ISSN: 0976-3376

Available Online at http://www.journalajst.com

ASIAN JOURNAL OF
SCIENCE AND TECHNOLOGY

Asian Journal of Science and Technology
Vol. 15, Issue, 12, pp. 13243-13248, December, 2024

RESEARCH ARTICLE

ANALYSIS OF THE PERFORMANCE OF MATHEMATICAL MODELS THAT CALCULATE THE TEMPERATURE OF PV MODULES USING METEOROLOGICAL DATA

***1,2Cheikh Saliou TOURE, 1Oumou BALDE and 2Senghane MBODJI**

1Photovoltaic Energy Department, Labe University, 210-Labe, Guinea
2Research Team Renewable Energies, Materials and Laser (2ERML), Alioune DIOP University of Bambey, Diourbel, 30 Bambey, Senegal

ARTICLE INFO

Article History:
Received 28th September 2024
Received in revised form
06th October, 2024
Accepted 17th November, 2024
Published online 09th December, 2024

Keywords:

Photovoltaic, operating temperature, PV module, weather condition, PV module temperature, mathematical models, experimental measurements.

ABSTRACT

Operating temperature is a critical factor affecting the performance of photovoltaic (PV) modules. In this study, we present models designed to predict the operating temperature of PV modules using ambient temperature and solar irradiance data collected from real measurements in a tropical region. Weather conditions were categorised based on irradiance and temperature levels, and the predicted PV module temperatures obtained from our models were compared with corresponding experimentally measured values. The results demonstrate that the PVSyst and Akhsassi models systematically consistently exhibit a lower Root Mean Squared Error (RMSE) compared to other models in the literature across all weather conditions, affirming the reliability of our approach.

Citation: Cheikh Saliou TOURE, Oumou BALDE and Senghane MBODJI. 2024. "Analysis of the Performance of Mathematical models that Calculate the Temperature of pv Modules Using Meteorological Data", *Asian Journal of Science and Technology*, 15, (12), 13243-13248.

INTRODUCTION

Research into the increase in the world's population, the invention of modern technologies and economic growth has shown that these have had a significant impact on the increase in global energy consumption. This has led to an increase in greenhouse gas (GHG) emissions into the environment [1, 2]. CO2 emissions into the atmosphere are mainly caused by the energy sector (76%), which is responsible for about 41% of global CO2 emissions [3'], [4']. To avoid these CO2 emissions associated with the use of fossil fuels, renewable energy sources (RES) can provide a viable alternative with a better environmental balance. Renewable energy is currently developing very rapidly, from residential and commercial installations to space systems. Research has shown that the sun is the most widely used energy source in the world, particularly in Asia and Africa due to its abundance [5', 6', 7']. Among solar energy sources, photovoltaic (PV) technology is the most widely used due to its simplicity of design and implementation [8', 9', 10']. PV technology is based on standard crystalline silicon solar cells with electrical conversion efficiencies between 16 and 20%. However, under certain standard test conditions (sunshine = 1,000 W/m² and temperature = 25°C), some modern silicon modules can convert up to 24.4% of solar radiation into usable electrical energy [11', 12']. Given that solar PV technology is widely used in all sectors of the world, we can conclude that this technology presents certain challenges. In fact, its operation is strongly influenced by variations in environmental conditions, which ultimately have a significant impact on PV cell performance. During the conversion of solar radiation by the PV cells, a large part of the solar radiation absorbed by the cells is dissipated as waste heat on the surface of the PV module [13'], [14'].Dust has a significant influence on the temperature evolution of PV modules. This is the case in the study carried out in [37], where a temperature difference was observed between a clean and a dirty module, with results showing that the temperature of the unclean module is higher than that of the clean module. This phenomenon is due to the absorption and diffusion of heat from solar radiation by dust particles. The electrical efficiency of a photovoltaic module depends on several factors: the base material, the location (tilt and orientation), the environmental conditions at the site (irradiation, temperature, wind, etc.), and dust and shading [26, 27, 28, 30]. In environments where the intensity of solar radiation is high, long-term exposure of PV modules to high temperatures leads to a significant decrease in their efficiency [29, 31, 32]. This is because the electrical efficiency of a PV module decreases as the module temperature increases [25, 33]. Increasing the temperature of PV cells reduces the efficiency of PV modules [25, 7]. The performance of PV modules is quantified at an operating temperature of 25°C. However, many researchers have quantified percentage losses above this operating temperature. This is the case of [34], which estimates that the efficiency of a crystalline silicon solar panel decreases from 0.15% to 0.6% of its nominal value for each degree increase in operating temperature. According to the authors of [35], who have carried out a state-of-the-art review of advanced PV module cooling techniques, if the temperature coefficient for a given panel is -0.5%, then the maximum power will be reduced by 0.5% for each 10°C increase. In the study in [2], the authors explain that an increase in temperature

