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Wind-Induced Cooling Effects on Photovoltaic Panel Performance

Jay S. Villan*, Sean Miles V. Pepito, Chauncey Earl R. Amierol, and Jhune Marc D. Buenacosa

Electrical and Electronics Engineering Department, Mindanao State University − General Santos, Fatima, General Santos City, 9500 Philippines
*Corresponding author: jay.villan@msugensan.edu.ph

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Abstract

This investigation evaluated the performance of a photovoltaic (PV) panel system under varied cooling speeds of a calibrated wind generator. The objectives encompassed the calibration of wind speed, integration of the wind generator with the PV panel system, monitoring the performance of the PV panel with wind-induced cooling, and analyzing overall performance under different wind generator settings. Parameters assessed included open circuit voltage, short circuit current, PV panel surface temperature, and power output. The tests were carried out both with and without wind cooling and under artificial and natural lighting conditions. Under artificial lighting conditions, the solar PV panel demonstrated suboptimal short circuit current compared to natural lighting conditions, leading to an overall decrease in power output. Moreover, the findings revealed a significant relationship between simulated wind speed and the overall performance of the PV panel, with notable variations in surface temperature, voltage level, current level, and power output. The statistical analysis supported these findings, with all dependent variables exhibiting statistically significant differences. The practical implications of these observations are pertinent to the design of more efficient and sustainable PV and PV-wind cooling systems. By comprehending the influence of wind on PV panel performance, system designers and operators can make informed decisions to maximize energy production and enhance the overall efficiency of the PV system.

Keywords: *active wind cooling, photovoltaic performance, wind generator, renewable energy, ANOVA*

The expansion of renewable energy sources, particularly PV installations, has prompted heightened research interest in efficiency enhancement. A mere 1% increase in efficiency holds substantial importance for sustainable energy development, particularly given the insufficient consideration of certain factors, such as wind speed, in PV systems [1]. Local wind speed, ambient temperature, and other environmental factors have been identified as significant influencers on PV system performance [2]. While the effects of ambient and cell temperatures on PV systems have been theoretically and empirically explored, the role of wind velocity, especially in inducing a drop in cell performance, remains an area of investigation [3].

Previous research by Kaldellis et al. [4] delved into the impact of temperature and wind speed on solar panel performance, revealing a decline in PV efficiency as temperatures rise. These results were corroborated by Schwingshackl et al.'s numerical investigation that underscored the importance of wind's cooling effects for precise power estimation [5]. Moreover, external factors affecting PV system efficiency, such as wind speed, become even more crucial in the context of active cooling methods. As highlighted by Shan et al. in 2014 [6], active cooling methods necessitate external electrical or mechanical energy sources, such as fans for air circulation and pumps for water circulation on the panels to effectively dissipate heat. Under high irradiation, forced convection cooling (air/water) is more efficient, resulting in up to 15% efficiency gain and temperature reduction [7].

Active cooling technologies utilize an external force to increase the flow of fluid, which leads to a significant reduction in heat and overcomes the limitation of space in solar energy production [8]. This further underscores the significance of employing effective cooling strategies to enhance the overall performance and efficiency of PV panels.

The evaluation of PV modules' health, degradation, and performance is paramount, with PV I-V curves (Figure 1) [9] serving as vital tools for this purpose. These curves, created through I-V tracers, offer insights into the condition of PV

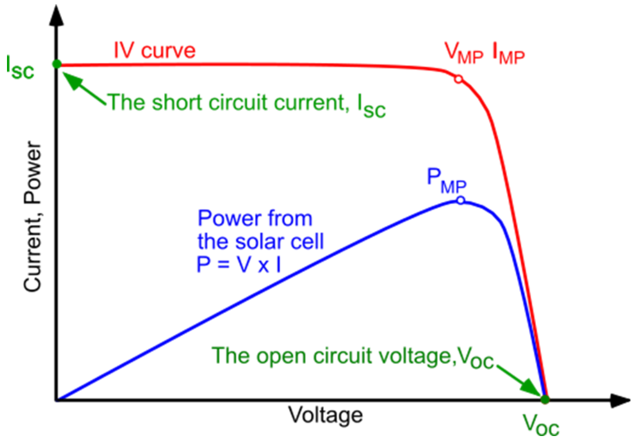

Figure 1. I-V Curve of a PV Panel, illustrating the relationship between the current (I) and voltage (V) across the panel under varying conditions. The open circuit voltage (Voc) is maximum when the current is zero while the short circuit current (Isc) is maximum when the voltage is forced to zero.

