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Comparison of the sensitivities and accuracies of optoelectronic transducers for solar irradiance measurement

Abstract

This paper compares the sensitivities and accuracies of four different optoelectronic transducers in measuring solar irradiance for the fabrication of portable and low-cost pyranometers. Trans-impedance conditioning circuits were designed for two phototransistors (BP103 and SFH3310) and two photodiodes (BPW21 and BPW34). The Arduino Mega 2560 was used as an interface between the analogue signal produced by the conditioning circuits and the digital output ports. The transducers with a standard pyranometer RSRA_05V were arranged on a vero board and exposed to the sun. Statistical analysis of the experimental results produced the least root mean square error value of 6.58794 W(m^−2) for phototransistor BP103 during the dry season followed by 13.35216 W(m^−2) for phototransistor SFH3310 during the dry season. The correlation coefficients of BPW21, BPW34, BP103, and SFH3310 with the standard pyranometer are 0.9489, 0.9916, 0.9976, and 0.9905, respectively. The experimental results obtained from the phototransistors BP103 and SFH3310 strongly correlated with those of the standard pyranometer coupled with lower root mean square error and mean bias error values than those of the photodiodes. Thus, the phototransistors BP103 and SFH3310 are more accurate and effective for measuring solar irradiance. This study contributes to the development of low-cost and accurate solar radiation meters.

Keywords

- Pyranometer: Device measuring solar irradiance.
- Transducers: Convert solar energy to electrical signals.
- Optoelectronic: Devices combining optics and electronics.
- Arduino Mega 2560: Microcontroller for data interface.
- RMSE (Root Mean Square Error): Measure of prediction accuracy.
- Correlation Coefficient: Indicates variable relationship.
- Bias Error: Difference between expected and measured values.
- Standard Pyranometer (RSRA-05V): Reference device for comparison.
- Radiant Sensitivity Area: Sensor area responding to radiant energy.

Paper

Solar irradiance is the primary source of energy on the earth and a major contributing factor to several other phenomena such as global or regional climate variations, ecosystems, telecommunication, and renewable energy applications. In recent years, diverse solar power systems are continuously installed worldwide as a measure to combat the negative impacts of climate change and global warming caused by greenhouse gasses from fossil fuels. The relevance of solar irradiance measurement in optimizing the performance of these power systems cannot be over-emphasized). For instance, the design of highly efficient solar photovoltaic (PV) systems mostly requires the estimation of global irradiation incidents on the earth's surface. Similarly, solar irradiance measurements are attracting increasing attention in agriculture where impact assessment of solar radiation is of utmost importance. Moreover, accurate measurements of solar irradiance play a critical role in the development and validation of radiation models widely utilized in solar resource assessments and energy simulations.

Solar radiation can be evaluated either in the form of total solar irradiance outside the earth's atmosphere using satellites or as global solar irradiance at the earth's surface by utilizing ground-based instrumentation such as pyranometers. Generally, satellite data are usually used in combination with ground data to determine inter-annual variability and long-term mean values. In the construction of a solar power plant, ground measurements normally exhibit incredibly greater accuracies compared to satellite data concerning the general guidelines for choice of location, instrument, system maintenance, and monitoring for optimum performance.

