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ENVIRONMENTAL FACTORS AND THE PERFORMANCE OF PV PANELS: AN EXPERIMENTAL INVESTIGATION

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ABSTRACT: *With the increase in demand for renewable energy, photovoltaic (PV) panels have emerged as a major alternative for harvesting solar energy. However, the efficiency and performance of PV panels are inextricably related to environmental conditions. This study examined the effect of ambient variables on the performance of photovoltaic (PV) panels. Through controlled tests, the researchers investigated critical environmental parameters such as sun irradiance, temperature, wind speed, humidity, and dust deposition. Modern sensors and data-gathering methods were used to monitor how these variables affected PV panel output. Statistical tools were used to determine the relationship between environmental factors and PV panel efficiency. The findings showed a clear relationship between environmental variables and PV panel performance. Solar irradiance was recognized as a major indicator for energy generation, while temperature had complex implications on current output. Wind speed, relative humidity, and dust deposition were discovered to have discernible detrimental effects on panel performance. This study adds to the increasing knowledge about PV systems by highlighting the complex links between ambient conditions and panel efficiency. The findings highlight the importance of site-specific considerations in building and running PV installations to ensure optimal energy output and system longevity. The article's results have practical consequences for both the solar energy sector and researchers, leading to the development of ways to improve PV panel performance and contribute to the sustainable energy landscape.*

KEYWORDS: Photovoltaic Panels, Environmental Factors, Irradiation, Temperature, Humidity

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INTRODUCTION

Recently, photovoltaic (PV) technology has emerged as a practical and ecological alternative for electricity generation. Harnessing solar energy through PV panels has many advantages, including reduced greenhouse gas emissions, energy independence, and localized power generation (Shaik et al., 2023). The PV modules, however, are typically exposed to direct sunlight, and several variables, including irradiance, temperature, dust concentration, soiling, wind, shade, humidity, etc., may significantly impact their performance and efficiency. To maximize the performance and improve the economic feasibility of PV panels, it is essential to comprehend the intricate interactions between these variables and their effects on the efficiency of the PV panels.

This article aims to experimentally quantify how different environmental factors, such as wind speed, dust particles, temperature, relative humidity, and sun irradiation, affect the performance of PV panels. The study aims to identify the correlations between these environmental factors and the electrical output of PV panels. The information gleaned from this research will help us better understand PV panel behaviour and to come up with strategies for opting for more efficient PV systems.

LITERATURE REVIEW

The evaluation of the effects of environmental factors on the performance of PV panels has been the focus of numerous researchers. An important element that has been thoroughly studied is solar irradiation, which is usually impacted differently by the weather, seasonal changes, location, time of day, and solar position in the sky (Prema & Uma, 2015). According to Santbergen et al. (2017), the PV modules receive both direct sunlight from the sun and reflected light from the surrounding environment. However, direct sun exposure does have a big impact (Fouad et al., 2017). Cloudy skies are the main cause of the varying irradiance values (Wang et al., 2020). Touati et al. (2013) studied the relationship between solar irradiation levels and PV panel output. Their results highlight the necessity for precise solar irradiance forecasting models to forecast power generation under various weather scenarios. The solar panel would have to face the sun directly to receive the highest solar irradiance. The latitude angle of the location determines the ideal tilt angle. It deviates from the latitude angle in summer to about 15° in winter (Viitanen, 2015).

Another factor that affects the performance of a PV module is the cell operating temperature. The operating temperature of the module has an impact on how much power is produced by solar cells. A PV system's behaviour is strongly influenced by module temperature since it alters its efficiency and energy output (Fesharaki et al., 2011). Rahman et al. (2015) noted that at an operating temperature of 56°C and a radiation output of 1000 W/m^2, the efficiency of a single-crystal silicon solar cell decreases by 3.13%. According to Nižetić et al. (2016), panel efficiency is lowered by 69% at 64°C and also decreases by 5% when the module temperature rises from 43 to 47°C. For every 1°C increase in PV module cell operating temperature, Odeh & Behnia (2009) found that electrical efficiency decreased by 0.03–0.05%.

Variations in ambient temperature also have a significant impact on the performance of PV panels. Gurturk et al. 2018, carried out a thorough analysis of temperature-dependent efficiency losses in PV panels, revealing the detrimental effect of high ambient temperatures on energy

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conversion. This emphasizes the importance of efficient cooling mechanisms, such as passive cooling strategies or active cooling systems, to maintain the best operating conditions.

When trash, water vapour, air molecules, dust particles, and other contaminants in the atmosphere hinder sunlight from accessing the PV panel, the PV modules' efficiency is reduced. Airborne dust particles that are larger than the wavelength of the sun's entering beam can bend sunlight, reducing solar irradiance arriving at the PV module (Mani & Pillai, 2010). Additionally, a substantial coating of dust may assemble on the PV module's surface. The output of PV modules can be increased by altering the optical properties of a dust layer to enhance light reflection and absorption and decrease surface transmissibility (Said et al., 2018). Environmental variables, including wind speed, relative humidity, rainfall, dust source, particle type, PV module technology, and PV module surface coverage, affect dust buildup. Field tests were carried out by Adinoyi and Said (2013) to show the impact of dust buildup on PV panel arrays. Their research demonstrated that, without cleaning, output power generation might fall to 50% of its maximum level. Similarly, Elminir et al. (2006) estimated that Egypt’s output power decreases by about 17.4% each month due to dust accumulation. Said et al. (2015) found that dust collecting for 45 days lowers the overall glass cover transmittance of a PV module by 20%.