modules. However, the traditional methodology for I-V curve generation is considered highly invasive and undesirable [10]. As emphasized by Ramos Hernanz [11], field I-V curve measurements allow for the testing of a substantial sample of modules directly at their installation sites, distinguishing weak modules and detecting faulty connections, a capability not present in laboratory measurements. Periodic field I-V curve measurements also prove valuable in unveiling degradation trends in PV modules. Among the parameters in the I-V curve, various characteristics such as short-circuit current (I_{sc}), the current through the solar cell when the voltage is zero [12], and open-circuit voltage (V_{oc}), the maximum voltage available when there is zero current [13], provide a comprehensive understanding of the operational status and reliability of PV modules. These parameters can be directly measured using handheld instruments in a laboratory setting. Additionally, characteristics like maximum power (W), voltage at maximum power (V_{mp}), current at maximum power (I_{mp}), and conversion efficiency (%) are encompassed in the I-V curve, contributing valuable data for the evaluation and enhancement of solar energy systems [14].

A wind speed generator prototype was developed to simulate local wind conditions in a controlled laboratory environment. The subsequent experiments, tests, and calculations, including the measurement of V_{oc} and I_{sc}, were conducted within this controlled setup. This not only contributed to a deeper understanding of the frequently overlooked cooling effect of wind speed but also carried practical implications for estimating the true potential of PV plants, informing market strategies, and guiding product development. This study, conducted explicitly for experimental purposes, prioritizes data acquisition centered around variable wind speeds, aiming to advance our comprehension of PV panel performance under controlled conditions.

Materials and Methods

The wind speed data crucial for the study was sourced from World Weather Online [15]. In the wind generator prototype, an AC asynchronous single-phase motor powered by an AC source was utilized, and a DC source activated the motor speed controller for generating variable wind speeds as the output. The solar panel used in the experimentation was a 10W/22.36V Voc/0.57A I_{sc} panel positioned at a 17° angle of inclination to optimize conditions for Philippine solar panels [16]. The experiment occurred in a simulated closed-room environment to ensure controlled conditions with monitored and regulated lighting.

To maintain consistent environmental conditions, an alternative light source, a 78mm/60Hz/220V halogen lamp, was employed. Wind speed testing was conducted using a digital anemometer to measure atmospheric parameters in km/hr. An infrared thermal gun, with a range of -50°C to 390°C and displaying readings in degrees Celsius, was employed to determine temperature variations in the solar panel. Crucial output parameters for PV cell performance were assessed for efficiency calculations. The statistical treatment involved the application of ANOVA, specifically a one-way, single-factor analysis, to investigate significant differences between means for temperature, voltage, current, and power output across varying conditions.

The wind generator prototype with a microcontroller was developed to measure and display fan speed. Figure 2.A. shows the dimensions of the prototype, while Figure 2.B. shows the actual working prototype. This prototype simulates and assesses wind's impact on solar photovoltaic (PV) systems. By gauging the fan's rotational speed, influenced by wind speed, valuable wind speed data and potential effects on PV performance are obtained. An organic light-emitting diode (OLED) display is used for motor shaft revolutions per minute (RPM) and wind speed readouts. An Arduino Uno microcontroller executes code, initializes the display, and processes interrupts from the infrared sensor. The data from RPM is correlated with wind speed measurements to display the prototype's wind speed generation, as elaborated in the wind speed calibration section. Figure 3 shows the experimental setup, dimensions, and clearance for the investigation.