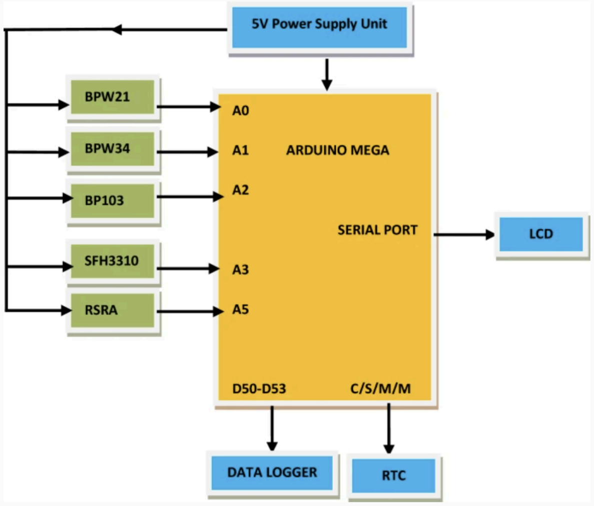
For most system applications, reasonable accuracy at a low cost is usually preferred over high accuracy at a high cost in measuring global solar irradiance. The pyranometers that give accurate readings are quite expensive and hence not used extensively. Consequently, there is a growing demand for inexpensive devices for accurate monitoring of solar irradiance. In meeting this demand, a wide range of low-cost pyranometers consisting of different optoelectronic devices have been reported by researchers. For instance, Tohsing et al. (2019) developed a low-cost pyranometer by using a phototransistor BPX43-4. Arduino Pro mini ATmega328P microcontroller was used as an analogue–digital converter (ADC). The components were assembled in FB05 for protection against environmental conditions. A Teflon sheet with a thickness of 1.0 mm was used as a solar radiation attenuator to prevent the transducer from saturation. Irradiance obtained from the model pyranometer CM21 and the prototype pyranometer were logged at 2-min intervals. Analysis shows that the sensitivity of the prototype was 1.65 mV/W.m−2 , mean bias difference −14.4%, and root mean square difference 15.5%. The difference might be due to the limitation of the field of view and the non-linearity of spectra between the pyranometers. According to the authors, the sensitivity of the prototype is satisfactory but can be investigated further for greater accuracy. Likewise, Rocha et al., (2021) developed a low-cost, surface solar radiation measurement system utilizing photodiodes BPW34 as transducers with a spectral range of 300–1400 nm integrating Internet of Things technology. The performance of the proposed system strongly correlated with that of the government meteorology station (INMet pyranometer) giving correlation coefficients (R2) of above 0.95. The authors reported that the solar irradiance meter functions like pyranometers built on thermopiles offering high accuracy, low maintenance cost, and wide applications in climatology and power generation. Moreover, Roy et al., (2021) fabricated a low-cost pyranometer using five phototransistors L14G2 connected in parallel and in series with a load resistor. The phototransistors were evenly placed on a semi-spherical body at an altitude of 11 m. The analogue voltage signal across the load resistor that is proportional to the irradiance level was converted to a digital signal by ATmega32L. The transmitter/receiver circuit was incorporated into the system to transmit the data from a remote area to the base station. The digital output was logged at an interval of 30 min for different weather conditions. Data analysis between the developed system and the standard pyranometer LP PYR 10 shows a mean bias error of −0.2819 W(m^−2), mean square error of 2.40 W(m^−2), mean absolute error of 1.27%, and an average directional response error of 6.76%. Their system provides an approach to acquire, compress, and store the solar irradiance signal and transmit it from remote areas to the base station.

Although several low-cost optoelectronic transducers for solar irradiance measurement have been reported in the literature, their accuracies are markedly lower than those of expensive standard pyranometers. Therefore, this study aims to develop a low-cost solar radiation meter with a very high accuracy comparable to that of a standard pyranometer. To achieve this, the sensitivities and accuracies of four optoelectronic transducers were compared to those of a standard pyranometer (RSRA-05 V) using statistical analysis tools such as correlation coefficient, the mean bias error, the root mean square error, and the standard deviation to identify suitable optoelectronic transducers for accurate measurements of solar irradiance. The novelty of this study lies in the use of Arduino Mega 2560 with an exceptionally high data logging rate of 6 s which is comparable to those of the standard pyranometers of 1 s.

Material and methods

The block diagram for the comparison of solar radiation transducers is illustrated in Fig. 1. It consists of six main modules: photodiode or phototransistor, standard pyranometer, conditioning circuit, integrated development environment (IDE), power supply unit/battery, memory, real-time clock (RTC), and output screen (LCD).

