Journal of Engineering and Technology

ISSN 2180-3811 eISSN 2289-814X https://jet.utem.edu.my/jet/index

DEVELOPMENT OF AN EMBEDDED WIRELESS PYRANOMETER USING NODEMCU

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Article history:
Received Date: 14 July 2023
Revised Date:17 November 2023
Accepted Date: 14 May 2024

Keywords: Embedded Systems, Internet of Things, Photovoltaic, Pyranometer, Solar Module

Abstract— Solar radiation monitoring is a crucial step in estimating the size of solar modules, as well as their best position and inclination angle for maximum power generation. Standard large-scale solar radiation measurement tools are prohibitively expensive, need specialist skills to operate, and are unavailable in emerging economies. As a result, this inquiry recommends the use of a NodeMCU development board as the processing unit for a low-cost wireless pyranometer. A solar module and an ACS712-05B current sensor as the sensory unit and a 16x2 LCD screen as the display unit make up the proposed instrument. By closely monitoring the short circuit current of the module and deducing the output voltage of the current sensor, the proposed meter determines the instantaneous solar radiation. In this study, the measurements are communicated to the ThingSpeak (an Internet of Things analytics platform that sends sensor data privately to the cloud) so that the measured data could be accessed remotely. Two daystar DC-05 pyranometers geo-located for solar irradiation measurements were used to compare the proposed meter's field performance. The pyranometers' performances were found to be equivalent, each exhibiting a Root Mean Squared Error of 0.0946705 and 0.064885 respectively.

I. Introduction

It has been revealed in the studies of Engelhardt et al. [1], Kakoulaki et al. [2], Xie et al. [3], and Widiartha and Yohandri [4] that concerns about climate change and the environment have accelerated global interest in the investigation, design, and integration of renewable energy technologies in recent years. According to the United Nations [5], about 29 % of global electricity comes from renewable sources which are available in abundance and are provided by heat from the earth, wind, water, waste and sunlight. While the utilization of non-renewable energy resource has far reaching effects in terms of global environmental degradation, the diversification from hydrocarbons to combat the effects of carbon emissions capable of depleting the ozone layer and other global warming-related issues has become necessary and timely. Therefore, there is a growing need to ensure that environmentally friendly power generation alternatives are readily available and made sustainable and efficient. One of these options is a photovoltaic (PV) system, which works by capturing solar radiation released by the sun and converting it to electrical energy equivalent using solar modules and other balance of the system components.

Has reported in Poudyal et al. [6], and Allouhi et al. [7], the design and optimization performance of a PV system requires accurate and up-to-date solar irradiation of the area in which it is to be mounted and installed. This, therefore, according to Parmar [8], and Korevaar [9] prompts the need to have a very effective, workable and precise remote solar radiation meter-a pyranometer; which is used to monitor and capture solar irradiance. Although many well-funded manufacturing companies may be producing different types of pyranometers, they may not be readily accessible due to their unavailability and high cost of procurement, and the need for specialized operating knowledge. This forms the basis and motivation for the development of pyranometers by many renewable energy researchers. For instance, Nwankwo et al. [10] designed a pyranometer that employs a photodiode and a digital multimeter to indicate the amount of solar radiation captured in Abakaliki, Nigeria. Despite the design's simplicity, reading accuracy, mobility, and appropriate validations were all clear limitations. It is also noted that the study did not account for the relationship between the sensor captured solar irradiance and the short circuit current flowing through the load. This relationship unaccounted for is a sine qua non in the development of pyranometers.

The work of Matsumoto et al. [11] has revealed that, when exposed to solar radiation particles, a PIN photodiode generated a pulsed charge output. In the design described in Matsumoto et al. [11], an Arduino-uno microcontroller, an XBEE wireless module, and a RF wireless module were employed. Despite its compact size, the PIN photodiode's small surface area hindered it from accounting for shading effects. Even, the meter proposed by Matsumoto et al. [11] required a personal computer to display measured irradiance. As good as the study in Matsumoto et al. [11], it failed to account for the relationship between the solar irradiance captured by the sensor and the short circuit current flowing through the load. It is to be noted that this is an essential condition in the design of pyranometer. It was articulated in Kaiser et al. [12] that the short circuit current of a solar cell is directly related to the solar irradiance; and it is the theoretical foundations for the design of pyranometers. Therefore, the work of Kaiser et al. [12] employed a single silicon crystal to trap solar irradiance, which was then coupled across a shunt resistor, converted to digital voltage, and shown on a liquid crystal display (LCD) only. Also, a minuscule shunt resistor was employed to convert the short circuit current via the sensor to a proportional voltage across the resistive component. The work of De Barros et al. [13], which used a light dependent resistor (LDR) in the development of a solar radiation meter, demonstrated an unusual approach to the design. The LDR voltages varied with different values of resistors attached to it; since voltages increase in a logarithmic manner with incident light on the surface of the LDR. The determination of the appropriate values of the shunt resistors in Kaiser et al. [12] and De Barros et al. [13] were not direct and may be questionable.