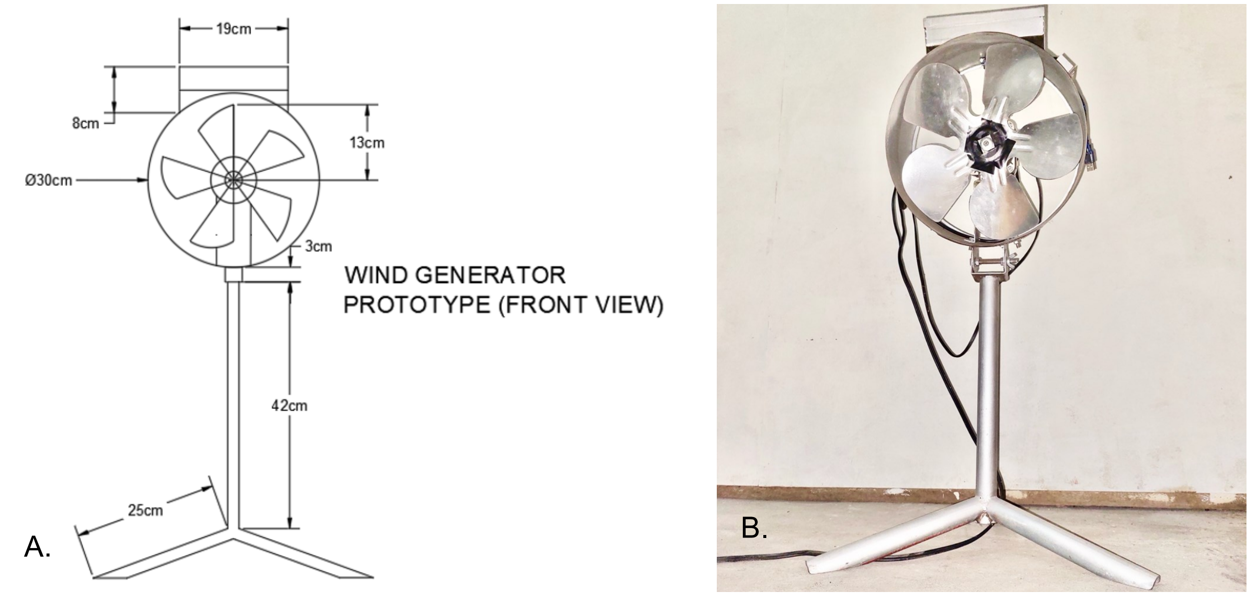

Figure 2. (A) Dimensions of the wind generator prototype carried out using a computer aided design (CAD) software. (B) Photograph of an actual wind generator prototype. Commercially available fan blades and a variable-speed AC motor were used in the assembly.

A relationship between motor RPM and wind speed was established. As motor RPM decreased, so did the generated wind speed. Calibration involved measuring wind speed 0.5m from the prototype, perpendicular to avoid shadow interference. Starting at 1472 RPM (12 km/h wind speed), RPM was decreased in 100-step increments until reaching 472 RPM (zero wind speed). Wind speed measurements at various RPMs led to the formula $y = 0.0111x - 3.958$, derived through linear regression. Shown in Figure 4 below is the regression line derived from the raw values of wind speed and motor shaft speed.

Results and Discussion

Figure 5 illustrates that, in the absence of wind speed under artificial lighting, the PV panel surface temperature peaks at 50.4℃. Conversely, at wind speeds of 7-8 km/h, 9-10 km/h, and 11-12 km/h, the recorded average temperatures are 35.31° C, 34.93℃, and 33.1℃, respectively.

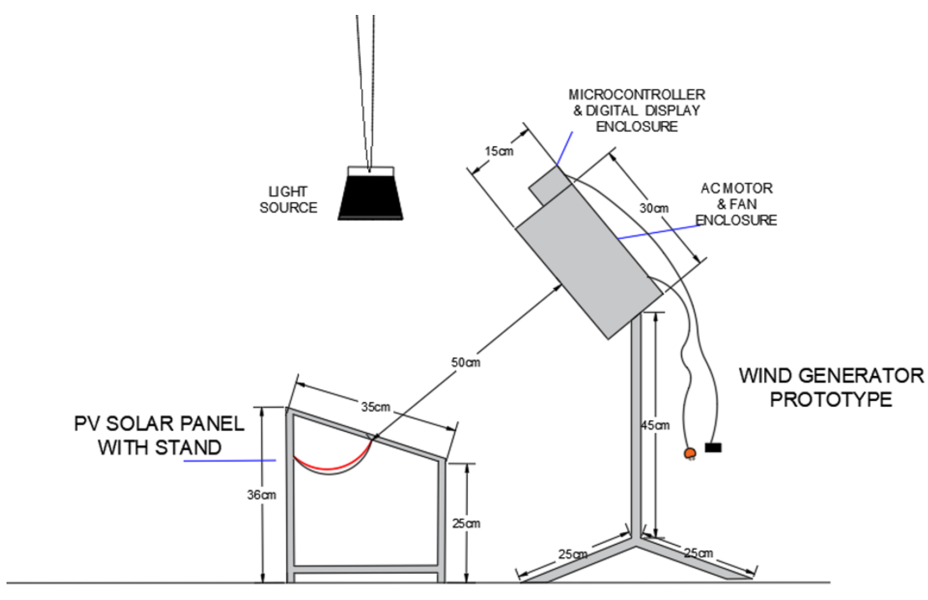

Figure 3. The experimental setup showing the PV panel, light source, and wind generator prototype. The dimensions and clearance of the wind generator prototype and the solar panel with stand is also indicated.