---

****Corresponding Author: Cheikh Saliou TOURE,***
Photovoltaic Energy Department, Labe University, 210-Labe, Guinea

reduces the voltage and power of photovoltaic panels, despite a slight increase in current. Each 1°C increase results in an average reduction of 0.51 W (0.43%) for monocrystalline panels and 0.9 W (0.78%) for polycrystalline panels. It is therefore important to understand how the ambient temperature evolves before the PV module is installed in order to compensate for and maximise these efficiency losses. Many researchers have carried out modelling studies of the operating temperature of PV modules in tropical zones based on real meteorological data. The main objective of their work has been to compare the different existing models in order to determine the model or models that are best suited to predict the theoretical temperature of a PV module operating in the same area [6, 36, 12]. It should be noted that the mathematical models for predicting the temperature of photovoltaic panels have been obtained and validated on the basis of real climatic data. However, many of them have been validated on the basis of studies conducted under different climatic conditions, but their validation in tropical areas such as Senegal has not yet been exhaustively discussed in the literature. Sophisticated models that can better predict the operating temperature of PV modules in an area such as Senegal would be useful for studying and modelling the performance of PV systems. With this in mind, this paper investigates the performance of some temperature models for PV modules in tropical regions based on existing environmental data.

Experimental setup: The environmental data used in this study was collected at the Bokhol solar power plant. This plant is located in the north of Senegal, in Dagana. The plant in question covers an area of 40 hectares, on which 77,112 polycrystalline solar panels of 260 Wp are installed, corresponding to a surface area of 12 hectares. The efficiency of the PV panels is approximately 16%. The installed solar panels are mounted on supports inclined at 15 degrees to the horizontal and facing south. This is an area with high temperatures in March, April, May and June. The photovoltaic system is equipped with a number of measuring devices to monitor and record solar radiation, ambient temperature, PV module temperature, wind speed and humidity. Figure 1 shows the Bokhol solar power plant.

Theoretical models: In this study, we will examine the temperature models and validate them against our actual outdoor test data. The data includes irradiance, ambient and PV module temperatures and wind speed. These data are recorded at 5-minute intervals on an annual basis and are used as input parameters for the mathematical models. Table 1 summarises the models used.

Models analysis method: To analyse the models, weather conditions are classified according to temperature and irradiance. Table 2 illustrates this. Figure 2 shows the variation of irradiance and ambient temperature for the different meteorological conditions mentioned above. As a reminder, HH and LL represent high and low irradiance and ambient temperature respectively. HL means high irradiance and low temperature and LH means low irradiance and high temperature. The period with the highest levels of radiation is the dry season, between March and June. This period is also characterised by very high temperatures. Low temperatures and irradiation occurred between November and February. However, the decrease in irradiation often occurred during the rainy season, from July to December, which is characterised by cloudy days most of the time. The approach used in this study makes it possible to measure the degree of performance of the models for a large number of metrological data. A regression method is used to determine a constrained minimum of model shapes, with the aim of predicting the operating temperature of a photovoltaic (PV) module as a function of several variables from an initial estimate.

