < KT < 0.8$,

The diffused solar radiation (Rani, 1982), Hd is given as

$$\frac{Hd}{Hg} = 1.391 - 3.650KT + 4.189KT^2 + 2.13KT^3$$

If $\omega > 81.4°$ and$0.3 < KT < 0.8$,

$$\frac{Hd}{Hg} = 1.311 - 3.022KT + 3.427KT^2 + 1.821KT^3$$

3. MATERIALS AND METHODS

3.1 Test Location

The University of Ilorin is located in Ilorin, the state capital of Kwara State, in Northcentral Nigeria. It is located on latitude and longitude 8.4912°N, 4.5950°E respectively. It is situated at an elevation of 320 meters above sea level, and the average annual temperature is 26.5°C.

3.2 Measurement Procedure

In this work, BMP 108 sensor was incorporated into a designed Arduino-based solar power parameter measuring system using Arduino Uno. This system measures different solar PV parameters, including the real-time temperature and real-time atmospheric pressure. The measuring system was designed and constructed using Arduino Uno and multiple sensors. The system was proficient in measuring different solar PV parameters, including actual-time temperature and real-time. The measured temperature parameters were simultaneously logged into a personal computer (PC) for future analysis or references (Oladimeji, 2020, p. 246). Figure 6 shows the diagram of an Arduino-based solar PV parameter-measuring system having sensors interfaced between the solar panel and Arduino board.

The system comprised of both hardware circuit design and software programming for interfacing solar with the Arduino board. The hardware development involves designing electronic components for the sensors interface between the solar panel to the Arduino UNO. The hardware unit comprises the voltage sensor, current sensor, light-dependent resistor (LDR) sensor, pressure-temperature sensor, and the Arduino Uno. The acquired data from sensors are analogue; thus, the conversion to digital equivalent was performed within the Arduino UNO analogue-to-digital converter module programmed in C- language (Oladimeji, 2020, p. 246).

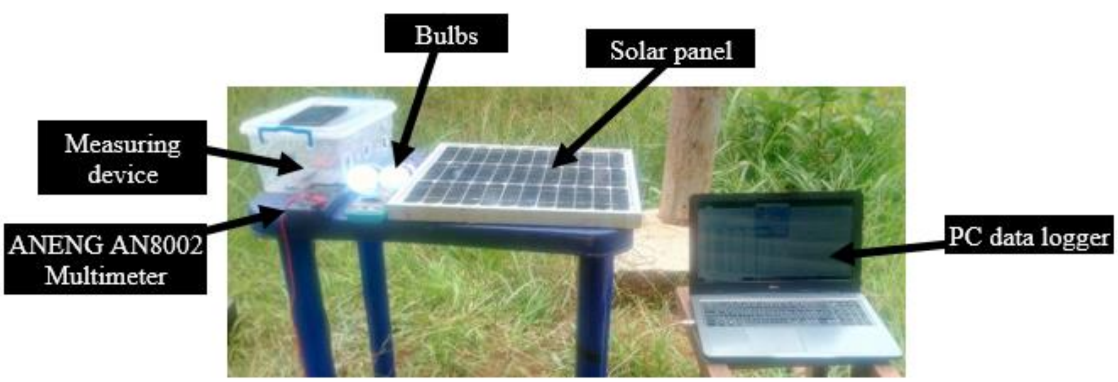

Fig 6. Solar Power Parameter Measuring System with a Data Logger

3.3 System Components

3.3.1 Arduino Microcontroller

It is a microcontroller board based on the ATmega328. Arduino is an open-source, The prototyping platform and its simplicity make it ideal for hobbyists or novices to use as well as professionals. The Arduino Uno has 14 digital input/output pins (of which six can be used as PWM outputs), six analogue inputs, a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; connect it to a computer with a USB cable or power it with an AC-to DC adapter or battery to get started (Oladimeji, 2020, p. 248).