The amount of electricity a solar module generates is also influenced by the direction and speed of the wind. The impact of wind on PV performance is described using different factors, such as module temperature, surface structure, and dust deposition. The most cost-effective cooling method is to use convective heat transfer by natural wind movement as much as possible (Vasel & Iakovidis, 2017). However, wind speed has a much greater impact on PV cell temperature increases than wind direction (Griffith et al., 1981). Experiments done in the US showed that 3.5 °C can reduce the operating temperature of a glass covered with grooves for winds of 10 m/s. Also, a wind speed of 12 m/s can lower the temperature by up to 10 °C in the KSA and by half in Slovenia. In addition, the wind removes dust particles from the PV module's surface and reduces dust deposition (Assi & Chaar, 2008). As an illustration, a study carried out in Egypt shows that, at a particular tilt angle, blowing wind reduces dust deposition from the module (Mekhilef et al., 2012).

Relative humidity is one of the elements that affect the buildup of tiny water droplets and water vapour from the atmosphere on solar panels. It is less probable that sunlight will directly strike solar cells and produce electricity when it has been refracted, reflected, or diffracted away from those cells by water droplets. The radiation intensity also varies nonlinearly with humidity because smaller water vapour particles have bigger scattering angles (Gwandu & Creasey, 1995). Sticky and adhesive dust layers can build up on PV surfaces due to high relative humidity (RH), which can result in soiling and a decrease in power output. The efficiency of solar cells increases from 9.7 to 12.04% as the relative humidity decreases from 60 to 48%, and a 20% rise in relative humidity causes a 3.16 W decrease in power output (Sala et al., 2009). Another study claims that the output of PV systems decreases by 40% during the rainy season at a relative humidity of 76.3% and by 45% during the cloudy season at a relative humidity of 60.5% (Gupta et al., 2019).

A thorough body of research has examined the complex interactions between environmental factors and the performance of photovoltaic (PV) panels. However, this article expands on that groundwork by identifying significant discoveries, approaches, and knowledge gaps while also offering a comprehensive assessment of the current state of knowledge. Through this investigation, we hope to support ongoing efforts to improve the performance and efficiency of PV panels, accelerating the shift to a more sustainable energy environment.

Experimental Design

The experimental set-up shown in Figure 1 below was mounted in the front of the Industrial Physics Laboratory at the Joseph Sarwuan Tarka, University Makurdi (Formerly Federal University of Agriculture, Makurdi). The set-up consisted of two monocrystalline solar panels with the specification: module type FL-M-280 W, dimensions of 1640 x 9920 x 35 mm, and a maximum system voltage of 1000 VDC were connected in parallel with the charge controllers, and the charge controllers to load (DC fan). A compass was used to determine the true North, and the panels were mounted at 50^o from the ground facing the North-East (NE) and tilted towards the South-East (SE). Six (6) YZP-PT100 temperature sensors (T_1, T_2, T_3, T_4, T_5, and T_6) were fixed under the cells of the photovoltaic (PV) modules at different points to monitor the distribution of the cell operating temperature. Another temperature sensor (T_A) was mounted on a stand but not in contact with any object other than air to measure the ambient temperature. The data for the distribution of the cell operating temperature was gathered by an Arduino data acquisition board to a personal computer at time intervals of 1 second.

Figure 1: Photograph of Experimental Setup

Incident solar irradiance received at the experimental site was measured using a TENMARS, Model TM – 206 Solar Power Meter (a pyranometer) manufactured by Tenmars Electronics Co. in Taipei City, Taiwan. According to the User's manual, the instrument has an accuracy of ± 10 W/m^2. A UNI-T UT363 handheld anemometer with an air temperature gauge of -10 °C to 50°C and LCD Backlit Max/Avg Data Hold was used to measure the wind speed. A mini hygrometer (0 – 100% RH and 10 – 60℃) mounted on a tripod stand, one meter above ground level, measured the relative humidity. All measurements were carried out at 2-minute intervals but averaged over 10 minutes throughout the days of research.

The maximum current and voltage output delivered by the photovoltaic panels were recorded from the charge controller at intervals of 2 minutes throughout the two days of experimental examination.

Data on the COT distribution on the panel, along with irradiation, ambient temperature, wind speed, relative humidity, and dust accumulation, were plotted and discussed. Linear regression analysis was used to specify models that provided the best fit to the specific curves in the plots.

Experimental Design for Effects of Dust on the PV Module

To investigate the impact of dust on the performance of solar PV panels, one panel was thoroughly cleaned to ensure optimal conditions, while the other was intentionally subjected to a controlled accumulation of dust, as shown in Figure 2. For the dusty panel, a consistent layer of dust was monitored to ensure real-world conditions; dust particle sizes were not monitored, but their distribution was controlled to ensure uniformity.