Fig. 1. Centrale solaire de Bokhol/Sénégal

Table 1. PV module temperature models

Models	Correlations	Comments
Akhsassi [38,39,40]	$T_m = \frac{U_L \cdot T_a + G_g[(\tau\alpha) - \eta_{STC}(1-\beta_{STC} \cdot T_{ref})(1+\gamma_{p_{mp}} \cdot Ln(\frac{G_g}{G_0}))]}{U_L + \eta_{STC} \cdot \beta_{STC} \cdot G_g[1+\gamma_{p_{mp}} \cdot Ln\left(\frac{G_g}{G_0}\right)]}$	$\gamma_{p_{mp}} = 0.04$ and $U_L = 24.68 + 6.13v$ $\eta_{STC} = 0.15$ for both Mono and Poly; 0.0987 for Amorp. $\beta_{STC} = 0.0045$ for Mono; 0.0041 for Poly ; 0.0028 for Amorp
PVSyst [39,40]	$T_m = T_a + \frac{(\tau\alpha) \cdot G_g[1-\eta_{PVSyst}]}{U_{L0} + U_{L1} \cdot v}$	$\eta_{PVSyst} = 0.1$; $U_{L1} = 6.28\ W.s/m^3/°C$; $U_{L0} = 29\ W/m^2/°C$
Mattei [38,39,40]	$T_m = \frac{U_L \cdot T_a + G_g[(\tau\alpha) - \eta_{STC}(1-\beta_{STC} \cdot T_{ref})]}{U_L + \eta_{STC} \cdot \beta_{STC} \cdot G_g}$	$U_L = 26.6 + 2.3v$. Others, same are used for Akhsassi.
Faiman [38,39,40]	$T_m = T_a + \frac{(\tau\alpha) \cdot G_g}{U_{L0} + U_{L1} \cdot v}$	$U_{L1} = 6.28\ W.s/m^3/°C$; $U_{L0} = 30.02\ W/m^2/°C$
Sandia [38,39,40]	$T_m = T_a + G_g e^{(a+b \cdot v)}$	$a = -3.56$ and $b = -0.075\ s/m$