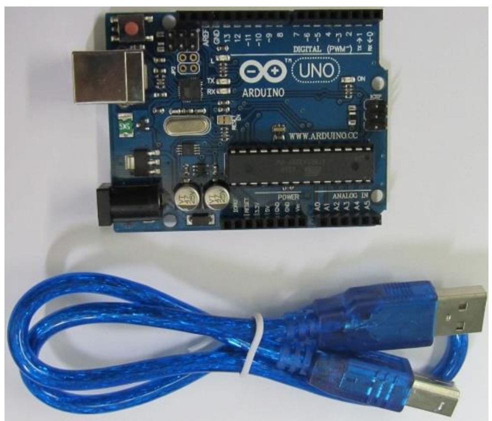

Fig 7: Arduino Uno

3.3.2 Temperature Sensor

The temperature and barometric pressure were measured using BMP180 temperature-pressure sensor. The BMP180 sensor is an environmental sensor for different weather sensing and can be used with I2C (inter-integrated circuit) and SPI (serial peripheral interface) communication protocol. This precision sensor from BOSCH Company is a popular low-cost precision sensing solution for measuring barometric pressure with ±1 hPa absolute accuracy and at temperature ±1.0°C accuracy. Figure 4 shows the BMP180 sensor with the connection pins for interface with the Arduino board (Oladimeji, 2020, p. 248).

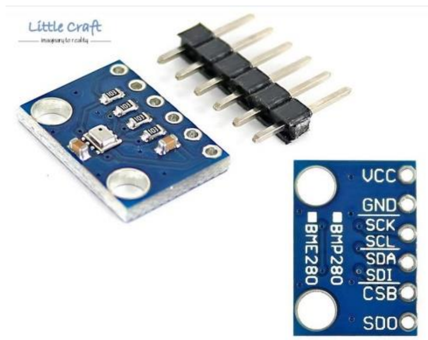

Figure 8: BMP 180 temperature-pressure sensor

3.4 Estimation of Solar Radiation using Daily Temperature Data only

When solar radiation data is unavailable, it is possible to get reasonably accurate radiation estimates using the proposed models. A widely used method is based on empirical relations between solar radiation and temperature. In this project, Global solar radiation is estimated using Hargreaves and Samani model solar radiation estimation model. This model was chosen as representative of the existing models that utilize extraterrestrial irradiation and the measured temperature.

In this project, we used the maximum and minimum temperature because it is easy to read and readily available. Over the years, it has been the most frequently used instrument for solar radiation estimation due to its accuracy and simplicity. Maximum and minimum air temperatures were measured and recorded from 28th – 31st May, 1-3rd June, 19th-21st of June.

3.4.1 Hargreaves and Samani model

Hargreaves and Samani (Hargreaves G.H, 1982) were the first to suggest that global radiation could be evaluated from the difference between daily maximum and daily minimum temperature. The equation form introduced by Hargreaves and Samani is

$$KT=\frac{Hg}{Ho} = a\Delta T^{\frac{1}{2}}$$

Where $\Delta T \ = Tmax - Tmin$ and a is an empirical coefficient. Initially, a was set to 0.17 for arid and semiarid regions. Hargreaves (Hargreaves, 1985) later recommended using a = 0.16 for interior regions and a = 0.19 for coastal regions.

4. Result and Discussion

4.1 Extraterrestrial Solar Radiation

The results of the declination angle, hour angle, and daily extraterrestrial solar irradiation (solar irradiation at the entrance into the Earth's atmosphere H_o) on a horizontal surface calculated in Ilorin, Nigeria (8.4912°N, 4.5950°E) for the selected days are shown in Table 4.1. The highest extraterrestrial solar irradiation value of 10.47kWh/m^2 was obtained on 28th May 2019, while the lowest value of 10.41 kWh/m^2 was obtained on 6th June 2019.

Fig. 9 displayed that the extraterrestrial solar irradiation was on the decrease continuously throughout the period. This may be attributed to the reduction of solar radiation by the cosine of the angle between the solar radiation and a surface normal (called cosine effect) outside the Earth's atmosphere or as a result of the reduction of the extraterrestrial solar radiation by the atmosphere due to absorption, scattering, reflection and transmission by water vapour, carbon dioxide, clouds, smog, and particulates. (Chiemeka, 2008). The average extraterrestrial solar irradiation at the entrance into the Earth's atmosphere known as obtained for the period at Ilorin is 10.44 kWh/m^2.