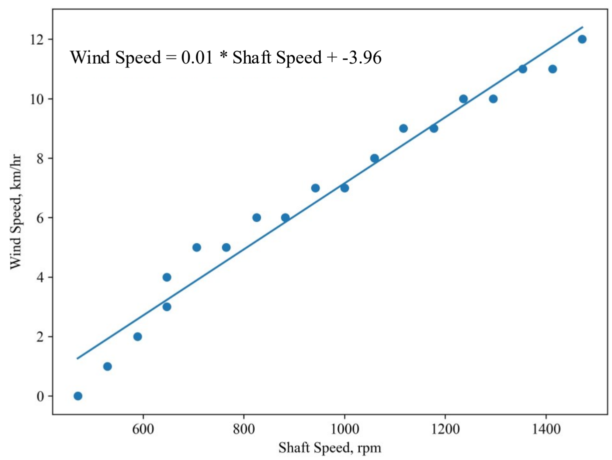

Figure 4. Correlation between shaft speed with wind speed for the calibration of the wind generator prototype. A linear correlation is observed between these two variables.

In natural lighting conditions, Figure 5 also depicts the PV panel surface temperature reaching up to 48.40℃ without wind. Conversely, at wind speeds of 7-8 km/h, 9-10 km/h, and 11-12 km/h, the average temperatures are 43.28℃, 41.58℃, and 41.42℃, respectively. In both cases, the results demonstrate a consistent decrease in temperature with an increase in wind speed, aligning with the findings of [17].

V_{oc} testing conducted under artificial lighting on PV panels exposed to varying wind speeds (Figure 6) indicates that the introduction of wind closely approaches voltage values to the optimal range for solar panels. Under wind speeds of 7-12 km/hr, average voltage measurements hover around 19.37 V, 19.37 V, and 19.47 V, respectively, compared to an average of 18.56 V without wind cooling.

Figure 6 also presents open circuit voltage values at various wind speeds applied to PV panels in natural lighting conditions. At wind speeds of 7-8 km/hr, 9-10 km/hr, and 11-12 km/hr, average voltage measurements are approximately 19.92 V, 20.04 V, and 20.18 V, respectively, compared to an average voltage of 19.059 V without air circulation. These findings underscore the influence of wind, consistently aligning open circuit voltage within the optimal value of 22.36 V. This observed influence on open circuit voltage aligns with [18], which noted a decrease in open circuit voltage with cell temperature, influenced by weather variables such as ambient temperature solar radiation, including wind speed. This finding is further consistent with the conclusions of [19, 21], which indicate that V_{oc} increases with an increase in wind speed.

Figure 7 presents I_{sc} testing results, indicating a notable difference in current values between artificial and natural light. Short circuit

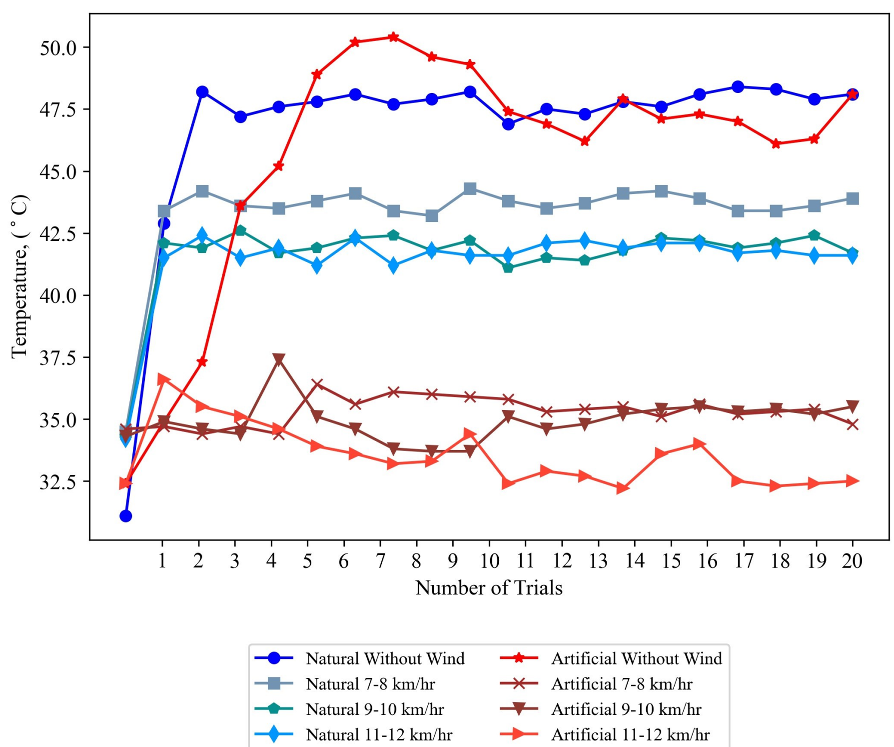

Figure 5. Comparison of the temperature readings between artificial and natural light sources measured from PV panel. Except for no wind condition, lower PV panel temperatures were obtained under artificial lighting conditions than under natural lighting conditions.