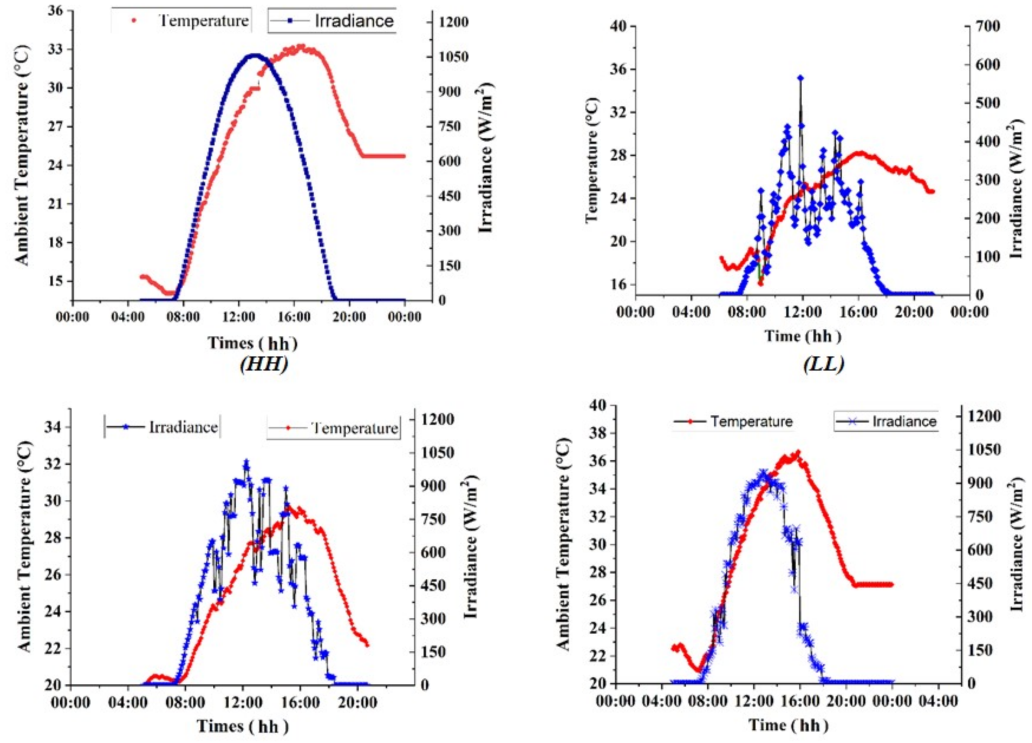
Table 2. Different weather conditions

Weather condition	Irradiance	Ambient temperature
HH	High	High
LL	Low	Low
HL	High	Low
LH	Low	High

These models are then analysed and compared with actual data obtained during outdoor testing of the PV modules.

RESULTS AND DISCUSSION

Operating temperature of PV panel: Figure 3 compares measured and modelled PV module temperatures for different models and weather conditions. It is evident that the PV module temperature variation reaches its maximum in the middle of the day, corresponding to solar noon, when the sunshine is at its peak. The results show that the Akhsassi and PVSyst PV module temperature models are closest to the measured PV module temperatures under HH, HL and LH weather conditions. The Faiman model best matches the measured temperatures under HL and LL conditions. The Sandia and Mattei models, on the other hand, show a better agreement with the



(HH) (LL)

(HL) (LH)