Table 4.1 Extraterrestrial Solar Irradiation

Date	Day of the year	Declination angle(°)	Hour Angle(°)	H_o(W/m^2)	H_o (KWh/m^2)
28/05/2019	148	21.43	93.36	436.31	10.47
29/05/2019	149	21.60	93.39	436.00	10.46
30/05/2019	150	21.75	93.41	435.70	10.46
31/05/2019	151	21.90	93.44	435.40	10.45
01/06/2019	152	22.04	93.47	435.12	10.44
02/06/2019	153	22.17	93.49	434.84	10.44
03/06/2019	154	22.30	93.51	434.57	10.43
04/06/2019	155	22.42	93.53	434.30	10.42
05/06/2019	156	22.54	93.55	434.05	10.42
06/06/2019	157	22.65	93.57	433.81	10.41

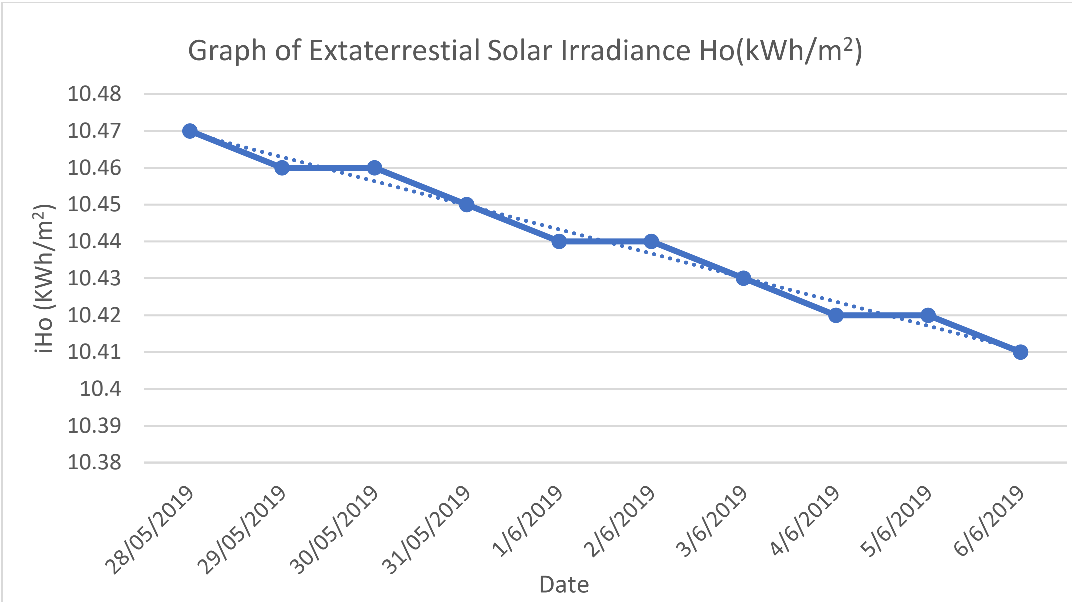

Fig 9. Graph of Extraterrestrial Solar Irradiance

4.2 Global Solar Irradiation

Table 4.2 Global Solar Irradiation

Date	Max Temperature (°)	Min Temperature (°)	Clearness Index KT	H_0 (KWh/m^2)	H_g (KWh/m^2)	H_d/H_g	H_d (KWh/m^2)
28/05/2019	34.43	23.00	0.54	10.47	5.67	0.97	5.48
29/05/2019	30.19	21.90	0.46	10.46	4.82	0.82	3.97
30/05/2019	32.97	21.93	0.53	10.46	5.56	0.95	5.26
31/05/2019	33.07	23.74	0.49	10.45	5.10	0.87	4.42
01/06/2019	33.46	23.28	0.51	10.44	5.33	0.90	4.82
02/06/2019	32.42	21.76	0.52	10.44	5.45	0.93	5.05
03/06/2019	31.73	21.37	0.51	10.43	5.37	0.91	4.90
19/06/2019	32.71	23.90	0.48	10.42	4.95	0.84	4.18
20/06/2019	31.06	24.04	0.42	10.42	4.42	0.78	3.46
21/06/2019	33.31	23.49	0.50	10.41	5.22	0.89	4.63