Fig. 1



Block diagram for the comparison of the four solar radiation transducers (BPW21, BPW34, BP103, SFH3310) using a standard pyranometer (RSRA) as the benchmark

The power supply unit/battery delivers 5 V and 10 V to power the solar irradiance measuring system. Transducers transform the solar energy received from the sun into electrical energy which is fed into the conditioning circuits to create the set-point for the output voltage of the transformed solar radiance. The optoelectronic transducers are usually calibrated using a standard pyranometer (RSRA-05 V) with its output connected to one of the analogue inputs of the Arduino Mega 2560 which performs the analogue to digital conversion (ADC). The converted digital signals are fed into the memory (data logger) and to the LCD. The Arduino circuit operates as a processor and does not store data. The digital output data obtained from the

Arduino circuit are stored in the memory. The output data from the Arduino circuit are monitored through the output screen.

Furthermore, the solar radiation of the wet season on 14 October 2021 and 20 October 2021 and dry season on 16 November 2021 and 3 January 2022 at the study location (Ede in southwestern Nigeria, 7° 44′ 20″ N latitude, 4° 26′ 10″ E longitude) was plotted against time and displayed in Figs. 13, 14, 15, 16. The four days chosen for solar irradiance measurement are good representations of the two major weather seasons in Nigeria: the wet season starts in March and ends in October, while the dry season usually begins in November and terminates at the end of February.

The mean bias error and root mean square error of the four optoelectronic transducers in measuring the solar irradiance of the wet season on 14 October 2021 and 20 October 2021 and dry season on 16 November 2021 and 3 January 2022 at the study location are shown in Table 2.

Considering the solar irradiance measurement during the wet season on 14 October 2021, the RMSE value for photodiode BPW21 is 65.8387 W(m^−2) which is relatively high compared to other optoelectronic transducers. Similarly, the RMSE for phototransistor SFH3310 is 9.5747 W(m^−2) indicating that the phototransistor correlates strongly with the standard pyranometer RSRA.

On the wet day of 20 October 2021, the degree of correlation is significant between 11:21 and 14:27 with solar irradiance of 386.712 W(m^−2) and 537.876 W(m^−2) , respectively, except for photodiode BPW34 that deviates (Fig. 14). There is a significant difference between the solar irradiance measurements of the four optoelectronic transducers and that of the standard pyranometer RSRA at 09:00–11:21 and 15:05–17:00 (Fig. 14). Despite the difference, photodiode BPW34 has the minimum MBE value of 0.1191 W(m^−2) . However, phototransistor BP103 has an RMSE value of 6.5879 W(m^−2) indicating a good correlation with the standard pyranometer compared to other transducers with higher RMSE values.

Moreover, there is a strong correlation between phototransistor BP103 and standard pyranometer RSRA on the dry day of 16 November 2021 (Fig. 15) with MBE of 3.0164 W(m^−2) and RMSE of 22.0249 W(m^−2) (Table 2) which implies that BP103 has a very good sensitivity at that period and is suitable for pyranometer transducer. As illustrated in Fig. 15, the four transducers have strong correlations with the standard pyranometer RSRA from 09:02 to 14:54, but there is a marked difference in irradiance measurements between 14:54 and 17:02. Photodiodes BPW21 and BPW34 exhibit MBE of −48.7466 W(m^−2) and −15.2427 W(m^−2), respectively, suggesting that the transducers over-estimated the measured data which may be largely due to dusty atmosphere or any other weather condition. Phototransistor SFH3310 with MBE of 28.4711 W(m^−2) demonstrates that the transducer under-estimated the measured data which could be attributed to solar radiation angle of incidence or weather conditions.

Furthermore, phototransistors BP103 and SFH3310 exhibited a strong correlation with the standard pyranometer RSRA in measuring the solar irradiance on the dry day of 3 January 2022 as depicted in Fig. 16. The RMSE value for BP103 and SFH3310 were 19.4983 W(m^−2) and 13.3521 W(m^−2), respectively, while the photodiodes displayed higher RMSE values 64.0275 W(m^−2) and 40.4330 W(m^−2) for BPW21 and BPW34, respectively. Between the hours of 12:21 and 13:28, there was a significant difference in irradiance measurements by the standard pyranometer and the transducers except for phototransistor BP103 which may be due to variation in temperature.