Figure 2. Weather conditions characteristic

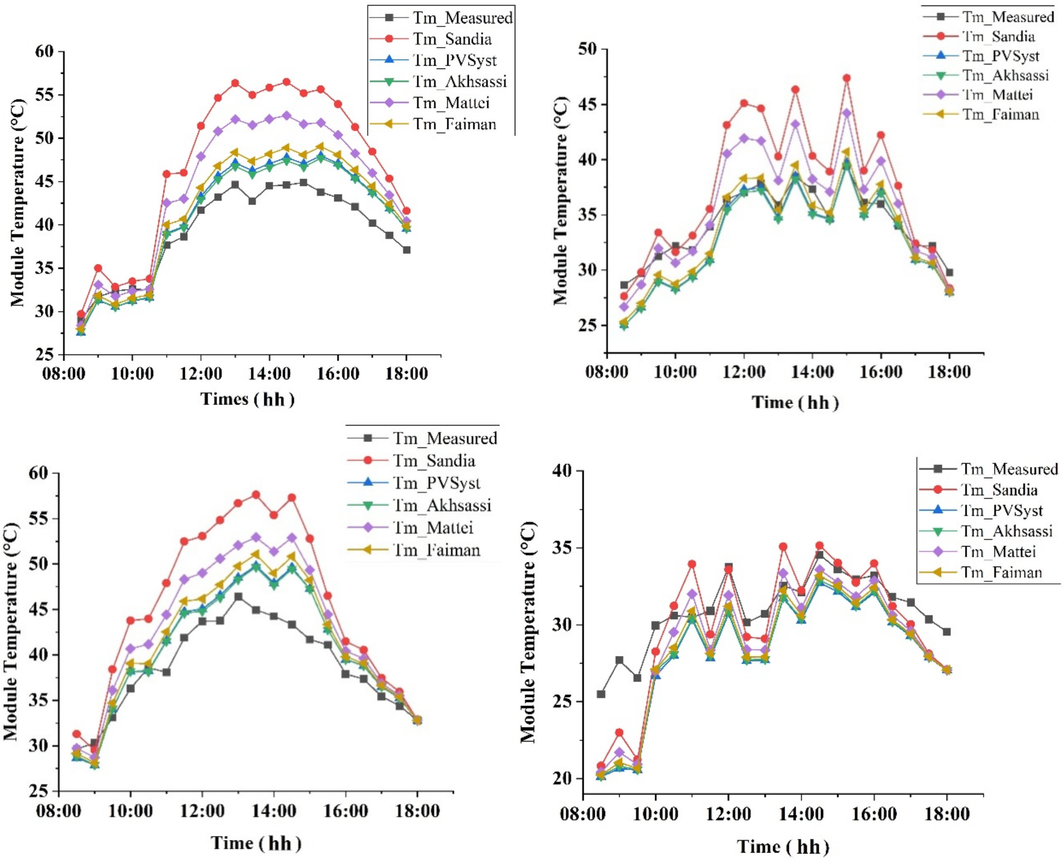
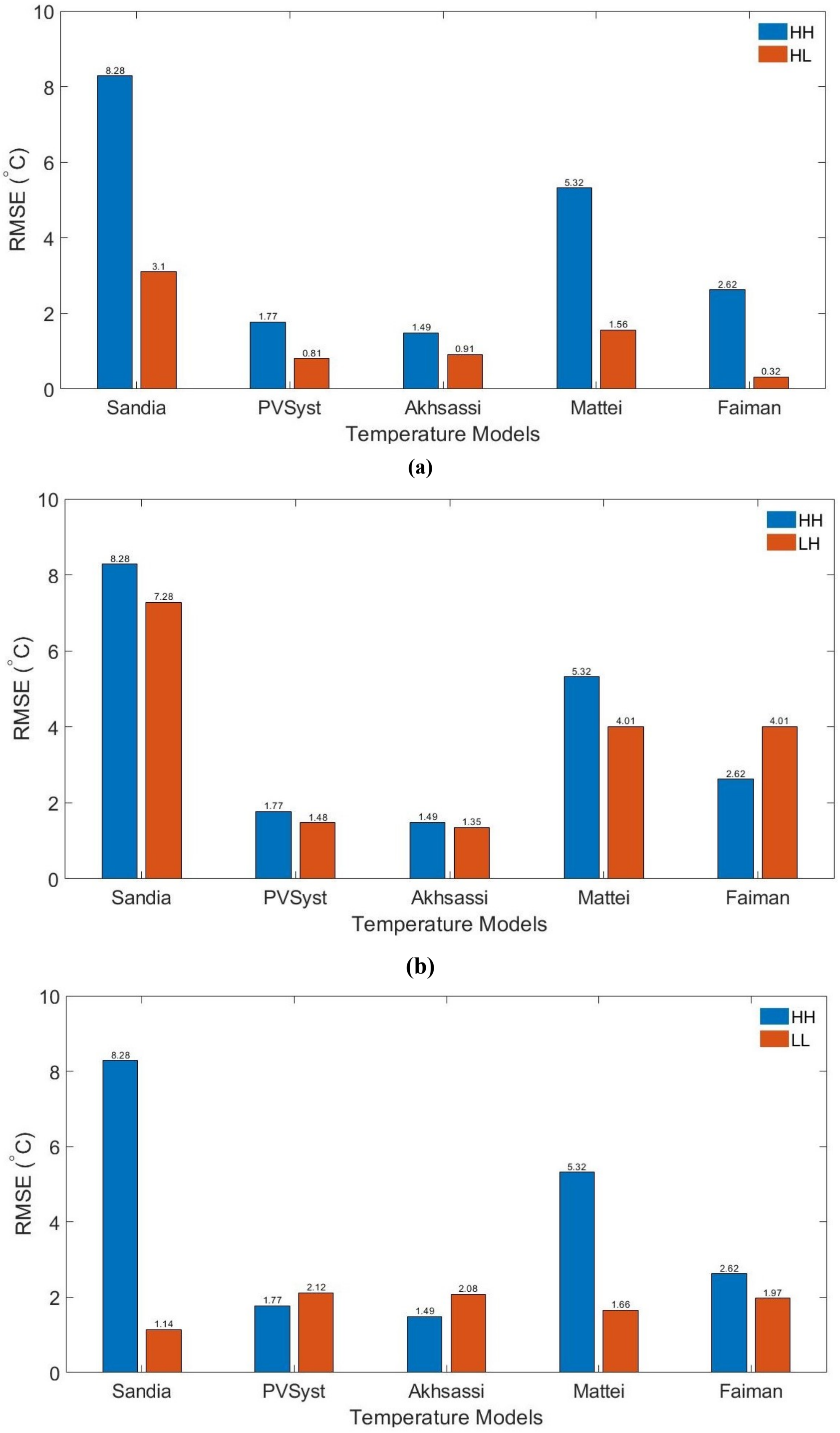


