JOURNAL OF RENEWABLE ENERGY AND SMART GRID TECHNOLOGY

Vol. 19, No. 2, July-December 2024

Cell Temperature Determination based on IEC61215: Solar Photovoltaic Experimental Study of Tropical Malaysia

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Article info:

Received: 21 August 2024
Revised: 30 September 2024
Accepted: 17 October 2024
DOI:
10.69650/rast.2024.258005

Keywords:

Nominal Operating Cell Temperature (NOCT)
Tropical Climate
Solar Photovoltaic
IEC61215 Standard
Standard Reference Environment (SRE)

ABSTRACT

Most commercial photovoltaic (PV) module data sheets include Nominal Operating Cell Temperature (NOCT) values, which assist PV system designers in estimating module temperatures under real outdoor conditions. However, the typical NOCT values of 45°C to 47°C do not account for tropical climates. This study seeks to develop an adjusted NOCT mathematical model and determine revised NOCT values suited for tropical conditions. The new proposed NOCT model follows the international standard IEC61215 but incorporates updated tropical Standard Reference Environment (SRE) parameters: solar irradiance (SI) of 800 W/m², ambient temperature (AT) of 31°C, and wind speed (WS) of 1 m/s. This modified NOCT model demonstrates improved accuracy over the existing model, with an average reduction of 2% in percentage error, root mean square error, and mean average percentage error. Outdoor NOCT testing conducted in Shah Alam, Malaysia, uncovered much higher NOCT values for various PV modules technology: 55°C for monocrystalline, 57°C for polycrystalline, and 59°C for thin film. These results emphasize the inadequacy of current NOCT values in commercial PV module data sheets, which do not accurately reflect conditions in tropical climates. The revised NOCT values from this study offer crucial thermal reference data for PV system designers, integrators, and researchers working in tropical regions, particularly Malaysia.

1. Introduction

The global installation of solar photovoltaic (PV) systems has seen a significant rise, driven by environmental concerns and the progressively competitive pricing of PV systems. Malaysia experiences tropical rainforest climate that is categorised as equatorial fully humid climate under Koppen- Geiger classification [1]. Government of Malaysia has implemented several significant initiatives and programs in succession to tap into renewable energy sources: Feed-In-Tariff (FiT), Net Energy Metering (NEM), Self-Consumption Scheme (SELCO), Large Solar Scale (LSS), Supply Agreement with Renewable Energy (SARE), and pilot project of Peer-to-Peer (P2P) [2]. The rapid expansion of PV systems installation worldwide has intensified the demand for accurate modelling of PV module temperature (MT), which plays a critical role in optimizing system performance and efficiency. This need is particularly pronounced in tropical regions like Malaysia, where PV installations encounter distinct challenges due to high ambient temperatures (AT), ranging from 22°C to 40°C, with an average AT of 30°C [3]-[5], despite the highly favorable annual solar irradiation levels, which range from 1420 W/m² to 1962 W/m² [6]. Every commercial PV module has it owns unique data sheet, which encompass the Nominal Operation Cell Temperature (NOCT) value. For the certification of PV module under IEC61215, the NOCT value was determined when the PV module is in open circuit regime of operation, experiences specific outdoor condition governed by the Standard Reference Environment (SRE). The SRE is based on specified condition; 800 W/m^2 of solar irradiance (SI), 20 °C of AT and wind speed (WS) of 1.0 m/s [7]. It is interesting to highlight that this package of SRE is impossible to obtain under tropical Malaysia outdoor environment.

The typical values of NOCT in commercial PV module data sheets are ranging between 45 °C to 47 °C. This range of NOCT values hypothetically does not reflect NOCT values for tropical Malaysia. This issue has brought significant attention to develop a modified NOCT model that incorporated modified SRE and consequently determine the revised NOCT values that are appropriate to guide PV system designers in the real outdoor condition within tropical climate vicinity.

A study by [5] proposed a modified SRE for NOCT testing to address Malaysian tropical climate condition. The study involved field testing and analysis of 12-month data on six parameters: SI, AT, relative humidity (RH), WS, wind direction (WD), PV module temperature (MT), and open circuit voltage. Initially, the study determined the median SI and median AT of 228 W/m^2 and 30 °C respectively. However, it was evident that the current method of determining the SRE using median ambient parameters was not suitable for tropical Malaysia, as it resulted in a percentage error of approximately 30 %. To overcome this issue, a new approach was implemented, which involved determining the corresponding AT for the same SI value 800 W/m^2 used in the existing SRE of IEC61215 standard. Finally, the study proposed SRE similar to IEC61215 except for AT of 31 °C. The SRE established in this study has utilized a specialized approach to better suit the tropical climate and proven in deriving to a more accurate NOCT for the tropical region [5].