The maximum and minimum temperature results using the BMP108 temperature sensor at Ilorin from 28th May 2019 to 6th June 2019 are presented in Fig. 10. The temperatures ranged from 30.19^{o}C (29th May) to 34.43^{o}C (28th May) for maximum and 21.37^{o}C (3rd June) to 24.04^{o}C (day6) for minimum temperatures.

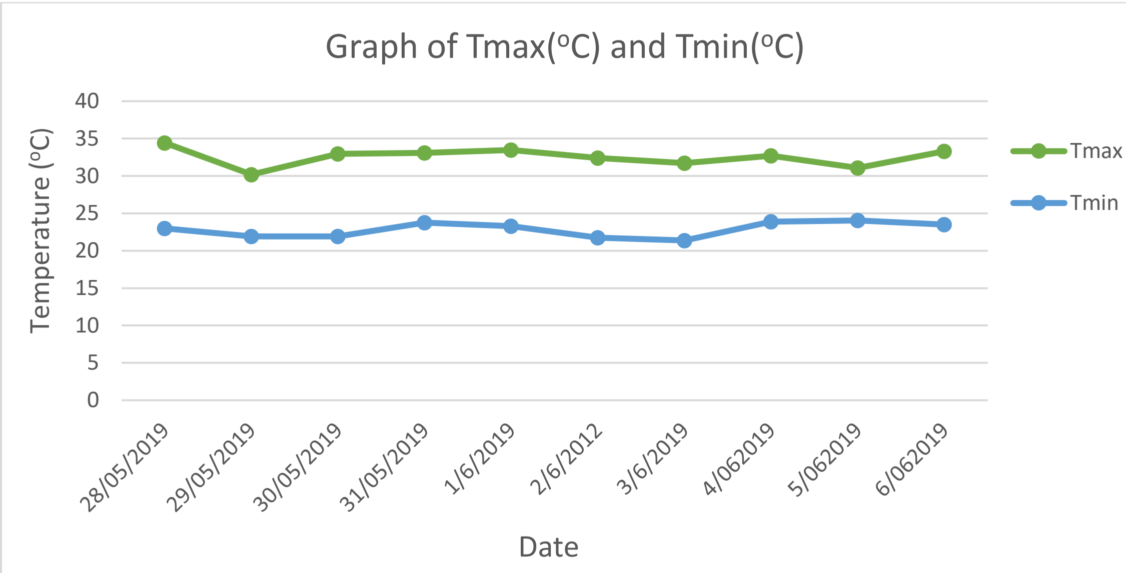

Fig. 10 Graph of Maximum and Minimum Temperature

The results of the global solar irradiation at Ilorin estimated using the Hargreaves and Samani model for the selected days are presented in Fig. 11. The Hargreaves and Samani model use daily temperature difference, clearness index, and extraterrestrial solar irradiation. The temperature difference should be less when cloud cover is greater. This is because the day temperatures remain high, and the heat is conserved so that the night temperature is also high, resulting in less temperature range during the day. The Td considers changes in radiation due to proximity to oceans, mountains, and the location's altitude (Chineke, 2007). The benefit of this equation is that it uses temperature data that is readily available at many locations (rural and urban) and requires a single empirical coefficient. Global Solar Irradiation is the amount of electromagnetic radiation received from the Sun per unit area (usually square meters). In other words, it is the amount of solar power detected by a measuring instrument. The highest global solar irradiation value of 5.677kWh/m^2 was obtained on 28th May 2019, while the lowest value of 4.42 kWh/m^2 was obtained on 5th June 2019. The average global solar irradiation obtained at Ilorin was 5.19kWh/m^2.