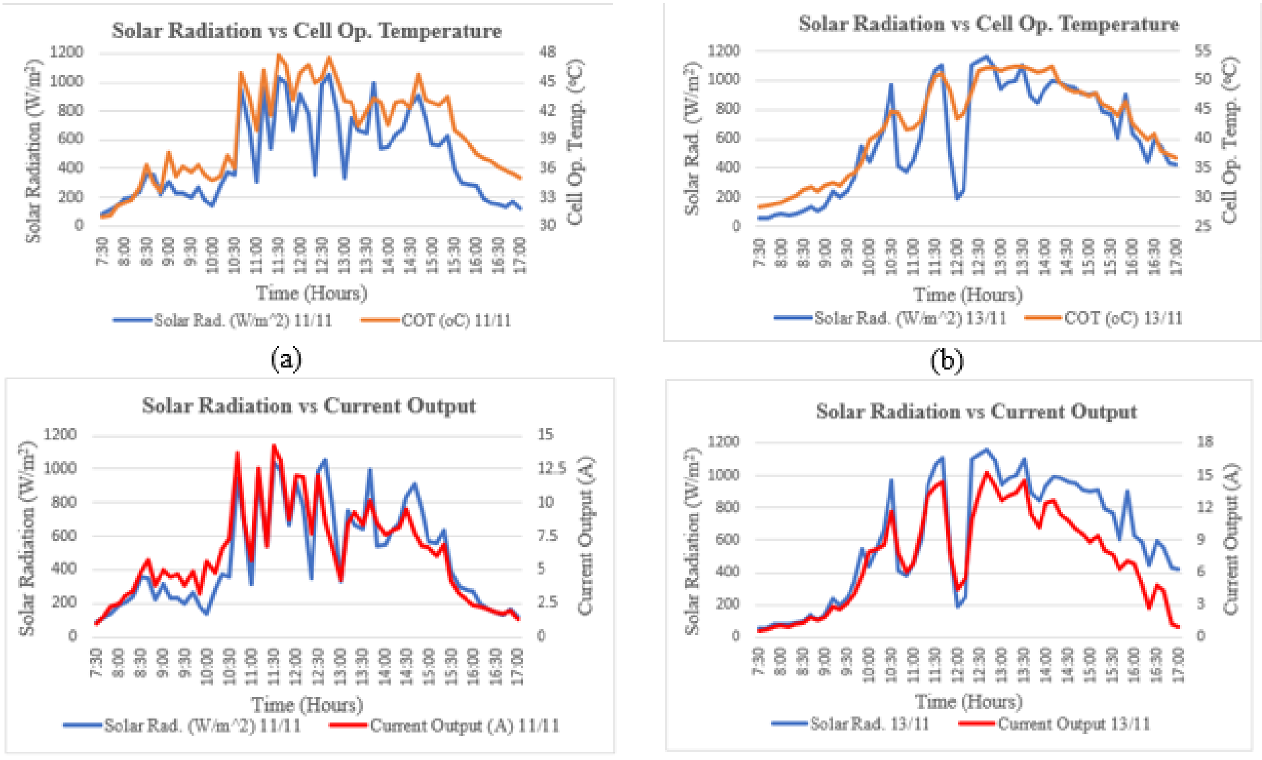
Figure 2: Experimental Setup for Effects of Dust on PV module

Solar irradiance, current output, and temperature were measured at regular intervals on both panels using precision instruments, as described in the previous section. The captured data was evaluated to see how well the two panels performed in comparison. The current output and operating temperature of the cell were compared.

Results and Discussion

Solar Radiation vs COT of PV Panels and Current Output

The variation of the irradiation for the 11th and 13th of November 2020 was plotted against COT and the current output of the photovoltaic (PV) panels as a function of the time of the day. The results are presented in Figure 3 (a, b and c, d) respectively.



(a)

(b)

(c)

(d)

Figure 3: Variation of Solar Radiation with COT of PV module (a, b) and Current Output (c, d) for 11/11/2020 and 13/11/2020

Figure 3 (a–d) shows that the values of the morning sun's radiation were initially fairly low before progressively increasing. This was most likely caused by the sun rising and gaining strength as it rises higher in the sky, peaking between 11:30 and 13:30 hours, resulting in the highest levels of solar energy reaching the Earth's surface and then declining due to the sun descending in the sky toward evenings. When the solar irradiation was less than 100 W/m^2, the PV modules' cell operating temperature and current output were both low, ranging between 28.3^{o}C to 31.02^{o}C and 0.95A to 1.85A, respectively.

Figure 3 (a and b) shows that the cell operating temperature of the PV modules increased with a rise in solar radiation, reaching an upper limit of 47.9^{o}C when the solar radiation of the day (November 11, 2020) reached 1035 W/m^2 at 11:30 hours, and a maximum of 52.38^{o}C on November 13, 2020. However, when the solar radiation was at its peak of 1160.5 W/m^2 on November 13, 2020, the maximum value of 52.38^{o}C for the cell operating temperature of the PV module was not recorded. This could be because the cell operating temperature of the PV module was still rising when solar irradiation for this day peaked at 12:40 hours. At about 13:30 hours, with solar irradiation of 1103.5 W/m^2, the maximum cell operating temperature of the PV module was measured. For the two days of the experiment, the greatest cell operating temperatures of the PV modules and solar radiation were measured between 11:30 hours and 13:30 hours. The two variables had a strong positive correlation, with a coefficient of correlation (r) of 0.9018 and 0.9214, respectively for the days studied. The results show that the cell operating temperature (COT) of the photovoltaic (PV) module was largely dependent on irradiation.

Similarly, an increase in solar irradiation led to an increase in the current output generated by the PV modules. However, during the intensely sunny midday hours, there were variations in the current output numbers. Although a maximum current output of 15.25A was detected at 12:30 hours on November 13, 2020, when irradiance reached a maximum value of 1160 W/m^2, a maximum current output of 14.2A was seen at 11:30 hours on November 11, 2020, when solar irradiance reached 1035 W/m^2 (Figure 3 c and d). This may indicate that other factors, including wind, humidity, or local weather, affect the current production. Nonetheless, a substantial positive connection between the two variables, with a coefficient of correlation (r) of 0.9110 and 0.934 for the days studied, indicates that the photovoltaic (PV) module's current output was heavily dependent on solar irradiation. This agrees with Touati et al. (2013), who also reported that the current output of PV panels directly depends on solar irradiation.