Several studies have investigated MT modelling in tropical regions, providing valuable insights into the intricate relationship between climatic parameters and MT. Notably, a study conducted in Thailand analysed different types of PV modules, including amorphous silicon, polycrystalline silicon, and heterojunction intrinsic thin-layer modules, under specific operating conditions. The findings revealed disparities between the temperature coefficient values of PV arrays and factory values, emphasizing the necessity of region-specific MT model in tropical climates [8].

To further refine MT modelling, another study conducted in, Serdang, Malaysia has introduced the concept of tropical field operation cell temperature (tFOCT), which considers the maximum daily standard climatic parameters. The results suggested the suitable outdoor testing conditions for measuring the tFOCT, it was based on extreme values; 886 W/m^2 of SI, 34 °C of AT and a WS of 3.2 m/s. By incorporating these extreme values, the study found that the improved MT model, which is tFOCT has demonstrated better accuracy compared to the current NOCT model [9].

Regarding reliability assessment, a study was also conducted in tropical region evaluated commonly used empirical correlations, including the NOCT model and the tFOCT model. The study has estimated PV module performance highlighting MT significant contribution. By comparing the models' estimations with experimental measurements, the research emphasised the need for improved estimation methods specifically tailored for tropical regions. Based on the five consecutive days experimental data, results indicated that MT estimated by tFOCT model has the closest value to the experimental back MT. Whereas the temperature estimated by NOCT model showed the highest deviation up to 25.8% compared to the experimental back MT [10].

It is important to notify that NOCT values have been found to exhibit an uncertainty range of 3°C to 5°C, with limited attention given to tropical regions [11]. Another study has also been conducted to investigate the tFOCT. However, this study contradicted the initial concept of ambient parameters proposed by Stultz, which was based on median solar irradiance. Furthermore, numerous studies have reported the minimum ambient temperature of 23℃ in tropical regions, significantly higher than the current median ambient temperature of 20℃ in the existing SRE, excluding highland areas [5][7].

In narrowing down the main issues, it becomes clear that the NOCT value listed in PV module commercial datasheets does not accurately reflect conditions in tropical climates. The underlying problem lies in the SRE specified in IEC61215, which does not account for the characteristics of tropical climate regions. Due to that, this study has chosen to encompass the modified SRE by [5], by incorporating changes on the AT value to become 31℃ instead of 20 °C in corresponding to the concurrent SI of 800 W/m^2, besides maintaining other parameters as in IEC 61215 standard.

Therefore, this study aims to develop a modified NOCT model and determine NOCT values for PV modules that are appropriate for tropical Malaysia. This study will be limited to the field testing and analysis conducted in Malaysia covering three types of PV module technologies: monocrystalline, polycrystalline and thin film.

2. Experimental detail

2.1 Methodology

This section presents the flow chart of the methodology to develop the modified NOCT model and the revised NOCT values that suits tropical climate region based on closest NOCT approach as in IEC61215. Nevertheless, the modelling of the new NOCT model was incorporating the modified SRE; SI of 800 W/m2, AT of 31℃ and WS of 1 m/s as determined in the study conducted in Shah Alam, Malaysia [5]. The process flow of the methodology in this study involved six sequential steps as shown in Fig. 1 for three types of PV module, which were monocrystalline, polycrystalline and thin film.