Figure 3. PV module operating temperature



(a)

(b)

(c)

Fig. 4. RMSE of PV module temperature models (a) under HH and HL weather conditions, (b) under HH and LH weather conditions, (c) under HH and LL weather conditions

measured temperatures under LL conditions, but tend to overestimate the temperatures for HH, HL and LH weather conditions. In the following we will examine the Root Mean Square Error (RMSE) of the temperature models used. As a reminder, the RMSE metric quantifies the dispersion of the residuals. In other words, it measures the concentration of the data around the line of best fit.

RMSE of PV module temperature models: Figure 4 compares the Root Mean Square Error (RMSE) of the PV module temperature models. Figure 4a shows that under high irradiation conditions, a decrease in ambient temperature leads to a decrease in RMSE for all temperature models. This decrease in RMS error is most pronounced for the Faiman model with an RMSE value of 0.32. When the irradiance and temperature conditions are simultaneously high, the RMS error increases for the Sandia and Mattei models.

Figure 4b shows that under high temperature conditions, a decrease in irradiance increases the RMSE for the Faiman model. However, for the Sandia, PVSyst, Akhsassi and Mattei models, a decrease in irradiance results in a slight decrease in RMSE. Figure 4c shows that low temperature and irradiance conditions lead to a large decrease in the RMSE for the Sandia and Mattei models, while they lead to a slight increase in the RMSE for the PVSyst and Akhsassi models. The results show that the PVSyst and Akhsassi models have the lowest RMSE values in all weather conditions, except for the LL condition where the Sandia model stands out as the best performer. Therefore, the PVSyst and Akhsassi models proposed in this study are more suitable for modelling module temperatures in tropical regions. Residual plots for the PVSyst and Akhsassi models are shown in Figure 5. The residual represents the difference between the measured value and the value predicted by the regression. Scatter plots comparing predicted and measured values are shown in Figure 5a. The R-squared and adjusted R-squared values are both 0.980 for PVSyst and 0.999 for Akhsassi, indicating a strong dependence and correlation between the measured and predicted values. The predicted operating temperatures of the PV modules are in close agreement with the measured results. The residual histograms show the distribution of the residuals for all observations. The symmetry of these histograms (Figure 5b) shows that the errors for the PVSyst and Akhsassi models are normally distributed. The normality of the residuals is checked by the normal probability plot of the residuals. The residuals are normally distributed when the points on the plot are close to the straight line. Figure 5c confirms that the residuals of the models follow a normal distribution. The residual curves indicate that the model fits are acceptable, as the scatter plots follow the theoretical curve, confirming the validity of our model choices.

CONCLUSION

In this work, PV module temperature models are developed using constraint minimisation based on monitored field data. The estimated PV module temperatures and the RMSE of these models vary with the weather conditions. The PVSyst and Akhsassi models achieve the lowest RMSE values in the HH, HL and LH weather categories, while the Sandia model has the lowest RMSE in the LL condition. The PVSyst and Akhsassi models are closer to the measured PV module temperatures for the HH, HL and LH weather conditions, while the Sandia model is better for the LL condition. For all weather conditions, the PVSyst and Akhsassi models consistently provide the lowest RMSE values, followed by the Faiman and Mattei models. The Sandia model comes last. The RMSE curves suggest that the model fits are acceptable as the scatterplots closely follow the theoretical curve, confirming the validity of our model choices. As a result, the PVSyst and Akhsassi models can be used to estimate PV module temperatures at the given site and in other areas with similar climatic conditions. In addition, we plan to investigate the sensitivity of PV module temperatures to various meteorological factors.

REFERENCES

Praveenkumar S, Agyekum E, Alwan N, Qasim M A, Velkin V, Shcheklein S, (2022). Experimental assessment of thermoelectric cooling on the efficiency of PV module. *International Journal of Renewable Energy Research.* 12:1670-1681. doi: 10.20508/ijrer.v12i3.13087.g8553.