Unlike other researchers, Mansur et al. [14] used a solar module rather than a photodiode to assess solar irradiation; since the module was thought to be a more accurate measurement method due to its vast surface area. The module’s open circuit voltage and short circuit current together with the ambient temperature were closely monitored to get the irradiance data. The voltage and current characteristics were mathematically translated to standard settings, and the irradiation meter was constructed around the electrical features and characteristics of mono-crystalline solar modules. It is worth noting that the Mansur et al. [14] did not take into account the remote wireless monitoring and measurement of the solar irradiance. But in Thakur and Sharma [15], a low cost and portable wireless solar irradiance meter was developed using a solar cell, an ADC, 8051 microcontroller, and a RF transmitter for onward transmission of the serialized 8-bit encoder output to the RF receiver. The received signal was consequently processed and the output displayed on a LCD. It was observed that the work of Thakur and Sharma [15], and Singh and Thakur [16] had some similarities in their designs. The studies in Kaiser et al. [12], De Barros et al. [13], Mansur et al. [14], Thakur and Sharma [15], and Singh and Thakur [16] designed shunt resistors to convert the short circuit current that flows through the sensor to the required voltage by the different microcontrollers employed. The determination of appropriate values of these shunt resistors were not direct and may be questionable; and as such, their values may eventually affect the accuracy of the solar irradiances presented by their proposed meters.

Following the critical review of some strong and weak points relative to the design of pyranometers in the technical literature, a simple wireless solar irradiation meter is proposed in this study by making use of a solar module as suggested by Mansur et al. in [14], and, Thakur and Sharma in [15]; to guarantee a larger surface area, and as well as giving room for module tilting for maximum solar radiation reading. Although, Thakur and Sharma in [15] made use of RF transmitter and receiver for wireless transmission, it is believed that it would be relatively cheaper and less complex to utilize a NodeMCU development board employed by Parihar in [17] and Setiawan in [18] for the wireless connections, which would give room for the solar radiation meter to interface with other related devices ranging from LCDs to mobile phones, Wi-Fi, remote databases, and personal computers. An ACS712-05B current sensor, designed by Allegro system and reported in [19], was used instead of building shunt resistors as in Mansur et al. [14], and, Thakur and Sharma [15] to acquire the appropriate voltage for the analogue pin of the NodeMCU development board. As a result, this research offers a portable, cost-effective, and efficient wireless solar radiation meter that measures solar radiation at a specific location in the hopes of using the data to construct practical and highly efficient PV systems.

The remaining part of this paper is organized as follows. The material and methods that were employed for the realization of the embedded wireless pyranometer using NodeMCU are presented in Section II. Section III is devoted to the experimental setup and field trial of the proposed meter. The results obtained from the field trial are also presented and discussed. Finally, in Section IV, some conclusions are drawn.

II. Methods and Material

A. Hardware Development

The schematic diagram of the proposed wireless, portable and low-cost pyranometer is presented in Figure 1. The entire system consists of the solar module, ACS712-05B current sensor, NodeMCU development board, Visual Display Unit and a Power Bank.

The proposed meter's sensory unit is made up of a solar module and an ACS712-05B current sensor. The solar module used in this study is a polycrystalline module that has a 7 V open circuit voltage, and 500 mA standard short circuit current. The module is used to capture solar irradiance (G) from space and to convert it to short circuit current (I_p). And it has been established in [12] and [20-22] that the G received by a solar module is directly proportional to I_p generated by the module; and is given by Equation (1).

$$I_P = k_1 G \quad (1)$$

where, k_1 is the constant of proportionality, which short circuit current I_{STD} divide by standard Irradiance G_{STD}.

