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Development of a Low-Cost Global Radiation Sensor Using Locally Sourced Materials

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Abstract **- This study presents the design, construction, calibration, and performance evaluation of a low-cost global radiation sensor developed using locally available materials and electronic components. The performance of the constructed global radiation sensor (CGRS) was evaluated against a standard Apogee SP-110 pyranometer installed at the WASCAL Meteorological Observatory, Federal University of Technology, Akure, Nigeria. Comparative measurements were conducted over a two-day field-testing period, and the sensor performance was assessed using statistical indicators, including the correlation coefficient (R), root mean square error (RMSE), mean bias error (MBE), and standard deviation. The results showed a correlation coefficient of 0.69, an RMSE of 0.1764 W/m², and an MBE of minus 0.0104 W/m², indicating a relatively good relationship and low systematic bias between the constructed and reference sensors. A third-order polynomial calibration equation was developed to improve the agreement between the two instruments. The findings demonstrate the potential of the constructed sensor as an affordable alternative for global solar radiation monitoring, particularly in resource-constrained environments. However, further calibration and long-term field validation are necessary to establish its reliability under varying atmospheric and environmental conditions.**

Keywords - Low-cost sensor; Global solar radiation; Sensor calibration; Pyranometer; Solar radiation monitoring; Meteorological instrumentation.

I. INTRODUCTION

Several researchers have investigated the development and performance evaluation of low-cost solar radiation measuring instruments. [3] presented a study titled *Construction of a Reliable Model Pyranometer for Irradiance Measurements*. Their work contributed to the development of locally constructed radiation measurement instrumentation and demonstrated the relevance of affordable pyranometer designs for solar radiation monitoring in Nigeria.

Similarly, [7] developed a low-cost solar irradiance instrument using locally sourced materials. Their instrument incorporated a BPW34 photodiode enclosed in a glass bulb, a signal-conditioning amplifier, an ADS1115 16-bit analogue-to-digital converter, an Arduino Mega 2560, an LCD, and a microSD storage module. The developed instrument was calibrated against an SRS100 pyranometer. Their results showed a correlation coefficient of 0.89 and an estimated measurement error of 9.67%. The authors also reported good agreement between the developed instrument and the reference pyranometer during the main daylight measurement period, although differences occurred during early morning and late afternoon periods. These findings demonstrate the feasibility of using relatively inexpensive electronic components to develop functional solar radiation monitoring instruments in Nigeria [7].

In another Nigerian study, [1] developed a low-cost solar pyranometer using a photodiode, thermistor, and other readily available electronic components. The instrument was calibrated using a reference pyranometer, and the reported daily mean global solar radiation was 16.00 MJ/m²/day, with a maximum value of 20.70 MJ/m²/day during the observation period. The study further highlighted the potential of locally developed instruments for improving access to solar radiation measurements.

[6] extended this research by comparing the performance of different optoelectronic sensing components. Their results indicated that phototransistors could provide better measurement accuracy than the tested photodiodes under the experimental conditions. This finding suggests that selecting an appropriate sensing component is an important consideration in developing affordable solar radiation instruments.

At the international level, [2] presented *A New and Inexpensive Pyranometer for the Visible Spectral Range*. Their design employed a silicon photodiode and incorporated features intended to improve measurement reliability, including noise immunity, temperature regulation, and reduction of cosine-response errors. The study demonstrated that photodiode-based instruments could provide a less expensive alternative for solar irradiance monitoring, particularly where instrument acquisition costs are a major consideration. However, the instrument's visible spectral range must be distinguished from the full broadband response required for conventional global solar irradiance measurements. Furthermore, [8] developed an embedded system for measuring ground-based solar irradiance. Their design focused on reducing directional-response errors, improving environmental protection, and providing remote monitoring capabilities. Their work demonstrated the importance of integrating sensor design with electronic data acquisition and communication technologies in the development of low-cost solar radiation instruments.