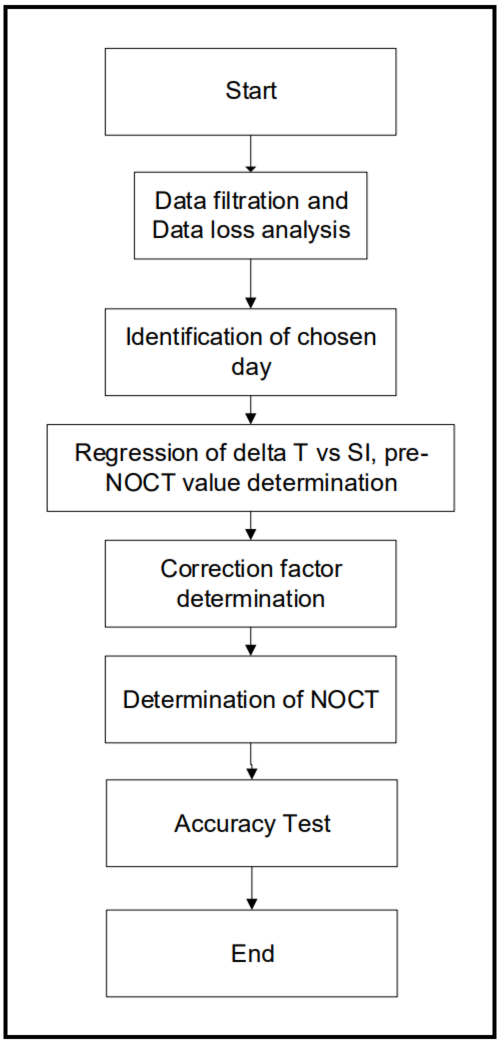

Fig. 1 Process Flow of methodology for NOCT determination for tropical Malaysia.

The first step of the process flow involved data filtration and data loss analysis on the raw data collected. The filtration analysis itself comprises seven steps, which was in line with the requirement of the IEC61215 standard. The steps of the sequential data filtration are as follows:

i. Daily data was selected within four hours before and after solar noon.
ii. Data below 400 W/m^2 was rejected.
iii. Data in a 10-minute interval after SI varies greater than 10% of the maximum and minimum value in 10-minute period was rejected.
iv. Data WS outside range of 0.25 m/s to 1.75 m/s was rejected.
v. Data AT outside range of 5℃ to 35℃ or varies more than 5℃ from maximum to minimum value in one collection run was rejected.
vi. Data in 10-minute interval after wind gust more than 4 m/s was rejected.
vii. Data WD within ±20 of east or west was rejected.

The second step of the process flow was the identification of the three chosen days. This was identified after the raw data went through the seven sequential filtration steps. These three selected days became the main raw data for the next step of analysis.

Next, the third step was the pre-NOCT value determination. The relationship of delta T (MT-AT) with SI was analysed for the three selected days. The relationship was represented in a form of linear regression models and subsequently the pre-NOCT values were determined.

The fourth step addressed the substitution of CF based on the Correction Factor Matrix (IEC61215, 2006). CF is a correctional value for NOCT which is determined from the average WS and average AT on the same day data collected for NOCT value. Thus, the calculation of the mean average AT and WS was conducted using the chosen data set from the three selected days, and now became the reference values.

The fifth step was the second final step that represent the NOCT model together with the CF. When the modified NOCT model was added with the CF, the NOCT model with CF was then compared to the model without CF in terms of accuracy. This step will decide whether the CF is significant or not significant to be part of the model.

The sixth or final step required the proposed modified NOCT model with or without CF to be tested on accuracy. The accuracy test applied were using PE, RMSE and MAPE. This step requires element of comparison between the current NOCT model and the improvised NOCT model. The improvised NOCT model that suits tropical Malaysia condition for three types of PV module technology; monocrystalline, polycrystalline and thin film were developed.

2.2 Error analysis

The error analysis used in the research consists of PE, root mean square error RMSE and mean absolute percentage error MAPE.

PE is expressed by:

$$PE = \frac{|\acute{y} - y|}{\acute{y}} * 100\ \% \quad (1)$$

Where:

ý = theoretical value

y = actual value

RMSE is expressed by:

$$RMSE = \frac{\sqrt{\sum (\acute{y} - y)}}{n} \quad (2)$$

Where:

ý = theoretical value

y = actual value

n = effective data points

MAPE is expressed by:

$$MAPE = \sum \frac{\left| \frac{|\acute{y} - y|}{\acute{y}} * 100 \right|}{n} \quad (3)$$

Where:

ý = theoretical value

y = actual value

n = effective data points

3. Results and Analysis

3.1 Determination of modified NOCT model and verification of the NOCT Model

This section presents the data filtration analysis in parallel with data loss analysis to come out with the three selected days that will finally determines the acceptable NOCT value for tropical Malaysia. This section will also include the new proposed NOCT model, which is the pre-NOCT values. Error analysis has been conducted on the new proposed model to verify the accuracy and suitability of the modified NOCT model for PV application in tropical Malaysia region.