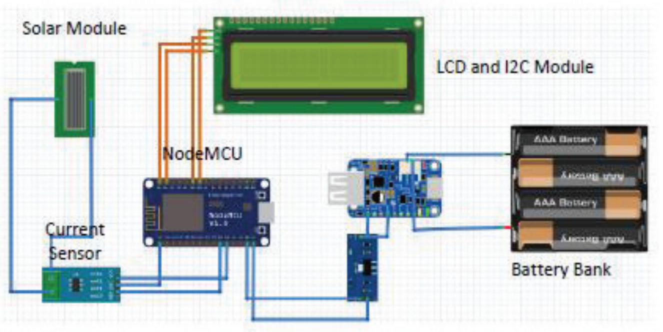

Figure 1: Schematic diagram of the proposed Pyranometer

In this study, the values of I_{STD} of the employed module and G_{STD} are 500 mA and 1000 W/m^2 respectively; hence Equation (1) becomes Equation (2).

$$I_P = \frac{0.5}{1000} G \quad (2)$$

To convert the I_p obtained from the solar module to the equivalent voltage value, which is required at the analogue input (A_0) pin of the NodeMCU, a current sensor was employed, which works on the principle of Hall Effect. In this study, the ACS712-05B current sensor [19] was utilized. The sensor is made up of linear Hall circuit with a copper conduction path placed very close to the outer boundary of the die. Whenever a current flows through the path, a magnetic field will be generated, which the circuit converts into a proportional voltage.

The ACS712-05B current sensor was selected in this study because it handles current up to 5 A and as low as 0.05 A. The sensor has an output sensitivity of 185 mV/A at 3.3 V power supply (V_{CC}) [19]. The output voltage of the current sensor with zero current, $V_{OUT(0A)}$ is $V_{CC}/2$ or $3.3/2$ or 1.65 V. However, the relationship between measured output voltage V_{OUT} and sensed current I_p has been revealed by [19] at different temperatures is given by Equation (3).

$$V_{OUT} = k_2 I_P \quad (3)$$

where, k_2 is the constant of proportionality, which is the sensitivity of the ACS712-05B; and it has a value of 0.185 V/A for the current sensor under consideration. With this information, Equation (3) can therefore be expressed as Equation (4).

$$V_{OUT} = 0.185\, I_P \quad (4)$$

It should be stated here that V_{OUT} is a function of $V_{OUT(0A)}$ that has been revealed to be 1.65 V, the resolution of the sampled signal (ΔV_{OUT}) [23-24], and the average of the analogue signal sampled at distinct points in time (AvgAcs) [24]; and can be expressed as Equation (5).

$$V_{OUT} = V_{OUT(0A)} - \Delta V_{OUT} \times AvgAcs \quad (5)$$

In this study, $AvgAcs$ and ΔV_{OUT} are given by Equations (6) and (7) respectively.

$$AvgAcs = \frac{\sum_{i=1}^{N} sampled\ data_i}{N} \quad (6)$$

$$\Delta V_{OUT} = \frac{Voltage\ Range\ of\ the\ ADC}{2^n - 1} = \frac{V_{OUT\,MAX} - V_{OUT\,MIN}}{2^n - 1} \quad (7)$$

where, N = numbers of distinct points considered = 150; and n = numbers of binary digits.

The central processing unit (CPU) of the proposed meter is NodeMCU development board; which is a member of Internet of Things (IoT) family [17-18][25]; that contains 'espressif' ESP8266 Wi-Fi [26] enabled chip. The chip has a CPU speed range of 80 MHz to 160 MHz, and 128 kb RAM and 4 MB Flash memory [17-18]. It was employed in this study because it is cost effective, it can be programmed using various development platforms, and that it helps to achieve simplistic wireless connectivity. Also embedded in the NodeMCU development board is 10-bit ADC; which has an input range of 0 V to 3.3 V; hence Equation (7) becomes as represented in Equation (8).

$$\Delta V_{OUT} = \frac{3.3}{2^{10}-1} = \frac{3.3}{1023} \quad (8)$$

Equation (4) can therefore be recast as Equation (9). Upon using Equation (9) in equation (2), we have the Equation (10).

$$I_P = \frac{1}{0.185}\left(1.65 - \frac{3.3}{1023} \times AvgAcs\right) \quad (9)$$

$$G = \frac{1}{0.185}\left(1.65 - \frac{3.3}{1023} \times AvgAcs\right)\frac{1000}{0.5} \quad (10)$$

Equation (10) produces the value of the irradiance, which would be displayed on the LCD and a server. In this study, the I2C module [27] was used to allow easy connectivity of the LCD to the NodeMCU by converting the 16 pins of the LCD to 4 pins namely GND, V_{CC}, SCL, and SCA. The server used in accomplishing this study is the "thingspeak.com". It is a free online server used in the IoT implementations. It is a platform that is powered by MATLAB.