Linear regression analysis was performed on the solar irradiation and PV modules' cell operating temperatures, as well as the solar irradiation and PV modules' current output, to provide a further understanding of the relationship between the variables. Equations 1–2 and 3–4 are the models that provide the relationship for the variables obtained for November 11 and 13, 2020, respectively.

$$y = 0.0144x + 32.809 \qquad (1)$$

$$y = 0.0106x + 1.1672 \qquad (2)$$

The models for solar irradiation and PV module cell operating temperatures, as well as solar irradiation and PV module current output, produced high coefficients of regression (r^2). The r^2 values are 0.8133 and 0.8299, respectively, for November 11, 2020, indicating that the PV module's COT was heavily dependent on solar irradiation

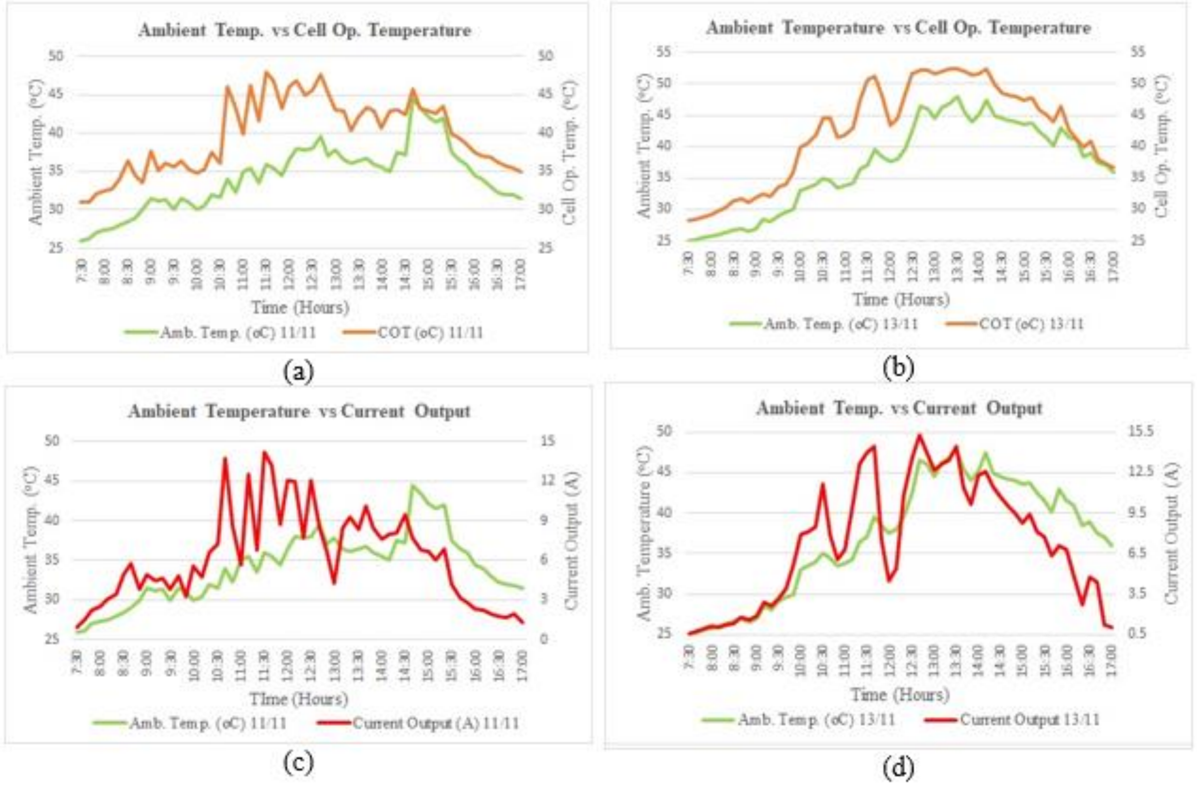
$$y = 0.0203x + 30.003 \qquad (3)$$

$$y = 0.0118x + 0.073 \qquad (4)$$

Similarly, the models for solar irradiation and PV module cell operating temperatures, as well as solar irradiation and PV module current output, produced high coefficients of regression (r^2). The r^2 values are 0.8489 and 0.8723, respectively, for November 13th, 2020, indicating that the PV module's current output was heavily dependent on irradiation

Ambient Temperature vs COT of PV Panels and Current Output

The variation of the ambient temperature for the 11th and 13th of November 2020 was plotted against the COT of the PV panels and the generated current output as a function of the time of the day. The results are presented in Figure 4 (a, b and c, d) respectively.



(a) (b) (c) (d)

Figure 4: Variation of Ambient Temperature with COT of PV module (a, b) and Current Output (c, d) for 11/11/2020 and 13/11/2020

The results show that the early morning temperature was around 26°C and 25°C, respectively, for November 11th and 13th, 2020, and progressively rose throughout the day without a steady pattern (Figure 4 a–d). The temperature rise was expected as the sun's energy warmed the environment. The peak of the ambient temperature (44.5°C and 48°C, respectively) occurred about midday (between 11:40 hours and 14:40 hours), similar to the trend observed in sun irradiation. This was because the sun was near its peak and emitted the most intense heat during this period. The afternoon temperature began to fall steadily after reaching its midday peak. The downward tendency was most likely due to the sun's angle shifting as it moved lower in the sky.

Figure 4 (a and b) illustrates that the cell operating temperature of the PV modules increased with an increase in ambient temperature and decreased with a decrease, reaching an upper limit of 47.9°C on November 11, 2020. This limit, however, was reached around 11:30 hours while the ambient temperature was 36°C, showing that other environmental conditions influenced it. On November 13, 2020, at 13:30 hours, the maximum COT value of 52.38°C was achieved, while the ambient temperature was similarly at its top of 48°C. The two variables had a strong positive correlation, with coefficients of correlation (r) of 0.8212 and 0.9317, respectively, for November 11 and 13, 2020, indicating that ambient temperature, a dependent variable of irradiation, affects the PV module's COT.