Data filtration comprises of seven steps was executed, as explained in methodology section. The data filtration and data loss analysis were conducted for day 1, day 2 and day 3 respectively as depicted in Fig. 2. Initially, the raw data of 23 days has an initial amount of 5760 raw data set.

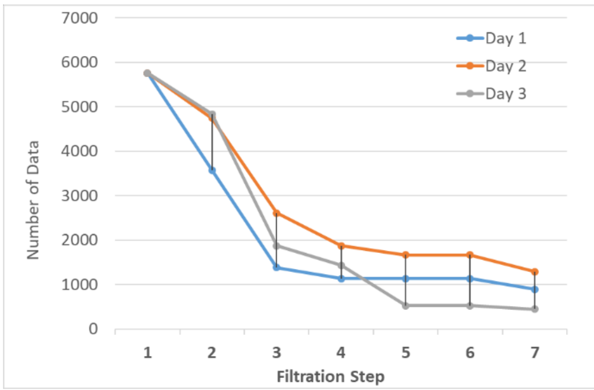

Fig. 2 Data Filtration Trend Line for 3 selected days.

3.2 Data Filtration, Data Loss Analysis and Identification of Chosen Days

From Fig. 2, it can be observed that main data loss happened at filtration step 2 and filtration step 3, which involved SI requirements. This result showed that the NOCT field testing conducted under tropical Malaysia condition has significant challenge to get data set which able to fulfil SI data filtration requirement set by IEC61215; SI greater than 400 W/m^2 and fluctuation of SI must be less than 10% within 10-minute interval. After going through the seven filtration steps, the remaining acceptable data points for day 1, day 2 and day 3 were 241, 375 and 446, respectively. This indicates a reduction of 94 % raw data after seven filtration steps applied. Finally, the study has succeeded to obtain the three chosen days after 23 days of data collection in March 2018.

3.3 Determination of Preliminary NOCT

The preliminary NOCT model was developed from regression analysis of the three selected days. The regression graph of delta T (temperature difference between PV module and ambient) as a function of SI was plotted. The regression trendline is a linear regression line as found in several studies [13-17]. A regression technique was applied in fitting the data points as mentioned in NOCT procedure of IEC61215.

The foundation of NOCT mathematical model using this regression analysis is as expressed by:

$$Delta\ T = mSI + c \quad (4)$$

Where,

$Delta\ T\ (°C) = MT - AT = NOCT - AT$

m = gradient of the graph

c = y-intercept

The regression analysis was conducted using the three selected days data, determined in earlier section for each PV cell technology namely monocrystalline, polycrystalline, and thin film. This regression analysis has supplied with three different set of m and c accordingly.

The regression graph plotted for monocrystalline PV technology is as illustrated in Fig. 3, with the m and c were 0.03021 and 0.6794 respectively. From the regression graph, the preliminary modified NOCT model for monocrystalline was developed and expressed by:

$$NOCT = (0.03021)SI + 0.6794 + AT \quad (5)$$

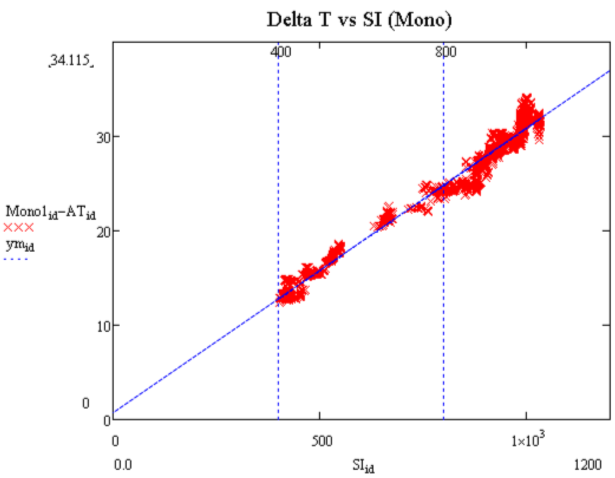

Fig. 3 Delta T as a function of SI for Monocrystalline.

In order to calculate the NOCT value, the SI of 800 W/m^2 and AT of 31 °C were substituted into Eq 6. The calculation of the preliminary NOCT is as shown by:

$$NOCT = 0.03021(800) + 0.6794 + 31 \quad (6)$$

NOCT=55.9 °C

NOCT~56 °C

Hence, the preliminary NOCT value for monocrystalline is approximately 56 °C.