More recently, [5] investigated the development and evaluation of solar radiation sensors using cost-effective light sensors and machine learning techniques. Their study explored the use of affordable ambient light sensors alongside statistical and machine-learning approaches for estimating solar irradiance. This research illustrates the continuing interest in developing alternative radiation measurement systems that reduce the cost of conventional instrumentation while improving the availability of solar radiation data. Collectively, these studies demonstrate that low-cost radiation sensors can provide useful measurements when appropriate sensing

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elements, electronic circuits, calibration procedures, and validation techniques are employed.

Calibration is an essential stage in the development of any solar radiation measuring instrument. It establishes the mathematical relationship between the electrical output of the developed sensor and the corresponding irradiance measured by a reference instrument. In low-cost solar radiation sensors, calibration is particularly important because variations in the characteristics of the sensing elements, electronic components, and environmental conditions may influence the output signal. A commonly adopted approach involves placing the developed sensor alongside a reference pyranometer under similar environmental and exposure conditions. Simultaneous measurements are collected over a suitable range of solar radiation intensities, after which the relationship between the output of the developed sensor and the reference measurements is established using regression analysis. The importance of calibration and correction is demonstrated by [4], who investigated the differences between silicon-based sensors and thermopile pyranometers. They identified temperature effects, cosine-response errors, spectral mismatch, and calibration factors as important sources of measurement differences. Their correction approach reduced the relative root mean square difference between daily solar irradiation measurements from 10.6% to 5.4%. This demonstrates that calibration may need to account for more than the electrical response of the sensing element alone.

The [9] also emphasises the importance of instrument exposure, maintenance, calibration, and measurement traceability in obtaining reliable meteorological observations. For evaluating the performance of a developed solar radiation sensor, statistical indicators such as mean bias error (MBE), root mean square error (RMSE), standard deviation (STDEV), and Pearson's correlation coefficient (R) are commonly employed. These parameters provide information about systematic measurement bias, the magnitude of measurement errors, the dispersion of the differences, and the strength of the relationship between the developed and reference instruments. Consequently, the combined application of calibration equations and statistical performance indicators provides a useful framework for determining the suitability of locally developed radiation sensors for meteorological and renewable energy applications.

II. METHODOLOGY

A. *Materials and Methods (Design processes of the low- cost solar radiation sensor)*

The flowchart of the design of the digital electronic system for the low-cost solar radiation is shown in Figure 1 with each block unit making particular output.

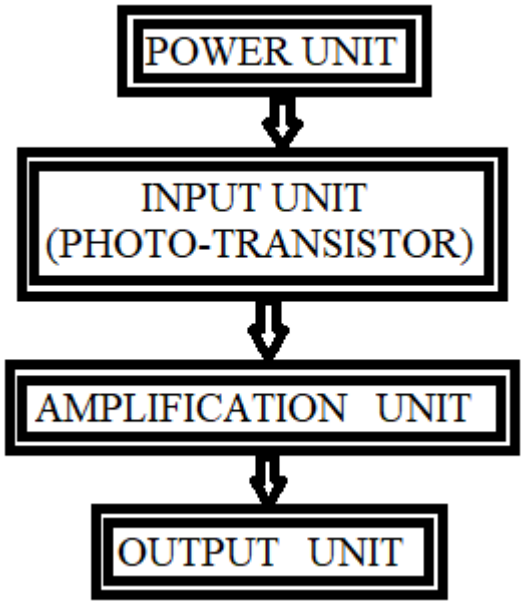


Fig. 1: A Flowchart for the Global Radiation Sensor that has been Designed.

B. *Power Supply Unit*

Figure 2 illustrates how the power supply circuit is made to supply the system with low voltage between 5 and 12 volts. A DC power source is utilized internally because digital equipment is highly sensitive to voltage. The three-terminal adjustable regulator, bridge rectifier, which is implemented as a network of IN4001 diodes, is the unit's first component. A 2200 F, 25 V, and 0.1 F capacitor pair filters away fluctuations and ripples that are superimposed on the rectifier DC voltage. The output DC voltage was amplified and regulated using the transistors TIP 42C, D882, C9014, and a three-terminal adjustable regulator. The three-terminal adjustable regulator controls the DC supply and serves as a voltage regulator, making the internal voltage independent of changes in main outlet voltage that might happen while the digital access monitor is in use.