Ekundayo K, Egbugha A, Egbugha M, (2023). Analysis of percentage of power loss for photovoltaic module under temperature condition in kaduna state, nigeria. fudma *Journal of Sciences.*7:51-59. doi: 10.33003/fjs-2023-0704-1810.

Shagdar E, Shuai Y, Lougou B G, Mustafa A, Choidorj D, Tan H (2022) New integration mechanism of solar energy into 300 MW coal-fired power plant: Performance and techno-economic analysis. Energy. 238:122005.doi: 10.1016/j.energy.2021.122005.

Dileep G, Singh S N, (2017). An improved particle swarm optimization based maximum power point tracking algorithm for PV system operating under partial shading conditions. *Solar Energy.* 158:1006-1015. doi: 10.1016/j.solener.2017.10.027.

Seyedmahmoudian M,al. (2016)State of the art artificial intelligence-based MPPT techniques for mitigating partial shading effects on PV systems – A review. Renewable and Sustainable Energy Reviews. 64:435-455.doi: 10.1016/j.rser.2016.06.053.

Ahmad F F, Ghenai C, Hamid A K, Rejeb O, Bettayeb M (2021) Performance enhancement and infra-red (IR) thermography of solar photovoltaic panel using back cooling from the waste air of building centralized air conditioning system. *Case Studies in Thermal Engineering.* 24:00840. doi: 10.1016/j.csite.2021.100840.

Yaqoob S, Saleh A L, Motahhir S, Agyekum E, Nayyar A, Qureshi B (2021) Comparative study with practical validation of photovoltaic monocrystalline module for single and double diode models. *Scientific Reports.* 11:19153. doi: 10.1038/s41598-021-98593-6.

Diyoke C, Ngwaka U, Chikwado U K. (2023). A comprehensive analysis on the grid-tied solar photovoltaics for clean energy mix and supply in Nigeria's on-grid power. *Journal of Energy Systems.* 7:1-17.doi: 10.30521/jes.988844.

Fezzani A, al. (2023) Performances Analysis of Three Grid-Tied Large-Scale Solar PV Plants in Varied Climatic Conditions: A Case Study in Algeria. *Sustainability.* 15:1-23. doi: 10.3390/su151914282.

Sawicka-Chudy P, Sibiński M, Cholewa M, Pawelek R, (2018) Comparison of solar tracking system and fixed photovoltaic modules in Lodz. *Journal of Solar Energy Engineering.* 140. doi: 10.1115/1.4039097.

Khan I, Malik H, Fazaeli M (2021). Novel approach to investigate the influence of optimum tilt angle on minimum cost of energy based maximum power generation and sizing of PV systems A case study of diverse climatic zones in India.

Toure C S,Sow P L T, Dia F, Mbodji S (2023). Adapted experimental set up for the study of the impact of the dust accumulation on the performance of PV modules in a semi-arid climate: The case of Bambey, Center Senegal. American Institute of Physics Conference Series, AIP. 020108. doi: 10.1063/5.0161236.

Agyekum E, Praveenkumar S, Alwan N, Velkin V, Shcheklein S, Yaqoob S (2021). Experimental Investigation of the Effect of a Combination of Active and Passive Cooling Mechanism on the Thermal Characteristics and Efficiency of Solar PV Module. Inventions. 6:63.

Andrea Y, Pogrebnaya T, Kichonge B (2019). Effect of Industrial Dust Deposition on Photovoltaic Module Performance: Experimental Measurements in the Tropical Region. *International Journal of Photoenergy.* 1:1892148. doi: 10.1155/2019/1892148.

Hüttl B, Gottschalk L, Schneider S, Pflaum D, Schulze A (2019) Accurate performance rating of photovoltaic modules under outdoor test conditions. *Solar Energy.* 177:737-745. doi: 10.1016/j.solener.2018.12.002.