Figure 4 (c and d) demonstrates that as the ambient temperature rose, so did the current output generated by the PV modules. Nonetheless, a peak current output of 14.2A was recorded at 13:30 hours on November 11, 2020, at an ambient temperature of 36°C, and a peak current output of 15.25A was identified at 12:30 hours on November 13, 2020, at an ambient temperature of 46.5°C. These temperatures were not the highest, implying that other elements such as solar irradiation, wind, and humidity may have influenced the present generation. A significant positive relationship between the two variables, with coefficients of correlation (r) of 0.5094 and 0.7950, respectively, for the days studied, suggests that the current output of the PV module was moderately dependent on the ambient temperature.

Linear regression analysis was performed on the ambient temperature and PV module's cell operating temperatures, as well as the ambient temperature and PV module's current output, to provide a further understanding of the relationship between the variables. Equations 5–6 and 7–8 are the models, providing the relationship for the variables obtained for November 11th and November 13th, 2020, respectively.

$$y = 0.9068x + 8.7233 \tag{5}$$

$$y = 0.4087x - 7.7392 \tag{6}$$

For November 11, 2020, the models for ambient temperature and PV module cell operating temperatures produced a high coefficient of regression (r^2) of 0.6743, while ambient temperature and PV module current output produced a low coefficient of regression (r^2) of 0.2594, indicating that while PV module cell operating temperature was strongly dependent on ambient temperature, photovoltaic (PV) module current output was only slightly dependent.

$$y = 1.0254x + 4.4032 \tag{7}$$

$$y = 0.5043x - 11.369 \tag{8}$$

High coefficients of regression (r^2) were obtained for the models for ambient temperature and PV module cell operating temperatures, as well as ambient temperature and PV module current output. For November 13th, 2020, the r^2 values are 0.8681 and 0.632, indicating a substantial dependency on ambient temperature.

Wind Speed vs. COT of PV Panels and Generated Current Output

The variation of the wind speed for the 11th and 13th of November 2020 was plotted against the COT of the PV panels and the generated current output as a function of the time of the day. The results are presented in Figure 5 (a, b and c, d) respectively.

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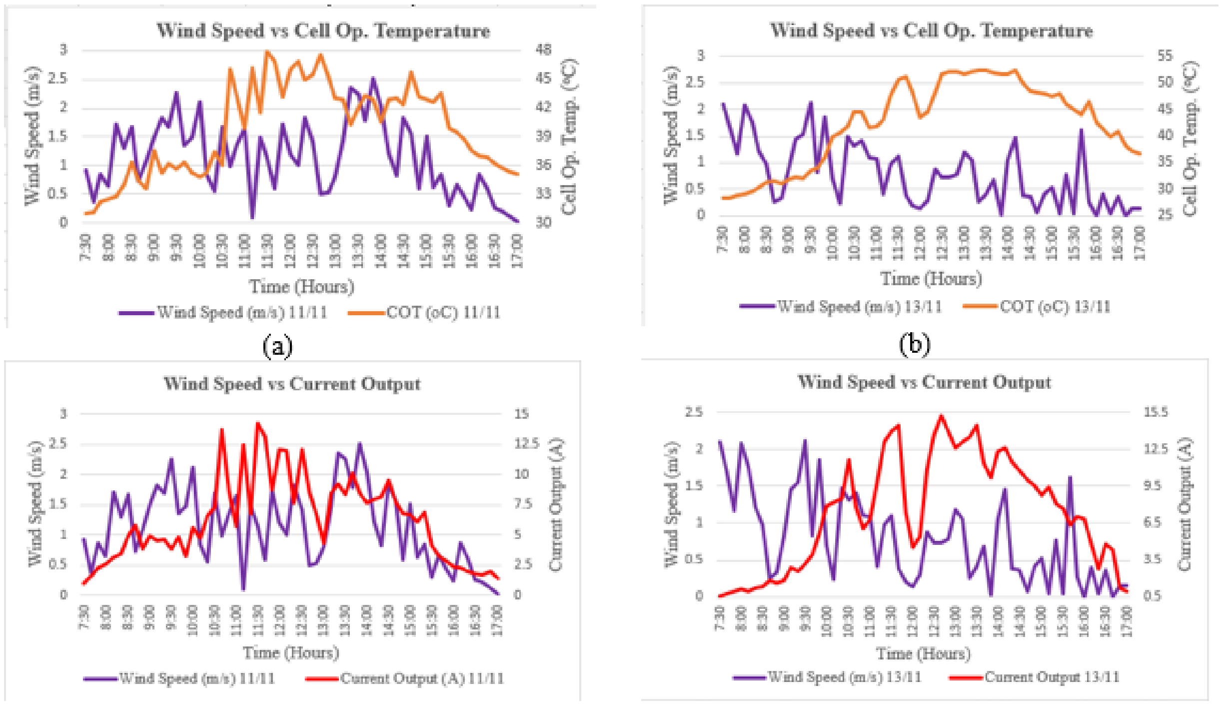

(a) (b)

(c) (d)

Figure 5: Variation of Wind Speed with COT of PV module (a, b) and Current Output (c, d) for 11/11/2020 and 13/11/2020

Figure 5 (a to d) shows that wind speed data for November 11 and 13, 2020, exhibited high variability and were low throughout the day, ranging between 0 and 2.51 m/s and 0 and 2.12 m/s, respectively, in an unstable pattern. This implies that wind conditions were not consistent and could have been impacted by factors such as weather patterns and local geographical features.