The power bank circuit for the energizing of the proposed meter has an on-board LCD that shows the total charge remaining, input-output voltages, and current. It has two USB ports for powering the NodeMCU development board. One is of 5 V, 1 A, and the other is of 5 V, 2.1 A ratings; consequently, it is suitable for charging the proposed metering device. One micro-USB port is also present on the board; which is used for charging the power bank. Here there is need to connect a 5 V, 1 A adapter. A power switch is also present on the board for turning ON/OFF the power bank. In this study, a Samsung 18650 Li-ion cell was used. A single cell outputs a voltage of 4.2 V when it is fully charged and has a capacity of 2200 mAH.

B. Software Development

The application was developed using the flow chart in Figure 2 and uploaded to the NodeMCU development board using the Arduino Integrated Development Environment (IDE) platform. The C and C++ were used to create the application in the IDE. All the processes that were undertaken by the IDE were categorized under setup () and Loop () functions.

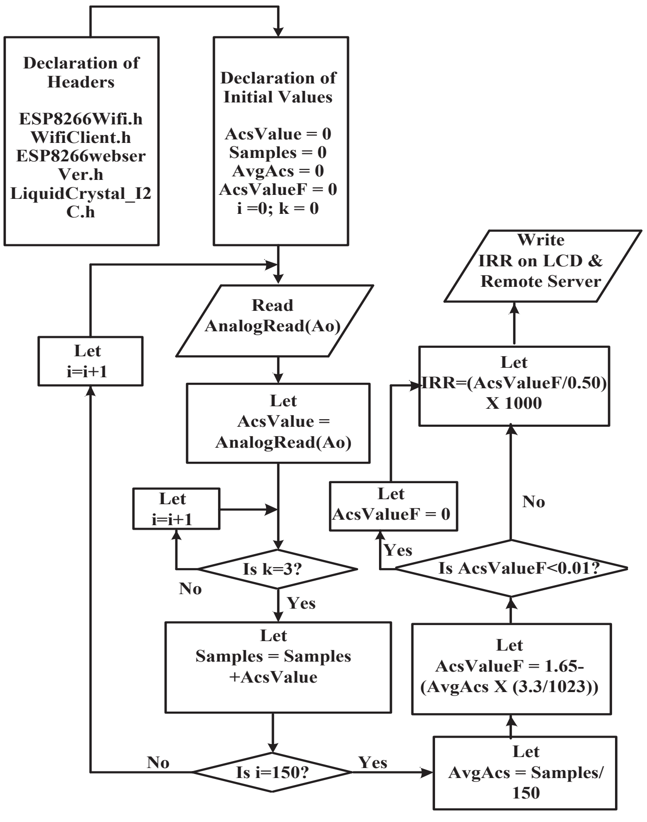

Figure 2: Flowchart for the implementation of the proposed meter

III. Results and Discussion

A. Experimental Setup

The physical features of the proposed pyranometer are shown in Figures 3 and 4. To validate the performances of the proposed meter; two industrial daystar DS-05 pyranometers labelled Meter A and Meter B were setup alongside the proposed meter within a 1 m^2 area as shown in Figure 5.

Figure 3: The exterior of the proposed pyranometer

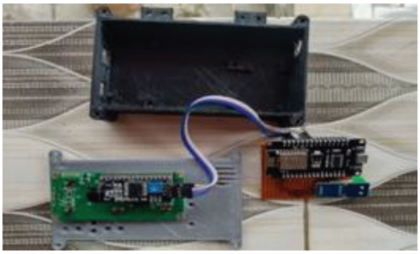

Figure 4: The interior of the proposed pyranometer

Figure 5: The proposed and two industrial daystar DS-05 pyranometers

To ascertain the size of sample data essential for the validation of the performances of the proposed meter, with the 98% confidence level and an error margin of 2%, with an inference of 5% population proportion, and having an unlimited population size, Raosoft calculator [32] was employed. The result obtained from the calculator reveals that 1259 or more readings are required to satisfy the mentioned statistical constraints. To that effect, the experimental data of the solar radiation meters were collected from 10:00 am to 5:10 pm at 10 minutes intervals on Monday the 3rd of February, 2022 through Saturday the 12th of March 2022 at FESTAC Town, Lagos, Nigeria; which gave a total reading of 1800 within the period.