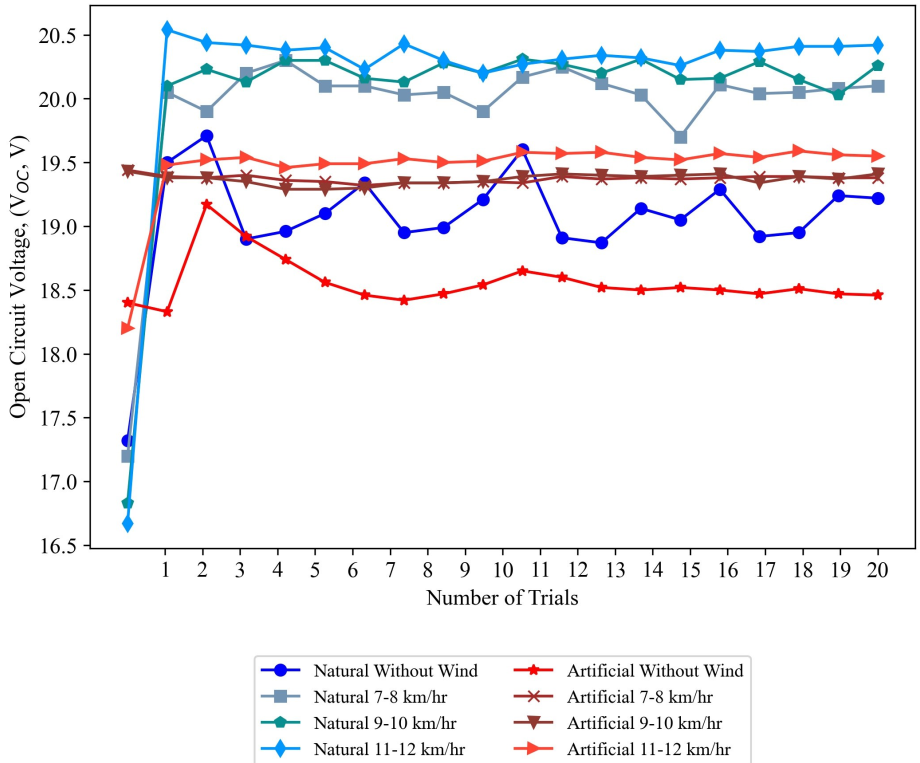

Figure 6. Conmparison of the PV panel open circuit voltage (V_{OC}) readings between artificial and natural light sources at various wind speeds. V_{OC} is higher under natural lighting conditions compared with artificial lighting conditions when wind was introduced on the PV panel surface. The highest V_{OC} was recorded at the wind speed of 11-12 km/hr.

currents from PV panels under artificial light indicate a relatively minorcurrent measurement range. At wind speeds of 7-8 km/hr, 9-10 km/hr, and 11-12 km/hr, average current measurements are 77.5 mA, 71.5 mA, and 78.0 mA, respectively. In contrast, without wind, the present value averages at 90.0 mA, indicating a slight increase. This suggests that the involvement of wind impacts the system, resulting in lower current values than cases without convective cooling. This finding aligns with [19], indicating a decrease in I_{sc} with increasing wind speed.

The same figure displays I_{sc} testing results, revealing a broader range of current measurements with higher magnitudes when the wind is introduced on the PV panel surface under natural lighting conditions. At wind speeds of 7-8 km/hr, 9-10 km/hr, and 11-12 km/hr, the current measurements are 400.0 mA, 453.5 mA, and 495.5 mA, respectively. In contrast, without wind, the current value averages 271.5 mA, representing a 45% lower value when the induced wind is not introduced on the module surface.

Insolation plays a significant role in PV panel characteristics [22, 23]. The limited range of current readings observed for the PV panel under artificial lighting can be linked to the lower output of the light source. On the contrary, Farahani [23] elucidates that natural illumination enhances the short circuit current due to heightened solar insolation levels.

During power output testing, as depicted in Figure 8, the incorporation of wind exhibited a diminishing effect on power output under artificial lighting conditions. Average power output values at wind speeds of 7-8 km/hr, 9-10 km/hr, and 11-12 km/hr were 1.50 W, 1.38 W, and 1.51 W, respectively. In contrast, the absence of integrated wind yielded a slightly higher average power output of 1.67 W. It is noteworthy that, despite the calibrated generator aligning with local wind speeds, power output is contingent upon the interplay of V_{oc} and I_{sc}. The increase in V_{oc} and a marginal rise in I_{sc} (Figure 6) explain the amplified power output for artificial lighting conditions without induced air circulation over the PV panel surface.