Figures 5 (a and b) demonstrate that wind speed had no direct effect on the cell operating temperature of the PV modules in the study area on November 11 and 13, 2020. As demonstrated, there were instances when the cell operating temperature of the PV modules increased with increasing wind speed but dropped at other times. On November 11, 2020, the two variables had a very weak positive correlation, with coefficients of correlation (r) of 0.0778, and a negative correlation, with coefficients of correlation (r) of -0.3945 on November 13, indicating that wind speed had no direct effect on the cell operating temperature (COT) of the photovoltaic (PV) module. Assi and Chaar (2008) found a 3.5°C drop in operating temperature for 10 m/s winds and up to 10 °C for 12 m/s winds. The levels obtained in this study were far lower than what is known in the literature to generate an effect.

Similarly, figures 5 (c and d) show that on November 11 and 13, 2020, wind speed did not directly affect the current output generated by the PV modules in the research region. As shown, the generated current output of the PV modules increased with rising wind speed but decreased at other times. On November 11, 2020, the two variables had a very weak positive correlation (r) of 0.2878 and a negative correlation (r) of -0.2064 on November 13, indicating that wind speed had no direct effect on the current output by the photovoltaic (PV) module.

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To better understand the link between the variables, linear regression analysis was performed on the wind speed and PV module cell operating temperatures, as well as the wind speed and PV module current output. The models which provide the relationship for the variables collected for November 11th and November 13th, 2020, respectively, are equations 9-10 and 11-12.

$$y = 0.5781x + 39.032 \tag{9}$$

$$y = 1.5537x + 4.4502 \tag{10}$$

The models for wind speed versus PV module cell operating temperatures and wind speed versus PV module current output produced very low coefficients of regression (r^2) of 0.0061 and 0.0828, respectively, on November 11, 2020, indicating that wind speed had little or no effect on both PV module cell operating temperature and PV module current output.

$$y = -5.1339x + 46.481 \tag{11}$$

$$y = -1.5484x + 8.551 \tag{12}$$

Equations 11 and 12 show negative trends, with very low coefficients of regression (r2) of 0.1557 and 0.0426 for wind speed versus PV module cell operating temperatures and wind speed versus PV module current output, respectively, indicating a negative effect and a slight dependency on wind speed for November 13th, 2020.

Relative Humidity (RH) vs COT of PV Panels and Current Output

The variation of relative humidity for the 11th and 13th of November 2020 was plotted against the COT of the PV panels and the generated current output as a function of the time of the day. The results are presented in Figure 6 (a, b and c, d) respectively.

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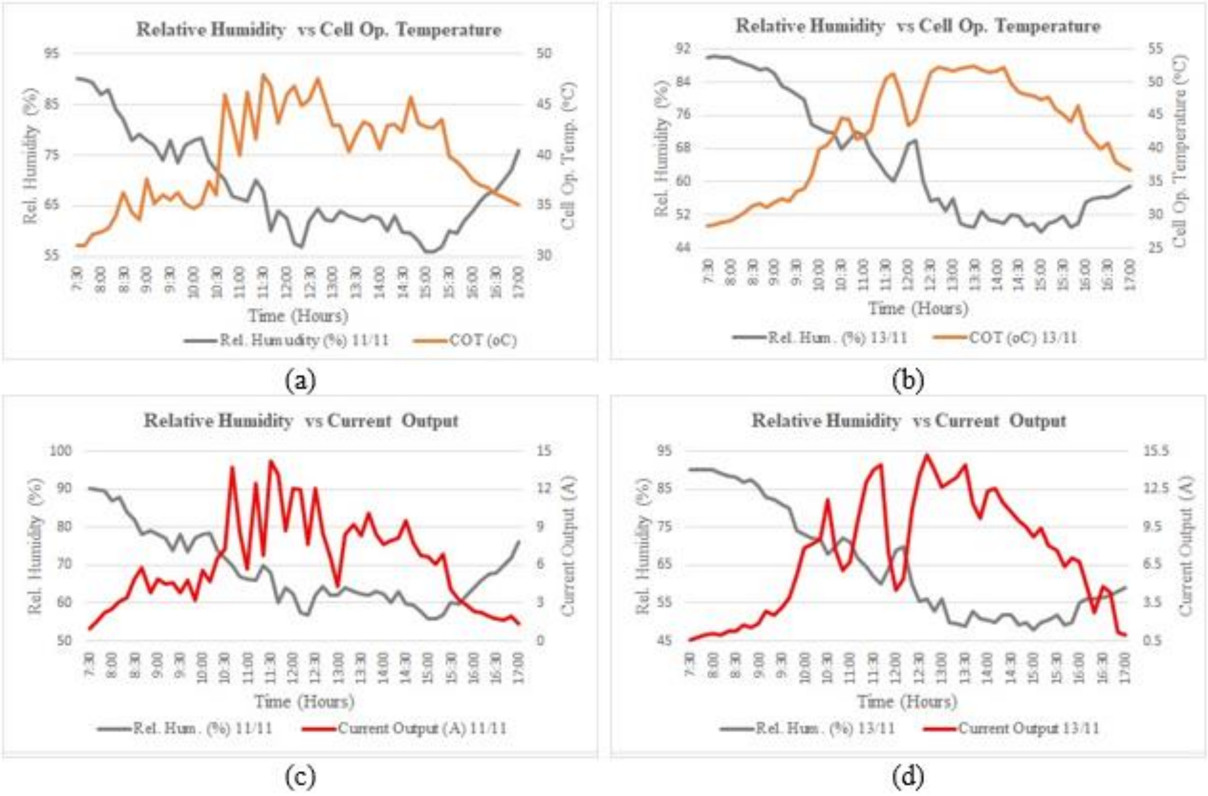