The measurement standard deviations of the four optoelectronic transducers are compared to those of the standard pyranometer RSRA as depicted in Table 3.

The measurement standard deviations of the four transducers on wet days of 14 October 2021 and 20 October 2021 are relatively lower than that of the standard pyranometer (Table 3). The lowest standard deviation of 66.62 W(m^−2) in the solar irradiance measurements was delivered by phototransistor SFH3310 on the wet day of 20 October 2021. Similarly, photodiodes BPW21 and BPW34 displayed standard deviations of 174.29 and 218.54 W(m^−2), respectively, lesser than that of the standard pyranometer, for the solar irradiance measurements captured on the dry day of 16 November 2021. However, the standard pyranometer exhibited the lowest standard deviation of 45.53 W(m^−2) in the measurement of solar irradiance on the dry day of 3 January 2022, closely followed by phototransistor BP103 with a standard deviation of 46.82 W(m^−2).

Moreover, to demonstrate the cost-effectiveness of the proposed pyranometer compared to a standard pyranometer, the price of fabricating the proposed pyranometer using phototransistor BP103 is presented in Table 4. While the cost of a standard pyranometer is 95 US dollars (excluding shipping fees and import duties), a locally fabricated phototransistor-based pyranometer costs just a modest sum of 4.45 US dollars. Hence, the proposed pyranometer is much cheaper than the standard pyranometer RSRA_05 V.

The sensitivities and accuracies of four optoelectronic transducers–two phototransistors (BP103 and SFH3310) and two photodiodes (BPW21 and BPW34)–have been compared to those of a standard pyranometer RSRA. Arduino Mega 2560 was used as an interface between the analogue signal produced by the conditioning circuits and the digital output ports. In this study, the use of Arduino Mega 2560 with an exceptionally high data logging rate of 6 s which is comparable to those of the standard pyranometers of 1 s was demonstrated. Statistical analysis was carried out using the correlation coefficient (R2), the mean bias error (MBE), and the root mean square error (RMSE) to compare the performance of the optoelectronic transducers to that of the standard pyranometer. The significant findings of this study are the following:

- The correlation coefficients of BPW21, BPW34, BP103, and SFH3310 in comparison to standard pyranometer RSRA are 0.9489, 0.9916, 0.9976, and 0.9905, respectively.
- Phototransistor SFH3310 displayed the lowest RMSE values of 9.5747 and 13.3521 W(m^−2) on the wet day of 14 October 2021 and dry day of 3 January 2022, respectively, indicating that the phototransistor correlates strongly with the standard pyranometer RSRA.
- Similarly, phototransistor BP103 recorded the lowest RMSE values of 6.5879 W(m^−2) on the wet day of 20 October 2021, signifying a good correlation with the standard pyranometer compared to other transducers with higher RMSE values.
- A strong correlation was observed between phototransistor BP103 and standard pyranometer RSRA on the dry day of 16 November 2021 with the lowest MBE of 3.0164 W(m^−2) and the lowest RMSE of 22.0249 W(m^−2), implying that the phototransistor has an outstanding sensitivity at that period which qualifies it for pyranometer transducer.

- Therefore, based on the experimental results obtained, phototransistors BP103 and SFH3310 are more accurate and effective in measuring solar irradiance than the photodiodes BPW21 and BPW34.

Paper 2: Energy Sustainability/Engineering

Question 1

Question: In the paper we can see that system applications can measure global solar irradiance. When examining most system applications regarding solar irradiance what is generally preferred as the main criteria?

a.) Reasonable accuracy at a low cost is usually preferred in measuring global solar irradiance.