B. Discussion

Figure 6 shows the result of solar irradiance from the ThingSpeak platform. The result reveals that the observed values vary over an average value of 500 W/m^2 for the duration of time. This shows that the proposed meter considers the remote wireless monitoring and measurement of the solar irradiance.

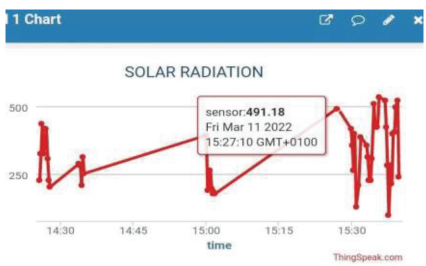

Figure 6: Irradiance captured on the ThingSpeak platform

Figures 7 to 9 present the average of the solar irradiation measurements of the proposed meter, the two DS-05 pyranometers, and the three meters respectively.

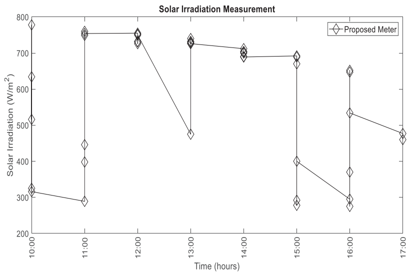

Figure 7: The average solar radiation measurement of the proposed meter

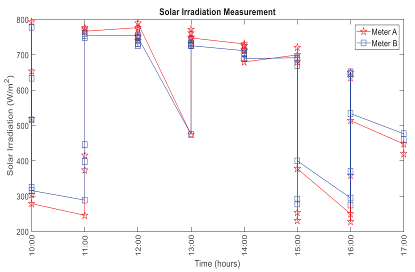

Figure 8: The average solar radiation measurement of the two commercialized meters

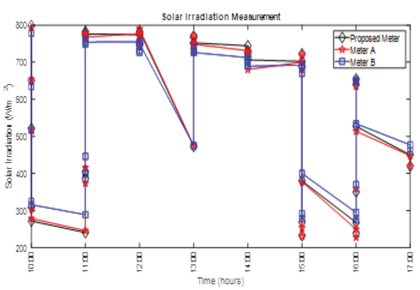

Figure 9: The average solar radiation measurement of the proposed and two commercialized meters

The irradiation values were seen to have varied with respect to time due to local conditions. The solar irradiation pattern of the proposed pyranometer shown in Figure 7 was seen to have followed directly the pattern of the DS-05 pyranometers shown in Figure 8, thereby validating the performance of the proposed meter.

In order to quantitate the precision of the readings from the proposed pyranometer, the Root Mean Squared Error (RMSE) [28-31] performance metric was employed. The metric is used to compare the readings from the proposed meter (p) and the two DS-05 daystar commercial meters (DS-05A and DS-05B). The mathematical expressions for the RMSEs are presented in Equations (11) and (12) respectively.

$$RMSE_{p\&DS-05A} = \sqrt{\frac{1}{n}\sum_{k=1}^{m}\left(G_p - G_{DS-05A}\right)^2} \quad (11)$$

$$RMSE_{p\&DS-05B} = \sqrt{\frac{1}{n}\sum_{k=1}^{m}\left(G_p - G_{DS-05B}\right)^2} \quad (12)$$

where, G_p is radiation from the proposed meter, G_{DS-05A} is radiation from the DS-05 meter (Meter A), G_{DS-05B} is radiation from the DS-05 meter (Meter B), and m is the total number of measurements.

The data comparison of the commercialized and proposed meters shown in Figure 9 revealed slight variations in measurement data with $RMSE_{p\&DS\text{-}05A}$ and $RMSE_{p\&DS\text{-}05B}$ of 0.094671 and 0.064885 respectively. The performances of the commercialized DS-05 meters and the proposed meter were seen to be closely related regardless of their geo-spatial separations. It is to be noted that the commercial value of a DS-05 pyranometer was $157 [33] at the time of this study while the proposed meter was a cost-effective way of detecting solar irradiation with a prototyping cost of $52.