Figure 6: Variation of Relative Humidity with COT of PV module (a, b) and Current Output (c, d) for 11/11/2020 and 13/11/2020

Figure 6 (a to d) indicates that relative humidity (RH) data for November 11 and 13, 2020, showed a range of values throughout the day, indicating fluctuations in moisture content in the air. The relative humidity began with rather high readings, around 89–90%, which could be indicative of early morning dew or moisture in the air. For November 11th and 13th, 2020, the relative humidity levels changed around midday, ranging from roughly 56% to 65% and 48% to 70%, respectively. This variability indicates variations in atmospheric conditions and the potential influence of elements such as temperature and air movement. Lower relative humidity in the afternoon may signal warmer and drier conditions. The relative humidity levels rose somewhat as the evening progressed, with occasional volatility.

Figure 6 (a and b) demonstrates that the cell operating temperature of the PV modules increased as RH decreased and declined as RH increased. Although the lowest temperatures of 31.02^{o}C and 28.3^{o}C, respectively, were observed at the start of work when RH values were highest, the maximum temperatures of 47.9^{o}C and 52.38^{o}C, respectively, reached at 11:30 hours and 13:30 hours, were not recorded when RH was at its lowest values of 55.8% and 48%. This indicates that other factors may have influenced the cell operating temperature of the PV module at these times. The inverse association between the variables is confirmed by a substantial negative correlation between RH and the solar module's cell operating temperature (COT), with coefficients of correlation (r) of -0.8209 and -0.8737, respectively, for the days analyzed.

Similarly, an increase in RH reduced the current output of the PV modules, while a drop in RH increased the current output of the PV modules. The lowest current outputs of 1.0A and 0.6A were recorded when RH values were at their highest, but the maximum current outputs of

14.2A and 15.25A, respectively, reached at 11:30 hours and 12:40 hours, were not recorded when RH values were at their lowest of 55.8% and 48%, respectively. This shows that other variables may have influenced the generated current output of the PV module during these times. A negative correlation between RH and the current output generated by PV modules, with coefficients of correlation (r) of -0.5247 and -0.7115, respectively, for the days studied, confirms the inverse association between the variables. This is in agreement with Gupta et al. (2019), who reported that the output of PV systems decreases by 40% during the rainy season at a relative humidity of 76.3% and by 45% during the cloudy season at a relative humidity of 60.5%.

Linear regression analysis was done on the RH and PV modules' COT, as well as the RH and PV modules' current output, to provide a better understanding of the relationship between the variables. The models, Equations 13-14 and 15-16, provide the relationship for the variables found for November 11th and November 13th, 2020, respectively.

$$y = -0.4099x + 67.945 \tag{13}$$

$$y = -0.1904x + 19.34 \tag{14}$$

For November 11, 2020, the models for RH and PV module cell operating temperatures showed a negative trend but a moderate positive coefficient of regression (r^2) with a r^2 value of 0.6739, while RH and PV module current output showed a negative trend with a low positive coefficient of regression (r^2) with a r^2 value of 0.2753, indicating that RH has an inverse effect on the PV module's cell operating temperature and generated current output.

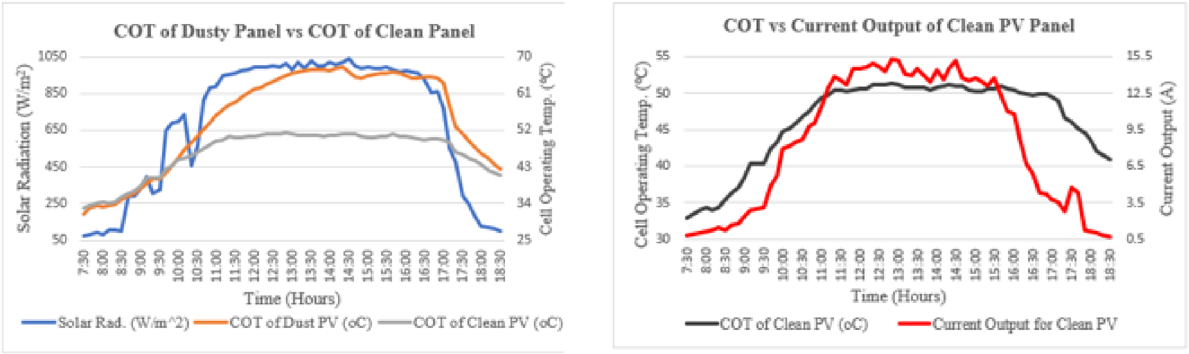
$$y = -0.4799x + 73.646 \tag{15}$$

$$y = -0.2253x + 21.985 \tag{16}$$

The models for RH vs PV module’s COT and RH versus PV module current output both exhibited a negative trend and moderately positive coefficients of regression (r^2) for November 13th, 2020, with r^2 values of 0.7633 and 0.5063, respectively. This demonstrates that RH has an inverse effect on the cell operating temperature and generated current output of the PV module.