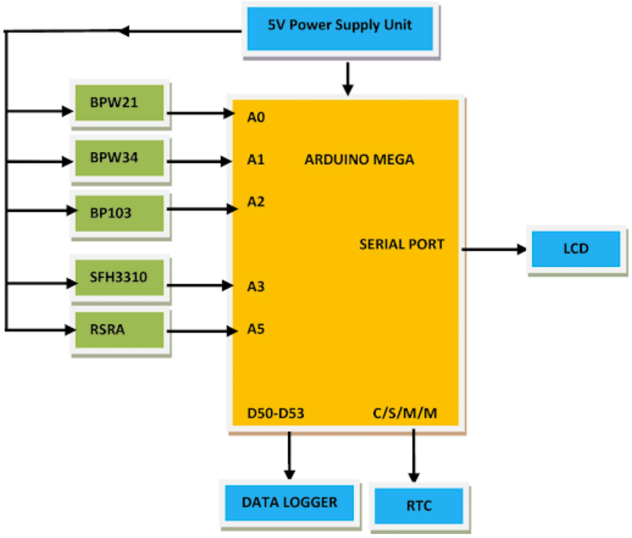
b.) High accuracy at a high cost is usually preferred in measuring global solar irradiance.

c.) Low accuracy at a low cost is usually preferred in measuring global solar irradiance.

d.) Reasonable accuracy at a reasonable cost is preferred in measuring global solar irradiance.

Question 2

Question: When looking at the block diagram for the comparison of the four solar radiation transducers (BPW21, BPW34, BP103, SFH3310) using a standard pyranometer (RSRA) as the benchmark what component makes this study novel?



a.) RSRA (Standard pyranometer)

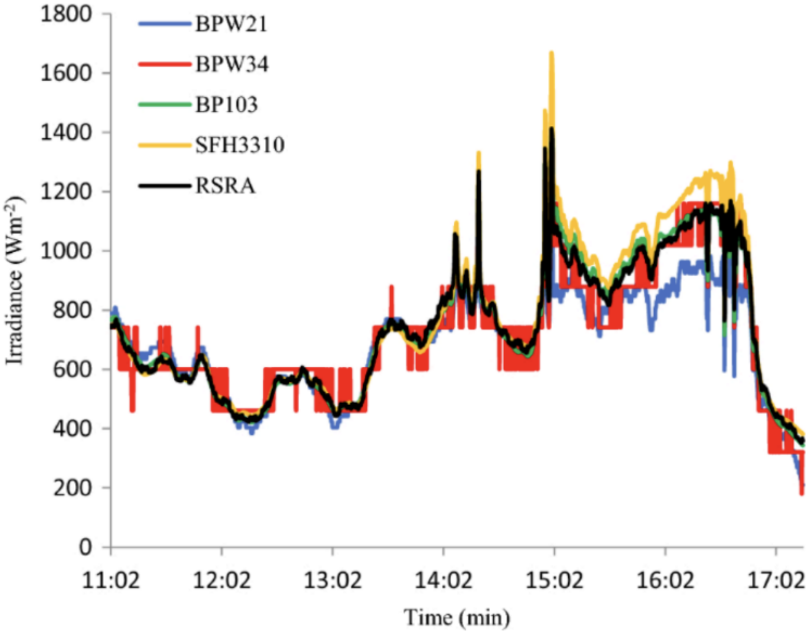
b.) Solar transition transducer BP103

c.) Solar transition transducer BPW34

d.) Arduino Mega 2560

Question 3

Question: When looking at the figure, the four transducers have strong correlations with the standard pyranometer RSRA from 09:02 to 14:54, but there is a marked difference in irradiance measurements between 14:54 and 17:02. Photodiodes BPW21 and BPW34 exhibit MBE of -48.7466 Wm^{-2} and -15.2427 Wm^{-2}. This is indicative of what when pertaining to the study in specific?



a.) Computing error where the transducers were no longer able to store data within themselves and produced varying results.

b.) Transducers over-estimated the measured data which was due to certain weather conditions.

c.) Solar radiation angle changed throughout the day and caused varying results for which the transducer was not able to account for.

d.) Change in setting of where the transducers were placed causing for varied results and outlier data points.