IV. Conclusions

This study has presented a cost effective approach to designing pyranometers. The proposed pyranometer was achieved through an integrative approach of an interworking architecture consisting of a programmable microcontroller, current sensor, digital display unit, solar module and power bank. The pyranometer was interfaced for realtime data gathering using NodeMCU development board and Thingspeak server for reading and monitoring data form the current sensor. The performance of the proposed pyranometer was validated by benchmarking it with two DS-05 daystar industry certified pyranometers. The proposed pyranometer achieved an acceptable performance ratio with a RMSE of 0.0946705 and 0.064885 respectively. It is therefore recommended that future work be carried out by extending the utilization of the proposed pyranometer for a much longer duration in diverse locations and that a reliability study be conducted on the device relative to its useful life.

V. Acknowledgement

The authors are pleased to acknowledge the support provided by the Department of Electrical and Electronics Engineering, Faculty of

Engineering, University of Lagos.

VI. References

[1] J. Engelhardt, J. M. Zepter, J. G. Lage, T. Gabderakhmanova, and M. Marinelli, "Energy management of a multi-battery system for renewable-based high-power EV charging", *eTransportation*, 14, 100198, 2022.

[2] G. Kakoulaki, R. G. Sanchez, A. G. Amillo, S. Szabo, M. De Felice, F. Farinosi, L. De Felice, B. Bisselink, R. Seliger, I. Kougias, and A. Jaeger-Waldau, "Benefits of pairing floating solar photovoltaics with hydropower reservoirs in Europe", *Renewable and Sustainable Energy Reviews*, 171, 112989, 2023.

[3] H. Xie, M. Jiang, D. Zhang, H. H. Goh, T. Ahmad, H. Liu, T. Liu, S. Wang, and T. Wu, "IntelliSense technology in the new power systems", *Renewable and Sustainable Energy Reviews*, 177, 113229, 2023.

[4] W. D. Widiartha, and Y. Yohandri, "IoT - based pyranometer using photodiode sensor", *Journal of Experimental and Applied Physics*, 1(1), 12 – 21, 2023.

[5] United Nations (2023). Climate action, Available: https://www.un.org/en/climatechange/raising-ambition/renewable-energy#:~:text=Renewable%20energy%20sources%20%E2%80%93%20which%20are,or%20pollutants%20into%20the%20air, Accessed November 11, 2023.

[6] K. N. Poudyal, B. K. Bhattarai, B. K. Sapkota, B. Kjeldstad, and N. R. Karki, "Estimation of global solar radiation using pyranometer and NILU-UV irradiance meter at Pokhara Valley in Nepal", *Journal of the Institute of Engineering*, 9(1), 69–78, 2014.

[7] A. Allouhi, S. Rehman, M. S. Buker, and Z. Said, "Up-to-date literature review on Solar PV systems: technology progress, market status and R&D", *Journal of Cleaner Production*, 362, 132339, 2022.

[8] R. D. Parmar, "Solar radiation and pyranometer: A review", *Journal of Information, Knowledge and Research in Electrical Engineering*, 1(2), 122–125, 2012.

[9] M. A. N. Korevaar, "Measuring Solar Irradiance for Photovoltaics, Solar Radiation – Measurement", *Modeling and Forecasting Techniques for Photovoltaic Solar Energy Applications,* IntechOpen, Oct. 26, 2022

[10] S. N. Nwankwo, M. N. Nnabuchi, and J. E. Ekpe, "Construction and characterization of a pyranometer using locally available materials for global solar radiation measurement", *Asian Transactions on Basic and Applied Sciences*, 2(4), 26–33, 2012.

[11] Y. Matsumoto, M. Satoh, and K. Ozaki, "A low power environmental wireless radiation monitoring system by using 920 MHz frequency band", *In Proceedings of the 7th International Conference on Sensing Technology*, 2013.

[12] M. S. Kaiser, A. K. M. F. Haque, M. A. Rahman, M. A. Z. Alam, M. M. Rahman, and S. K. Aditya, "Low-cost digital solar insolation meter", *Daffodil International University Journal of Science and Technology*. 1(1), 34–38, 2016.

[13] R. C. De Barros, J. M. S. Callegari, D. D. C. Mendonca, W. C. S. Amorim, M. P. Silva, and H. A. Pereira, "Low-cost solar irradiance meter using LDR sensors", *In Proceedings of 13th IEEE International Conference on Industry Applications,* Sao Paulo, Brazil, 72–79, 2019.