Figure 8 also illustrates observations from power output testing, revealing that the integration of wind contributed to an augmented power output under natural lighting conditions. At wind speeds of 7-8 km/hr, 9-10 km/hr, and 11-12 km/hr, average power output values reached 8.02 W, 9.16 W, and 10.09 W, respectively. Conversely, in the absence of wind circulation on the panel, the power output averaged 5.19 W, representing a

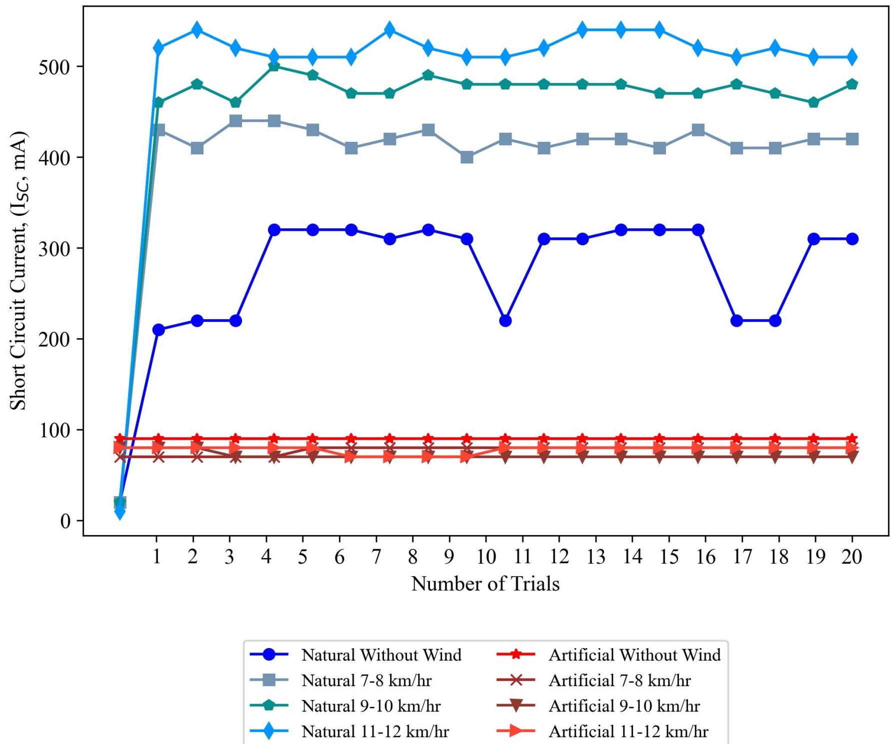

Figure 7. Comparison of the short circuit current (I_{SC}) between artificial and natural light sources at various wind speeds. Natural lighting conditions provide the largest current (~200-550 mA) compared to artificial lighting.