Question 4

Question: A strong correlation was observed between phototransistor BP103 and standard pyranometer RSRA on the dry day of 16 November 2021 with the lowest MBE of 3.0164 Wm^{-2} and the lowest RMSE of 22.0249 Wm^{-2}. When compared to phtotransitor BPW34 and standard pyranometer RSRA on the dry day of 16 November 2021 the MBE was -15.2427 Wm^{-2} and the RMSE was 40.4330Wm^{-2}. What conclusions can be made from the evidence provided?

a.) Phototransistor BP103 has an outstanding sensitivity at that period compared to BPW34 which qualifies it for pyranometer transducer.

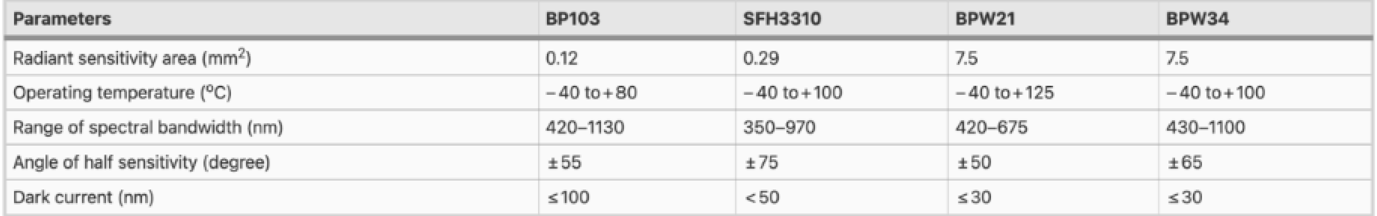
b.) Phototransistor BP103 has poor sensitivity at that period compared to BPW34 which doesn't qualify it for pyranometer transducer.

c.) Phototransistor BP103 has poor sensitivity at that period compared to BPW34 which does qualify it for pyranometer transducer.

d.) Phototransistor BP103 has an outstanding sensitivity at that period compared to BPW34 which doesn't qualify it for pyranometer transducer.

Question 5

Question: For this specific study 4 certain types of optoelectronic transducers were used to have the best solar irradiance measurement. Looking at the table down below what parameters made these 4 transducers optimal for this research study?



Parameters	BP103	SFH3310	BPW21	BPW34
Radiant sensitivity area (mm^2)	0.12	0.29	7.5	7.5
Operating temperature (^{o}C)	−40 to+80	−40 to+100	−40 to+125	−40 to+100
Range of spectral bandwidth (nm)	420–1130	350–970	420–675	430–1100
Angle of half sensitivity (degree)	±55	±75	±50	±65
Dark current (nm)	≤100	<50	≤30	≤30

a.) They radiant sensitivity area of the photodiodes for BPW21, BPW34, BP103, and SFH3310 is extremely low and they also have low operating temperature ranges.

b.) The radiant sensitivity area of the photodiodes for BPW21 and BPW34 is much greater than those of the phototransistor BP103 and for phototransistor SFH3310 indicating that the photodiodes receive more solar energy than the phototransistors.

c.) Phototransistor BP103 cannot withstand an operating temperature range of −40 to 80 °C which is the smallest but least suitable for the weather in southwest Nigeria, the location of this study. The minimum angle of half sensitivity is ±40° indicating that the performance of the transducers should be equal to almost 100°.

d.) The radiant sensitivity area of the photodiodes for BPW21 and BPW34 is much lower than those of the phototransistor BP103 and for phototransistor SFH3310 indicating that the photodiodes receive less solar energy than the phototransistors.

Question 6

Question: A hurricane wreaks havoc and all our photoiodes/phototransitors are gone! A new photoiode/phototransitor needs to be chosen for solar irradiance measurement in northeast Nicaragua. The ideal temperature in northeast Nicaragua 21°C − 27°C. is Based on the information in the paper, which of the following photoiode/phototransitor is optimal to use?

a.) Photodiode R - High sensitivity, High Cost, Operating Temperature (0 - 20)

b.) Photodiode A - Medium sensitivity, Medium Cost, Operating Temperature (0 - 10)

c.) Photodiode I - Low sensitivity, Low Cost, Operating Temperature (0 - 19)

d.) Photodiode N - High sensitivity, Reasonable Cost, Operating Temperature (0 - 26)