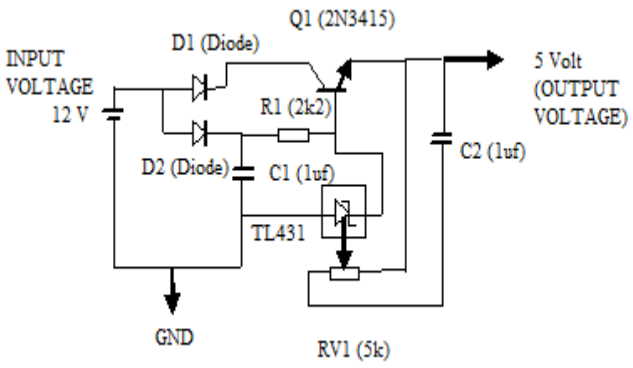


Fig. 2: Power Supply Circuit Diagram.

Figure 4 illustrates how LM358 is used as an amplifier to boost the output voltage from the photo-transistor, or incoming radiation.

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Fig. 3: Diagram of the input device (Photo-transistor).

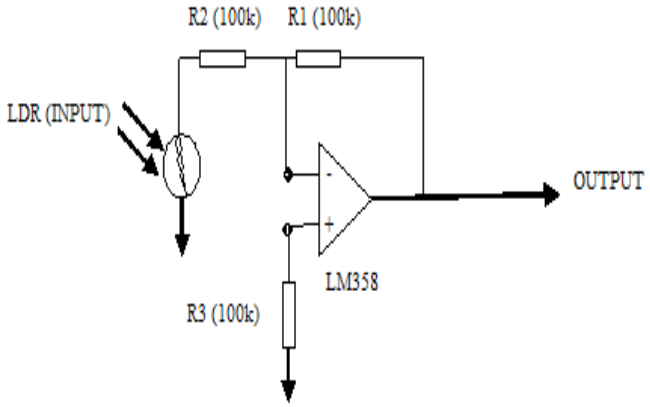


Fig. 4: Amplifier Circuit Diagram.

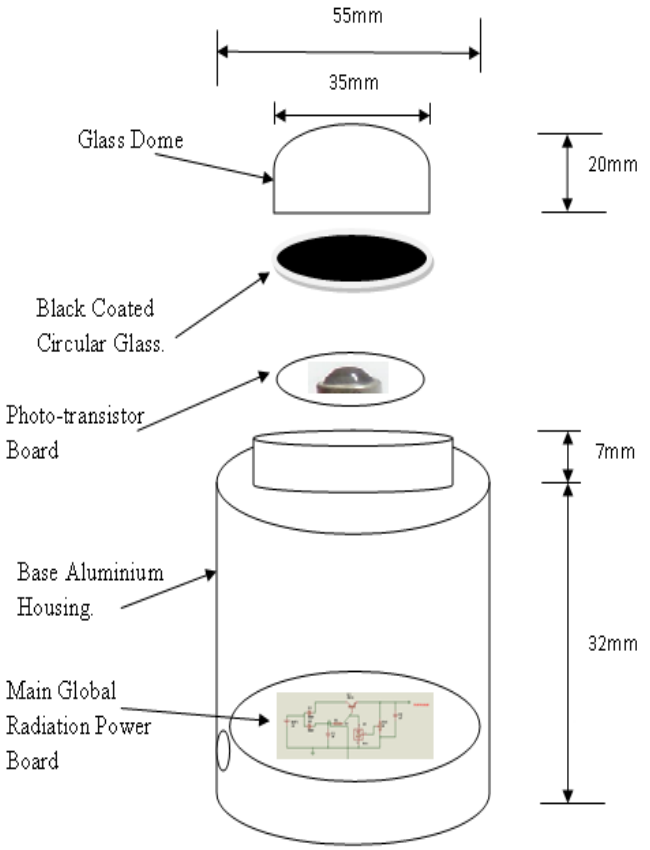


Fig. 5: 3-D Designed Global Radiation Sensor.