[14] A. Al Mansur, B. Shil, K. K. Islam, M. A. Hoque, and M. H. Bhuyan, "Design and implementation of a solar radiation meter using pv panel as a sensor", *GUB Journal of Science and Engineering*, 1(1), 32–37, 2014.

[15] D. S. Thakur, and A. Sharma, "Wireless solar irradiance meter", *In Proceedings of International Conference on Renewable Energy*, H.P, India, pp. 1-9, 2012.

[16] D. Singh, and A. S. Thakur, "Microcontroller based digital solar insolation meter", *International Conference on Recent Advances in Electronics and Computer Engineering*, Eternal University, H.P., India, 17-18, December 2011.

[17] Y. S. Parihar, "Internet of Things and Nodemcu: A review of use of Nodemcu ESP8266 in IOT products", *Journal of Emerging Technologies and Innovative Research*, 6(6), 1085–1088, 2019.

[18] A. Setiawan, Y. Suprapto, M. I. Fachrurrozi, K. R. N. Manab, N. R. Sasmita, and I. G. S. M. Diyasa, "Real-time home bell notification using NODE-MCU through e-mail (Base on the Internet of Things)", *Journal of Physics: Conference Series,* 1845, 012007, 2019.

[19] AllegroMicro System: Fully integrated, hall-effect-based linear current sensor IC with 2.1 kVRMS isolation and a low-resistance current conductor, ACS712-DS, Rev. 20, February 7, 2022.

[20] M. Muhleis, I. Kroger, and J. Hohl-Ebinger, "Fast and accurate short-circuit current versus irradiance determination of a spectrally nonlinear solar cell using a spectral shaping setup", *Solar Energy Materials and Solar Cells*, 230, 111208, 2021.

[21] B. Li, A. Migan-Dubois, C. Delpha and D. Diallo, "Irradiance dependence of the short-circuit current temperature coefficient of sc-si PV module", *2020 47th IEEE Photovoltaic Specialists Conference (PVSC)*, Calgary, AB,

Canada, 2020, pp. 0564-0568.

[22] IEC 60891:2021. Photovoltaic devices - Procedures for temperature and irradiance corrections to measured I-V characteristics, *IEC Standard*, 2021.

[23] Freescale Semiconductor, Inc. How to increase the Analog-to-Digital converter accuracy in an application, *Application Note*, Rev. 0, 01/2016.

[24] J. W. Valvano, "Embedded systems: Real-time operating systems for ARM Cortex-microcontrollers", Vol. 3, 2017.

[25] K. V. S. S. Ganesh, S. P. S. Jeyanth, and R. A. Bevi, "IoT based portable heart rate and SpO2 pulse oximeter", *HardwareX*, Vol. 11, 2022.

[26] Espressif Systems IoT Team: ESP8266EX datasheet version 6.6, *Espressif Systems*, 20.10, 2020.

[27] Handson Technology, I2C Serial Interface 1602 LCD Module. [Online] Available: http://www.handsontec.com/dataspecs/module/I2C_1602_LCD.pdf

[28] K. Tyagi, C. R. Harshvardhan, M. Manry, "Regression analysis", *Artificial Intelligence and Machine Learning for EDGE Computing*, Academic Press, pp. 53-63, 2022.

[29] P. Singla, M. Duhan, and S. Saroha, "Different normalization techniques as data preprocessing for one step ahead forecasting of solar global horizontal irradiance", *Artificial Intelligence for Renewable Energy Systems*, Woodhead Publishing, pp. 209-230, 2022.

[30] D. Christie, and S. P. Neill, "Measuring and observing the ocean renewable energy resource", Comprehensive Renewable Energy, second edition, *Elsevier*, pp. 149-175, 2022.

[31] Y. Chu, M. Li, C. F. M. Coimbra, D. Feng, and H. Wang, "Intra-hour irradiance forecasting techniques for solar power integration: A review", *iScience*, Vol. 24, Issue 10, 2021.

[32] Sample Size Calculator, Raosoft Inc. [Online] Available: http://www.raosoft.com/samplesize.html

[33] Raydec, Inc. Daystar DS-05A Solar meter. [Online] Available: https://raydec.com/solar_meter.html#features11-4f