The same scheme of calculations was applied for day 1, day 2 and day 3 for polycrystalline and thin film PV cell technologies respectively. The preliminary NOCT values for each selected day and each PV cell technology are as tabulated in Table 1. The preliminary NOCT values for monocrystalline for day 1, day 2 and day 3 are 55.03 °C, 55.85 °C and 55.27 °C, respectively. The polycrystalline PV module recorded higher values of 56.57 °C, 57.51 °C and 56.89 °C. The most striking result came from the thin film technology, which recorded the highest values of 58.95 °C, 60.86 °C and 59.35 °C.

Table 1 Preliminary NOCT values for monocrystalline, polycrystalline, and thin film PV module**.**

	Preliminary NOCT (°C) (Monocrystalline)	**Preliminary NOCT (°C) (Polycrystalline)**	**Preliminary NOCT (°C) (Thin Film)**
Day 1	55.03	56.57	58.95
Day 2	55.85	57.51	60.86
Day 3	55.27	56.89	59.35

3.4 Correction Factor Determination

The preliminary NOCT value will be added with correction factor (CF) based on NOCT CF of IEC61215. The CF was determined based on the average AT and average WS of the final acceptable data for each selected day. The average AT and WS together with the corresponding CF were as tabulated in Table 2.

Table 2 Average AT, WS and CF for monocrystalline, polycrystalline and thin film PV module.

	Average AT (°C)	Average WS (m/s)	CF (°C)
Day 1	31.52	0.95	2
Day 2	33.02	1.04	2
Day 3	33.87	0.95	2

Error analysis was conducted in evaluating the NOCT values with CF and without CF. In this study, the error analysis was conducted using PE, RMSE and MAPE. The predicted MT using the modified NOCT model has been compared with the actual MT from field testing. The proposed NOCT models with CF and without CF were evaluated for the three types of PV module. The results of the error analysis conducted are as tabulated in Table 3.

Table 3 Error analysis of NOCT model with CF and without CFT.

PV Technology	PE(%)		RMSE (%)		MAPE (%)	
	wCF	woCF	wCF	woCF	wCF	woCF
Monocrystalline	4.03	2.8	3.3	2.32	4.03	2.81
Polycrystalline	4.26	3.22	3.46	2.64	4.27	3.22
CIS Thin Film	4.2	3.48	3.65	2.82	4.2	3.48

wCF = with correction factor; woCF =without correction factor

The results show that the PE, RMSE and MAPE are lower for NOCT model without CF for the three PV modules. These findings provide evidence that the NOCT model which suits tropical Malaysia is more accurate without CF. Thus, the final NOCT values for monocrystalline, polycrystalline, and thin film PV technology in this study, were 55 °C, 57 °C and 59 °C. These values were reverted to the preliminary NOCT values that were determined earlier due to the exclusion of CF. Thus, from this point, the NOCT value that suits tropical Malaysia is without CF and will be specified as modified NOCT model.

3.5 Accuracy Test: Comparison between Modified NOCT Model and Current NOCT model

Comparison was made between the modified NOCT model developed in this study and the current NOCT model in IEC 61215. The results of the accuracy test using error analysis are as shown in Fig. 4. The accuracy test has verified that modified NOCT model with the new proposed SRE (pSRE) was more accurate than NOCT model with current SRE (cSRE) stated in IEC61215 standard.

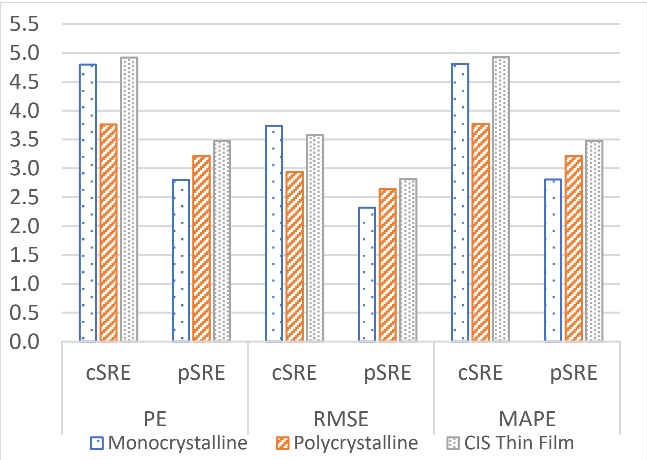

Fig. 4 Accuracy comparison of the model using cSRE and pSRE (y-axes: PE in %, RMSE in °C and MAPE in %).