Radiation sensors were design using photo-transistor technology as an active sensor Figure 3 above. A photo-transistor is a light-dependent electrical switching and current-amplification component Figure 4. It has the ability to transform light energy into electrical energy. Reverse current, which flows when light hits the junction, is proportional to brightness. In order to detect light pulses and transform them into digital electrical signals, photo-transistors were widely utilized.

The wavelength of incident light affects a photo-transistor's output. A wide range of light wavelengths, including those in the near ultraviolet (UV), visible, and near infrared (IR), are responsive to phototransistor technology. The maximal spectral response occurs in the near IR at about 840 nm, absent the usage of optical filters. The peak response occurs at a wavelength that is slightly shorter than that of a normal photodiode. This is due to the fact that epitaxial silicon wafers, rather than silicon crystals, are employed to generate the dispersed junctions of a phototransistor.

A photo-transistor is a device that combines a photodiode and a transistor; it has a higher output current than a photodiode. A junction transistor with only the collector, emitter, or base leads, with the base exposed to light through a small lens in the housing; collector current rises with light intensity as a result of the transistor's amplifying the base current. Figure 5 shown the 3-D design Global Radiation Sensor.

C. The Materials used for Constructing Global Radiation Sensor are:

Ferro board was cleaned after being cut to the necessary size (3 cm in diameter), and then soldered with a photo-transistor Figure 6. By soldering the base and emitter of the npn (base-emitter-collector) phototransistors together and connecting them in parallel, they are connected as photodiodes.



Fig. 6: Preparation of ferro board for soldering photo-transistor.

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Fig. 7: Radiation shield.

In order to protect the sensor (photo-transistors) from being burned by direct radiation, a circular glass was painted black with black abro spray paint. The spherical glass had a black coating under Figure 7 above.

The global radiation sensor was built specifically for the glass dome. It was first blown to a spherical bottom before being chopped in half. Glass was blown and cut in the Federal University of Technology glass blowing workshop, which is located in Akure, Nigeria. Glass was chosen because it keeps air out of the pyranometer and lets only shortwave radiation through Figure 8.

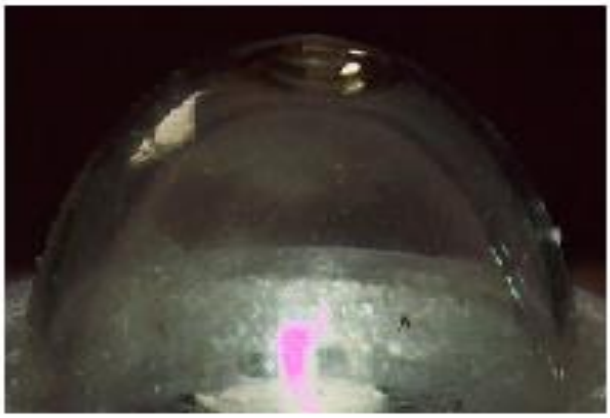


Fig. 8: Glass dome global radiation

The body of the global radiation sensor is made of aluminum at the mechanical workshop, Federal University of Technology Akure, Nigeria Figure 9. The glass dome used for the global radiation sensor allows only shortwave radiation to reach the sensing element. The dome's purpose is to protect the phototransistor sensor from convectional heat transfer caused by air particle circulation. After that, white silicone sealer was used to fill it (a water resistance substance or moisture absorber). The complete constructed global radiation sensor Figure 10.



Fig. 9: Casing for global radiation sensor.



Fig. 10: Complete constructed sensor for global radiation sensor.