Toure C S, Sow P L T, Mbodji S (2023). Experimental study on the effect of tilt angle and dust fouling on the electrical parameters of PV modules in Bambey, Senegal. *Journal de Physique de la SOAPHYS.* 3:1-6. doi: 10.46411/jpsoaphys.2023.014.

Bocca A, al. (2018). Multiple-Regression Method for Fast Estimation of Solar Irradiation and Photovoltaic Energy Potentials over Europe and Africa. Energies. 11:3477. doi: 10.3390/en11123477.

Toure C S, Sow P L T, Mbodji S (2022). Experimental Analysis to Extract the Maximum Output of Serial and Parallel PV Module Configurations Under Partial Shadow Conditions: A Case Study for Bambey, Senegal.Energy and Power Engineering. 14:233-247. doi: 10.4236/epe.2022.147013.

Damarwan E, Hakim M, Wardhana A, Budiastuti P (2023). The Effect of Luminous Intensity, Humidity, and Temperature on The Output Voltage of Solar Panels », Jurnal Edukasi Elektro. 7:26-35. doi: 10.21831/jee.v7i1.60179.

Faye I, Ndiaye A, Gecke R, Blieske U, Kobor D, Camara M (2019). Experimental study of observed defects in mini-modules based on crystalline silicone solar cell under damp heat and thermal cycle testing. *Solar Energy.* 191:161-166. doi: 10.1016/j.solener.2019.08.054.

Toure C S, Sow P L T, Mbodji S (2023) New Experimental Analytical Approach to study the Effects of Temperature and Irradiance on the Physical Parameters of the solar Photovoltaic module in Sunny and Temperate Zones. IJMET. 22(1):23-42. doi: 10.17654/0975044423003.

Hossain M S, Pandey A K, Selvaraj J, Rahim N A, A. Rivai A, Tyagi V V. 2019. Thermal performance analysis of parallel serpentine flow based photovoltaic/thermal (PV/T) system under composite climate of Malaysia. Applied Thermal Engineering.153: 861-871.doi: 10.1016/j.applthermaleng.2019.01.007.

Chandra S, Agrawal S, Chauhan D (2018) Effect of ambient temperature and wind speed on performance ratio of polycrystalline solar photovoltaic module: An experimental analysis. *International Energy Journal.* 18:171-179.

Chow T T 2010. A review on photovoltaic/thermal hybrid solar technology. *Applied Energy.* 87(2):365-379. doi: 10.1016/j.apenergy.2009.06.037.

Dwivedi P, Sudhakar K, Soni A, Solomin E, Kirpichnikova (2020). Advanced cooling techniques of P.V. modules: A state of art. Thermal Engineering. 21:100674. doi: 10.1016/j.csite.2020.100674.

Kardaš Ančić D,Komatina M, Gvero P. (2022). Theoretic photovoltaic cell/module temperature based on real weather data for continental climate

Diouf M, Faye M, Thiam A, Ndiaye A, et Sambou V (2022) Modeling of the Photovoltaic Module Operating Temperature for Various Weather Conditions in the Tropical Region. *Fluid Dynamics and Materials Processing.* 18:1275-1284. doi: 10.32604/fdmp.2022.02128.

Dong X -J, Shen J -N, He G -X, Ma Z -F, He Y -J (2021). A general radial basis function neural network assisted hybrid modeling method for photovoltaic cell operating temperature prediction. Energy. 234:121212. doi: 10.1016/j.energy.2021.121212.

Zouine M, al. (2019). Mathematical Models Calculating PV Module Temperature Using Weather Data: Experimental Study. In Proceedings of the 1st International Conference on Electronic Engineering and Renewable Energy. 630-639.

Aoun N, (2022). Methodology for predicting the PV module temperature based on actual and estimated weather data. *Energy Conversion and Management.* 14:100182. doi: 10.1016/j.ecmx.2022.100182.

Akhsassi M, *al.* (2018). Experimental investigation and modeling of the thermal behavior of a solar PV module. *Solar Energy Materials and Solar Cells*. 180:271-279. doi: 10.1016/j.solmat.2017.06.052.

****