Table 4 summarized the findings of this study by comparing between the current and modified NOCT model together with the respective NOCT values. The summary shows that the modified model is following closely the current NOCT model by IEC61215 with only one difference, which is the AT, from 20 °C becomes 31°C. However, the corresponding NOCT values of this modified model from current model compared to improvised model has a big temperature difference up to 14°C.

It is important to highlight that the modified model has revised the NOCT values to serve as a realistic reference for outdoor PV system testing in tropical climates, specifically in Malaysia, with the limitation that it applies only to free-standing mounting configurations.

Table 4 Comparison between current and modified NOCT model and revised NOCT values.

NOCT	**Current**	**Modified (Dedicated for tropical Malaysia)**
Model	$MT = AT + \frac{SI}{800}(NOCT - 20°C)$	$MT = AT + \frac{SI}{800}(NOCT - 31°C)$
Values	45 °C to 47 °C	55 °C to 59 °C

3.6 Comparison between actual MT and predicted MT using modified NOCT model: Three actual PV systems

A comparative study was made between the actual MT and predicted MT using the modified NOCT model developed in this study. A monthly comparison was conducted for three sites A, B and C between MT_actual and MT_predicted as shown in Fig. 5-7. The results from the three systems show similar trend. System A was found to be having the closest trend compared to system B and C. As expected, the MT_predicted showed a consistent overprediction as compared to the MT_actual. This is due to the fact that open circuit MT is higher than module operating MT as also reported by [16]. System B was having the most significant variation between the actual and predicted compared to system A and C.

The results under both working conditions; operating (on-load) and open-circuit, verified that the on-load or operating PV module temperature is lower than NOCT condition. Under open circuit condition, the heat produced is trapped within the PV modules and thus increasing the MT, while the heat is able to be channelled via resistive losses during on load condition. This is supported by studies from [16-17].

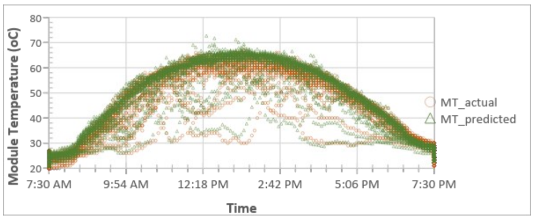

Fig. 5 Monthly comparison between MT_actual and MT_predicted for system A.

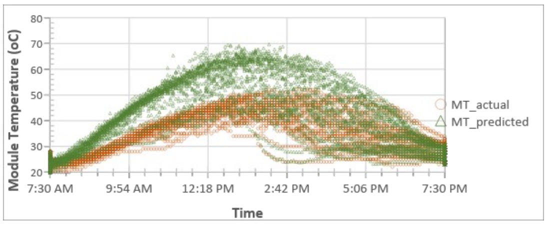

Fig. 6 Monthly comparison between MT_actual and MT_predicted for system B.

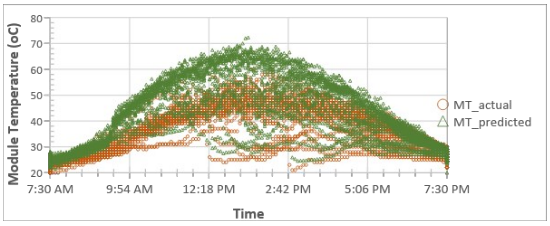

Fig. 7 Monthly comparison between MT_actual and MT_predicted for system C.

4. Conclusion

This study has successfully introduced a modified NOCT model for PV modules suited to tropical climate conditions. Using this modified model, the NOCT values obtained for monocrystalline, polycrystalline, and thin film PV modules were 55°C, 57°C, and 59°C, respectively. These values are notably higher than those listed in most commercial datasheets, as they better reflect tropical Malaysia climate conditions. Additionally, the modified NOCT model was validated with actual measurements from three case studies, showing consistent trends between the predicted and actual measurements. Future research should consider applying this model to other PV module technologies, such as cadmium telluride thin film, gallium arsenide thin film, and dye-sensitized modules.

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