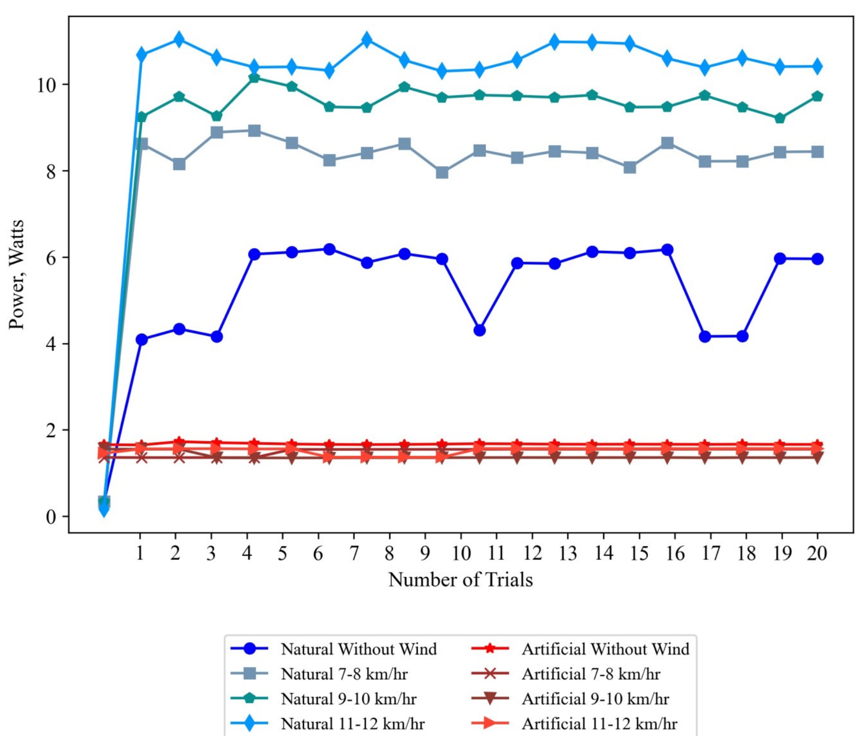

Figure 8. Comparison of the power output in the PV between artificial and natural light sources at various wind speeds. Natural lighting condition delivered more power that ranged from ~4-11 W.

significantly lower performance. These findings underscore the consequential impact of introducing wind as a contributing factor, resulting in enhanced power output compared to scenarios without forced convection on the PV panel surface.

Statistical Analysis

The analysis reveals a robust and statistically significant relationship between the simulated variable wind speed and various crucial solar PV panel performance metrics. In each instance, the F-values substantially exceed the F-critical value, while the p-values are exceptionally low, emphasizing the strength of these associations.

Firstly, the research shows a significant connection between wind speed and the surface temperature of the solar PV panel under artificial lighting, with an F-value of 90.78 and a p-value of 4.68×10^{-25}. Secondly, the open-circuit voltage of the solar PV panel under artificial lighting exhibits a pronounced relationship with wind speed, as indicated by an F-value of 110.71 and a p-value of 1.16×10^{-27}. Thirdly, the study demonstrates a notable correlation between wind speed and PV short-circuit current under artificial lighting, with an F-value of 96.13 and a p-value of 8.48×10^{-26}. Moreover, wind speed significantly influences the power output of the solar PV panel under artificial lighting, with an F-value of 56.58 and a p-value of 2.53×10^{-19}.

In addition to these findings, there is a substantial relationship between wind speed and the surface temperature of the solar PV panel under natural lighting (F-value: 19.23, p-value: 2.23×10^{-09}). Similarly, wind speed is significantly linked to the open-circuit voltage under natural lighting (F-value: 10.61, p-value: 6.64×10^{-06}) and short-circuit current under natural lighting (F-value: 20.24, p-value: 9.68×10^{-10}) of the solar PV panel. Lastly, the power output of the solar PV panel under natural lighting is significantly affected by wind speed, with an F-value of 23.65 and a p-value of 6.51×10^{-11}. These results collectively highlight the substantial influence of wind speed on the performance of solar PV panels across various critical metrics.

Conclusion

This study successfully addressed its objectives, offering a holistic view of a PV panel system's performance when integrated with air cooling using a calibrated wind generator. The meticulous assembly and thorough monitoring of key parameters enabled a comprehensive assessment. Moreover, the analysis of the PV panel's response to varying wind speeds and different wind generator settings provided valuable data for optimizing system efficiency. Nevertheless, during laboratory experiments, it is crucial to ensure that artificial lighting conditions align with the specified values to replicate outdoor insolation accurately. These findings highlight the potential of hybrid energy systems, advancing sustainable and dependable power generation technologies. To further enhance this field, recommendations are proposed. Firstly, incorporating local wind speed data into predictive models is recommended to improve power output forecasts. Second, research into the optimal synergy between wind speed and solar irradiance can maximize PV panel system efficiency. Assessing system performance under diverse environmental conditions is crucial, as it provides insights into their impacts on power output and efficiency. Lastly, considering scaling up the system and implementing Artificial Intelligence (AI) for advanced control and decision-making could result in enhanced efficiency. These recommendations aim to continually refine and optimize solar PV panel systems, addressing dynamic factors affecting their performance.

Authors' Contribution

JSV designed the framework and oversaw the data gathering, design implementation, testing, and data analysis. SMVP, CERA, and JMDB conducted design implementation, testing, and data gathering.