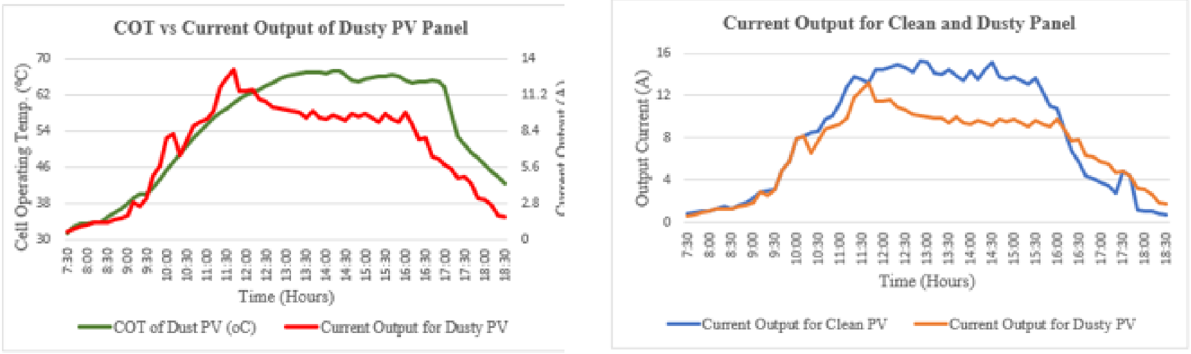
Effect of Dust Accumulation on COT of PV Panels and Current Output

The irradiation values for this day were plotted against the COT of the dusty and clean panels as a function of the time of the day (figure 7a). To compare COT and current output, the dataset of the COT of the clean and dusty panels was plotted against the current output generated as a function of the time of the day (figure 7 b and c, respectively). The current output of the dusty and the clean panels are compared in Figure 7 d.



(a) Solar Rad. Vs COT of Dusty and Clean Panel

(b) COT vs Current Output of Clean Panel



(c) COT vs Current Output of Dusty Panel

(d) Current Output of Dusty and Clean Panel

Figure 7: COT and Current Output of the PV Module for Dusty and Clean Panels

The COT of the clean and dusty panels differs significantly, according to the analysis (Figure 7a). With solar radiation levels generally low (between 74 and 398.5 W/m^2) in the early to mid-morning hours (7:30 to 9:50), the COT difference between the dusty PV and clean PV panels was minimal, with dusty PV panels just slightly cooler. The temperature difference increased as the morning advanced from mid-morning to midday (about 9:00 to 12:00 hours), with solar radiation values ranging from 648.5 to 990 W/m^2. When compared to clean PV panels, dusty PV panels regularly display higher temperatures. This temperature difference could be related to greater sunlight exposure and heat absorption caused by the dust layer on the PV panel. The temperature difference was large in the afternoon (12:30 to 16:30 hours), with dust PV panels constantly retaining higher temperatures. The cell operating temperature difference peaked at 16.4^{o}C at about 13:50 hours, when solar radiation was 1002.5 W/m^2, before gradually decreasing in the late afternoon. The temperature difference began to narrow in the late afternoon and early evening (16:00 to 18:30 hours), but dusty PV panels still maintained slightly higher temperatures. The dataset highlighted the effect of dust deposition on the cell operating temperature of PV panels.

Figure 7b demonstrates that the current output of the clean PV panels was relatively low (between 0.8 A and 3.15 A) throughout the early to mid-morning hours (7:30 to 9:30), consistent with the panels receiving little sunshine. During this time, the corresponding cell operating temperatures of the panel are also quite low (between 32^{o}C and 40^{o}C). Both current output and panel temperatures increased significantly from mid-morning through midday (about 9:30 to 12:00). This period coincided with relatively high sunlight, resulting in maximum energy generation and warmer panel temperatures. The current output of the clean PV panels grew further in the afternoon (12:30 to 15:50 hours), remained consistently high, and peaked at 15.25^{o}C at about 12:50 hours when the COT was likewise at its highest point of

51.41°C. The current output significantly decreased in the late afternoon and early evening (16:00 to 18:30). As the sun began to set and the intensity of the sunlight reduced, both current output and panel temperatures dropped to extremely low levels. The clean PV panels had a 0.8338 coefficient of correlation (r) value between the panel's COT and generated current output.

The current output of the dusty PV panels followed a similar pattern to that of the clean panel between early morning and about midday (7:30 to 11:40) when the COT was 60°C or lower (figure 7c). The panel COT increased significantly from around noon (11:50 to 17:00 hours), with values reaching 67.41°C. This was attributed to greater energy absorption from collected dust due to peak irradiation. This resulted in a drop in current production of up to 6 A during this period. Shaik et al. (2023) reported that greater temperatures can raise the resistance of the semiconductor materials in the panel, resulting in larger energy losses. Some of the energy collected by the panel was lost as heat rather than being converted to electricity. The current production decreased considerably in the evening (17:00 to 18:30). The dusty PV panel, like the clean PV panel, showed a correlation between panel COT and current output with a coefficient of correlation (r) value of 0.8664.

Figure 7d shows the current output trends of clean and dusty PV panels. It demonstrates that both displayed identical current output patterns until the COT of the dusty PV panel was above 60°C. Within this period, the clean PV panel had higher current outputs. Clean PV panels may have somewhat greater current outputs due to their cleaner surfaces, which allows for more efficient energy conversion when compared to dusty panels. This agrees with Adinoyi and Said (2013), who observed that the absence of cleaning can cause power generation to fall by 50% of its maximum level.

CONCLUSION

This study emphasizes the significance of routine maintenance, such as cell operating temperature regulation and cleaning, for maximum solar panel performance. It demonstrates that dust accumulation can have a considerable impact on energy output and efficiency, hence compromising the economic viability of solar systems. The performance differences between the clean and dusty panels highlight the importance of frequent maintenance to ensure the long-term efficiency and sustainability of solar energy systems. The findings also indicate the need for additional research into the relationship between dust accumulation, meteorological conditions, and cleaning frequency. This study not only advances our understanding of photovoltaic systems but it also supports the development of appropriate maintenance procedures for increasing energy generation from solar panels.

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