D. Calibration of the Constructed Low-Cost Global Radiation Sensor.

To evaluate how closely instrument output matches each other over the anticipated range of operation, calibrations include comparing a manufactured sensor to a standard sensor. When an instrument is calibrated in a lab, it is implicitly assumed that its properties are stable enough to maintain the calibration in the field. The built-in global radiation sensor was calibrated using the WASCAL observatory's Global Radiation Sensor Model: SP-110 Table 2, referred to as the reference sensor in this paper. The performance of the created sensor was compared to the regular sensor during its installation and testing period of two days. Using the well-known statistical performance measures, such as the correlation coefficient (R), root mean square error (RMSE), mean bias error (MBE), and standard deviation, the observed data from the manufactured sensor was compared with the data acquired from the reference sensor.

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III. Results and Discussion

Figure 11 displays the scatter plot from which the global radiation calibration equation is derived. This equation is a polynomial equation of order three ($y = ax^3+bx^2+cx + d$), where m is the slope and d is the intercept (in our case the offset). The offset is the result of different error causes, some of which are engineering-related and others which are related to environmental factors.

A. Performance Evaluation of the Sensor

The performance of the built-in sensor in comparison to WASCAL Meteorology observatory standards is shown in Table 1. The R values clearly demonstrate that the data from the built-in global radiation sensor and the correlations are quite good (0.69).

Table 1: Results of statistical analysis of the constructed sensor.

Constructed Sensor	MBE	RMSE	STDEV	R
Global Radiation	-0.01036	0.176444	95.758	0.690

From the MBE and RMSE values, it was noticed that the error margins between the constructed and the standard sensors were quite small, indicating high performance of the sensor. Table 1 also included the MBE value for the global radiation sensor, which was -0.01036W/m^2, and the RMSE value for the global radiation sensor, which was 0.176444W/m^2. A modest underestimating of the standard's values is indicated by the fact that the MBE for global radiation is negative. Table 3 displays the calibration equation, sensitivity, calibration constant, and offset value for the individual sensors found in Figure 11 along with their respective values.

Figure 12 showed the variance in global radiation observed on days 1 and 2 at Akure, Nigeria, using the constructed global radiation sensor and the standard. The equipment used to calibrate and test the created sensor's functionality are mentioned in Table 2, while Table 3 shown the correlation coefficient and sensitivity analysis of the constructed sensor below.

Table 2: List of the instrument deployed during the calibration and performance of the constructed sensor.

Parameters	Device and model	Manufacturer	Accuracy	S/No
Global Radiation	Global Radiation Sensor. model: SP-110	Apogee Instrument	0.2mV/W/m^2,	95047

Table 3: Correlation coefficient and sensitivity analysis of the constructed sensor.

Constructed Sensor	Calibration Equation	Sensitivity	Calibration Constant	Offset
Global Radiation	$-1.431x^3 + 31.28x^2 - 136.6x + 5.773$	0.0317864 mv/W/m^2	31.46 W/m^2/mv	+ 5.773

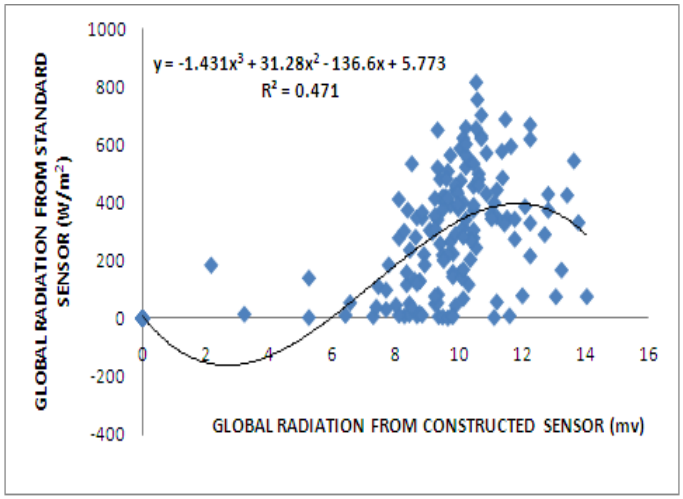


Fig. 11: Calibration of constructed global radiation against standard global radiation.