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References

[1] Gökmen, N., et al. (2016). Investigation of wind speed cooling effect on PV panels in windy locations. *Renewable Energy*, *90*, 283-290. Doi: 10.1016/j.renene.2016.01.017

[2] Rao, A., et al. (2014). Influence of dust deposition on photovoltaic panel performance. *Energy Procedia*, *54*, 690-700. Doi: 10.1016/ j.egypro.2014.07.310

[3] Goossens, D., and Van Kerschaever, E. (1999). Aeolian dust deposition on photovoltaic solar cells: The effects of wind velocity and airborne dust concentration on cell performance. *Solar Energy*, *66*(4), 277-289. Doi: 10.1016/S0038-092X(99)

00028-6

[4] Kaldellis, J., et al. (2014). Temperature and wind speed impact on the efficiency of PV installations: Experience obtained from outdoor measurements in Greece. *Renewable Energy*, *66*, 612-624. Doi: 10.1016/j.renene.2013.12.041

[5] Schwingshackl, C., et al. (2013). Wind effect on PV module temperature: Analysis of different techniques for an accurate estimation. *Energy Procedia, 40*, 77-86. Doi: 10.1016/j.egypro.2013.08.010

[6] Shan, F., et al. (2014). Dynamic characteristics modeling of a hybrid photovoltaic–thermal solar collector with active cooling in buildings. *Energy and Buildings*, *78*, 215-221. Doi: 10.1016/j.enbuild.2014.04.037

[7] Mazón-Hernández, R., et al. (2013). Improving the electrical parameters of a photovoltaic panel by means of an induced or forced air stream. *International Journal of Photoenergy*, *2013*, Article ID 830968, 10 pages. Doi: 10.1155/2013/830968

[8] Parthiban, R., and Ponnambalam, P. (2022). An enhancement of the solar panel efficiency: A comprehensive review. *Frontiers in Energy Research*, *10*. Doi: 10.3389/fenrg.2022.937155

[9] PVeducation. (n.d.). IV curve. Retrieved from https://www.pveducation.org/pvcdrom/solar-cell-operation/iv-curve

[10] Chi, H. B., et al. (2019). Internet of Things (IoT) based I-V curve tracer for photovoltaic monitoring systems. *Indonesian Journal of Electrical Engineering and Computer Science*, *13*(3), 1022-1030. Doi: 10.11591/ijeecs.v13.i3.pp1022-1030.

[11] Ramos, J., e et al. (2010). Modelling of Photovoltaic Module. *Renewable Energy and Power Quality Journal*. *1*. Doi: 1186-1190. 10.24084/repqj08.619.

[12] PVeducation. (n.d.). Short-circuit current. Retrieved from https://www.pveducation.org/pvcdrom/solar-cell-operation/short-circuit-current

[13] PVeducation. (n.d.). Open-circuit voltage. Retrieved from https://www.pveducation.org/pvcdrom/solar-cell-operation/open-circuit-voltage

[14] Messenger, R. A., and Ventre, J. (2005). *Photovoltaic Systems Engineering* (2nd ed.). New York: Taylor and Francis.

[15] WorldWeatherOnline. (n.d.). General Santos City weather charts. Retrieved from https://www.worldweatheronline.com/general-santos-city-15day-weather-chart/general-santos/ph.aspx

[16] Malicdem, E. (2015). Optimal tilt of solar panels in the Philippines. Schadow1 Expeditions. Retrieved from https://www.s1expeditions.com/2015/02/179-solar-panels-optimal-tilt-philippines.html

[17] Skoplaki, E., and Palyvos, J. A. (2009). On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations. *Solar Energy*, *83*(5), 614-624. Doi: 10.1016/j.solener.2008.10.008

[18] Zondag, H. A. (2008). Flat-plate PV-Thermal collectors and systems: A review. *Renewable and Sustainable Energy Reviews*, *12*(4), 891-959.

[19] Al-Maghalseh, M. (2018). Experimental Study to Investigate the Effect of Dust, Wind Speed, and Temperature on the PV Module Performance. *Jordan Journal of Mechanical and Industrial Engineering*, *12* (2).

[20] Goverde, H., et al. (2015). Spatial and temporal analysis of wind effects on PV module temperature and performance. *Sustainable Energy Technologies and Assessments*, *11*, 36-41. Doi: 10.1016/j.seta.2015.05.003

[21] Dubey, S., Sarvaiya, J. N., and Seshadri, B. (2013). Temperature Dependent Photovoltaic (PV) Efficiency and Its Effect on PV Production in the World – A Review. *Energy Procedia*, *33*, 311-321. Doi: 10.1016/j.egypro.2013.05.072.

[22] Suman, P., and Goyal, P. (2021). Analyzing the effects of solar insolation and temperature on PV cell characteristics. *Materials Today: Proceedings*, *45*(6), 5539-5543. Doi: 10.1016/j.matpr.2021.02.301.

[23] Farahani, G. (2019). Considering the Correlation of Insolation and Temperature on the PV Array Characteristics. *Paper presented at the 2019 9th International Conference on Power and Energy Systems (ICPES)*, Perth, Australia, Dec. 10-12, 2019 (pp. 1-6). Doi: 10.1109/ICPES47639.2019.9105585