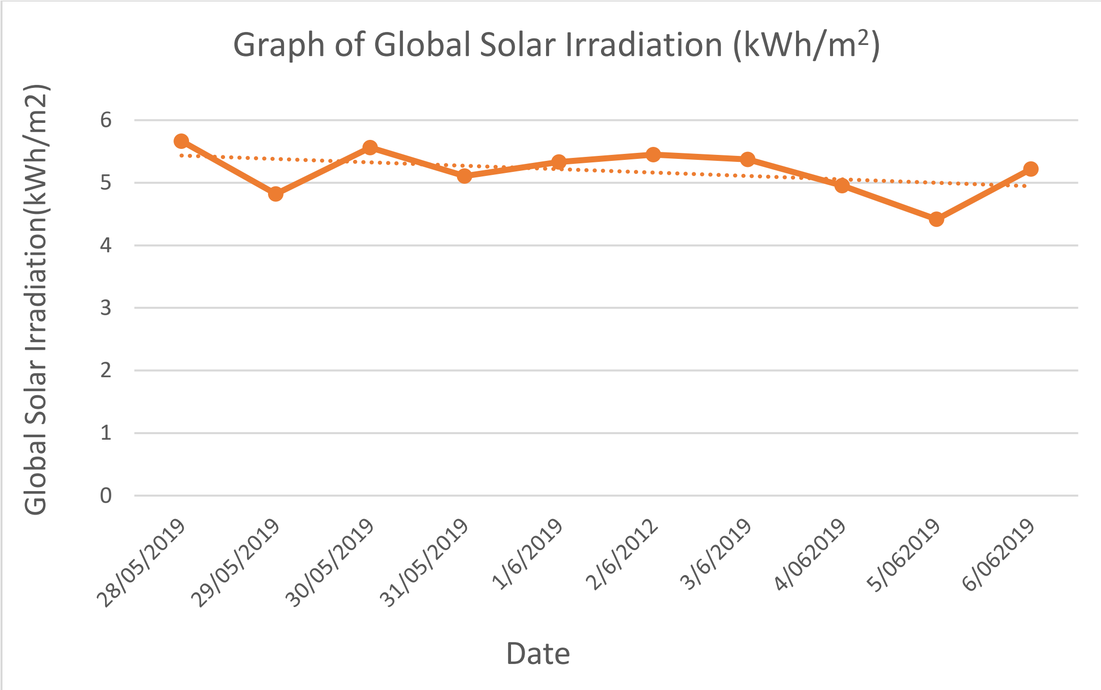

Fig 11. Graph of Global Solar Irradiation

4.3 Diffuse Solar Irradiation

The results of the calculated Diffuse Solar Irradiation are shown in Fig. 12. Using arithmetic equations as suggested by (Rani, 1982). This equation makes use of the clearness index and Global Solar Irradiation. Diffuse Solar describes the sunlight that molecules and particles have scattered in the atmosphere, but that has still made it down to the surface of the Earth. The highest diffuse solar radiation value of 5.48kWh/m^2 on 28th May, while the lowest value was 3.46kWh/m^2 on 5th June.