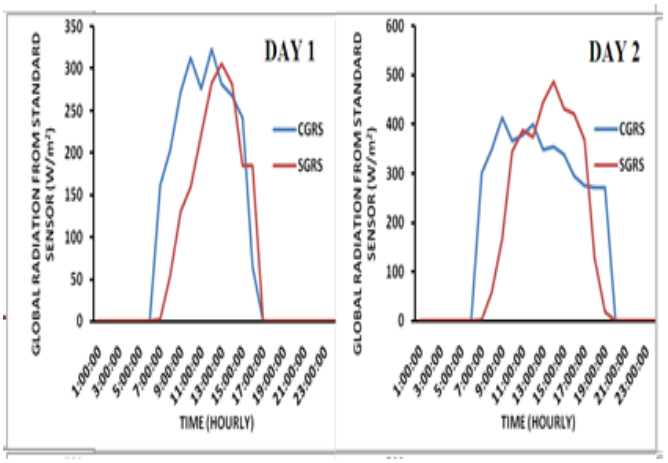


Fig. 12: The difference in global radiation measured on days 1 and 2 in Akure, Nigeria, using the constructed global radiation sensor (CGRS) and the standard global radiation sensor (SGRS).

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IV. Equations

The voltage gain equation is:

$$A_v = -\frac{R_1}{R_2} \quad (1)$$

Where A_v is voltage gain of the operational amplifier, R1 is feedback resistor (100 kΩ) and R_2 is input resistor (100 kΩ) Substituting the resistor values (1)(2):

$$A_v = -\frac{100k\Omega}{100k\Omega} \quad (2)$$

$$A_v = -1$$

The output equation and voltage is given by:

$$V_{out} = -\frac{R_1}{R_2} V_{in} \quad (3)$$

Since R_1 equal to R_2 equal to 100kΩ (3).
The following are the mathematical equations for evaluating the performance of your developed low-cost global radiation sensor against a reference instrument (standard sensor).

A. Mean Bias Error (MBE)

MBE measures the average bias or systematic error between the measured values from the developed sensor and the reference sensor (4).

$$MBE = \frac{1}{N}\sum_{i=1}^{N}(P_i - O_i) \quad (4)$$

B. Root Mean Square Error (RMSE)

RMSE measures the average magnitude of errors between the developed sensor and the reference instrument (5).

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)\text{^}2} \quad (5)$$

C. Standard Deviation (STDEV)

Standard deviation (6) measures the dispersion of the differences between the developed sensor and reference sensor.

$$STDEV = \sqrt{\frac{\sum_{i=1}^{N}(d_i - \bar{d})\text{^}2}{N-1}} \quad (6)$$

Where:

$$d_i = P_i - O_i$$

$$\bar{d} = \frac{1}{N}\sum_{i=1}^{N} d_i$$

D. Correlation Coefficient (R)

The Pearson correlation coefficient measures the strength and direction of the linear relationship between the developed sensor readings and the reference instrument readings (7).

$$R = \frac{\sum_{i=1}^{N}(P_i - \bar{P})(O_i - \overline{O})}{\sqrt{\sum_{i=1}^{N}(P_i - \bar{P})^2 \ \sum_{i=1}^{N}(O_i - \bar{O})\text{^}2}} \quad (7)$$

Definition of symbols for equations (4 to 7), where $\bar{P}$ is mean of developed sensor measurements; $\bar{O}$ is mean of reference sensor measurements; $\bar{d}$ is mean difference; P_i is measurement from the developed sensor; O_i is measurement from the reference sensor; d_i is difference between paired measurements; and N is total number of paired observations.

CONCLUSIONS

The design, construction, and calibration of a low-cost global radiation sensor have been achieved. At the Federal University of Technology, Akure's WASCAL Meteorological Observatory, the data from the developed sensor was compared to that from a standard sensor. A calibration coefficient of correlation was provided by Nigeria and the proposed global radiation sensor (0.686). The developed sensor was proven to be workable and field deployed, and it may be made locally with freely available components.

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I also appreciate the technical assistance, facilities, and institutional support received during the design, fabrication, installation, and testing of the instrument. Finally, sincere appreciation goes to all individuals whose contributions and encouragement supported the successful completion of this research.

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