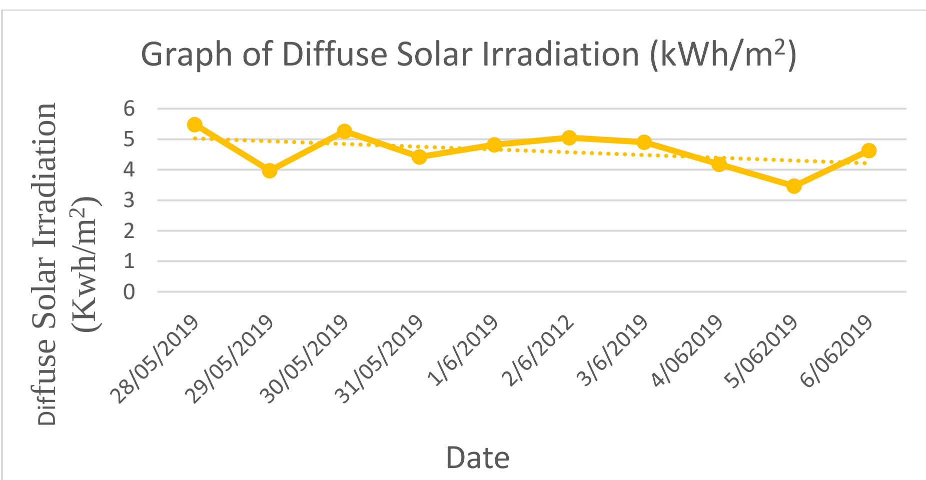

Fig. 12 Graph of Diffuse Irradiation

5.0 CONCLUSION

In this project, the estimation of global solar radiation in Ilorin, Nigeria (8.4912°N, 4.5950°E) has been carried out using maximum and minimum temperature data and the Hargreaves and Samani Model. The maximum and minimum temperature data was measured using BMP 108 sensor, which was incorporated into a designed Arduino-based solar power parameter measuring system and logged into a PC. The temperature data were measured and recorded from 28th – 31st May, 1-3rd June, 19th-21st June 2021.

For the selected days, the estimated extraterrestrial solar irradiation varies from 10.41kWh/m^2 to 10.47 kWh/m^2, while the mean extraterrestrial solar irradiation is 10.44 kWh/m^2. The estimated global solar irradiation varies from 4.42 kWh/m2 to 5.677kWh/m^2, while the estimated mean global solar irradiation is 5.19kWh/m^2 per day. The estimated diffuse solar irradiation varies from 3.46kWh/m^2 to 5.48kWh/m^2, while the mean diffuse solar irradiation is per day is 4.61kWh/m^2. **Then what?**

References

Abood, A. A. (2015). A comprehensive solar angles simulation and calculation using matlab. *INTERNATIONAL JOURNAL OF ENERGY AND ENVIRONMENT* .

Alsamamra, H. (2015). A comparative study of various models for estimating global solar radiation in hebron city, Palestine. *International Journal of Current Research*.

Angstrom, A. (1924). Solar and terrestrial radiation. Report to the international commission for solar research on actinometric investigations of solar and atmospheric radiation. *Quarterly Journal of Meteorological Society* , 50.

Bhatia, S. (2014). Advanced Renewable Energy Systems.

Chiemeka, I. U. (2008). Estimation of solar radiation at Uturu, Nigeria. *International Journal of Physical Sciences, 3*, 126-130.

Chineke, T. (2007). Renewable Energy: Equations for Estimating Global Solar Radiation Data Sparse Regions. *Science Direct*, 1-13.

Duffie, J., Beckman, W., & Worek, W. (2003). *Solar Engineering of Thermal Processes* (4th ed., Vol. 116). New York: Willey.

Garner, R. (2018, 4th May). Solar Irradiance. Retrieved from http://www.nasa.gov/mission_pages/sdo/science/solar-irradiance.html

Hannah Ritchie, M. R. (2019). *Access to Energy.* Retrieved from OurWorldInData: https://ourworldindata.org/energy-access

Hargreaves G.H, S. Z. (1982). Estimating potential evapotranspiration. *J Irrig Drain Eng.*

Hargreaves GL, H. G. (1985). Irrigation Water Requirements for Senegal River Basin. *Journal of Irrigation and Drainage Engineering*, 264-275.

Hargreaves, G. L. (1985). Irrigation Water Requirements for Senegal River Basin. *J..irrig. & Drain. Engr.*, 264-275.

Oladimeji, I. ,. (2020). DESIGN AND CONSTRUCTION OF ANARDUINO-BASED SOLAR POWER PARAMETER-MEASURING SYSTEM WITH DATALOGGER. *ARIDZONEJOURNALOFENGINEERING,TECHNOLOGY&ENVIRONMENT*.

Prescott, J. A. (1940). Evaporation from Water Surface in Relation to Solar Radiation. *Transactions of the Royal Society of South Australia*, 114-118.

Rani, H. P. (1982). Theoretical and experimental studies on collector/storage type solar water heater. *Solar Energy, vol. 29*, 467-478.