Analysis on the Features of NOCT and NMOT Tests With Photovoltaic Module

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ABSTRACT The operating temperature of the photovoltaic (PV) module plays a major role among the parameters affecting the energy yield of photovoltaic (PV) power generation systems. This paper compared the requirements of Nominal Operating Cell Temperature (NOCT), which is used to estimate the PV module operating temperature according to IEC 61215:2005, with those of the recently revised IEC 61215: 2016 Nominal Module Operating Temperature (NMOT). Through this, each feature of the parameters used to calculate the NOCT and NMOT could be determined, and it was assumed that the NMOT is lower than NOCT. And, among the parameters, the wind speed was found to be a significant variable affecting the temperature, and non-linear clusters and skewed data are improved if some data in the morning were deleted considering the period of module activation. Moreover, it is found that the method summing up the daily data for the calculation can reduce the correlation and deviation of NMOT.

INDEX TERMS NMOT, NOCT, photovoltaic power system, operating temperature, reliability.

I. INTRODUCTION

The PV module temperature has a significant effect on the energy output of a PV power system because it determines the maximum power output. Atmospheric parameters, such as the ambient temperature, irradiance, and wind speed, vary according to the installation conditions [1], [2]. Because of these environmental factors, it is common to use Nominal operating cell parameter (NOCT) according to IEC 61215:2005 [3] as an indicator of the module operating temperature. Most PV module manufacturers include the following: the Standard Test Conditions (STC), which are the irradiance of 1000 W/m^2, ambient temperature of 25 °C, and output characteristics at air mass of AM 1.5 G, and NOCT with an irradiance of 800 W/m^3, ambient temperature of 20 °C, and output characteristic at air mass of AM 1.5 G in the module data sheets [1].

NOCT is also simulated by defining NOCT as 45 °C ± 5 °C, even in software PVsyst, which is used widely for energy output forecasts. In addition, high-efficiency PV modules have recently been developed to have NOCT over 50 °C. On the other hand, manufacturers have questioned the

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uncertainty due to large fluctuations in NOCT and continued to express doubt as to whether the actual energy output based on NOCT should be applied to a forecast, but no clear value has been presented thus far [4]. Indeed, the energy output of PV power generation systems is usually generated based on the conditions of the PV module temperature which is determined mainly by environmental factors, such as the irradiance, ambient temperature, and wind speed [5].

According to these environmental parameters, the range of changes in NOCT can vary. Therefore, the international Certification Body Testing Laboratory (CBTL) and manufacturers around the world examined NOCT by obtaining and reviewing the seasonal and regional values of NOCT with long-term testing [1]. Through this process, Working Group 2 of the International Electrotechnical Commission Technical Committee 82 considered the uncertainty of NOCT. As a result, the testing standard of the PV module, IEC 61215:2005 [3], has recently been abolished and revised to IEC 61215-2:2016 [6] with an elimination of NOCT test items, which were replaced with the Nominal Module Operating Temperature (NMOT) test items. The NMOT diversified the parameters more than the NOCT and especially differentiated in the consumption of generated power by connecting loads to modules.

TABLE 1. Data acquisition equipment and sensors.

Equipment/Sensor	Manufacturer and model	Accuracy
Data acquisition	Hioki / LR8402-20	±0.1%
Pyranometer	Kipp & Zonen / CMP21	±3%
Ambient temperature	Delta-Ohm / HD9008TRR	±0.1 °C at 25 °C
Relative humidity	Delta-Ohm / HD9008TRR	±2%RH
Wind speed	Thiesclima / 4.3820.01.3101	±0.1 m/s (< 4 m/s) ±2% (5~85 m/s)
Wind direction	Thiesclima / 4.3820.01.3101	±1°
Temperature	dhtc / K-type thermocouple	±0.4%
DC Electronic Load	NI / sbRIO-9627	0.2% ±0.02 V 0.2%±0.01 A

Therefore, this paper analyzed how the parameters of the ambient temperature, PV module temperature, wind speed, and irradiance affect NOCT and NMOT. In addition, the measurement procedures of the NOCT and NMOT were compared, and the results were analyzed. Consequently, the non-linear data cluster and skewed distribution of the data were observed.

II. EXPERIMENTAL SETUP

The PV module used for data collection in this study was a module of a Passive Emitter and Rear Contact (PERC) cells. As shown in Fig. 1, M1, and M2 were installed under the necessary condition of NMOT, which has the function of an electronic maximum power point tracker (MPPT) by connecting with the loads, whereas M3, and M4 were installed in open circuit form under no-load based on NOCT required condition. In addition, the solar irradiation strongly depends on the location, especially on the latitude and the geographical border conditions. Thus, the systems of NOCT and NMOT were installed side by side at Yeungnam University (Gyeongsan, South Korea) at latitude of 35.8° and an elevation of 61 m above sea level with a tilt angle of 40° to the south, as shown in Fig. 1, so that all modules were exposed to the same condition of batch and tilt angle for a reliable comparative analysis. Thermocouples (K-type) were attached to each backside of the test modules at four positions to measure the module temperature, as shown in Fig. 2, in compliance with IEC 61853-2:2016 [7]–[9].

To achieve accurate and reliable measurements, the equipment used to collect data was calibrated to meet the IEC 61724-1:2017 [9]. In Table 1, the accuracy of each equipment is summarized and all data was collected every five seconds [1], [8].

III. METHODOLOGY

NOCT and NMOT have the same irradiance conditions, but there are differences in the other conditions, such as wind speed, wind direction, and module temperature. Table 2 lists these differences [1], [3], [6], [7], along with the calculated values.
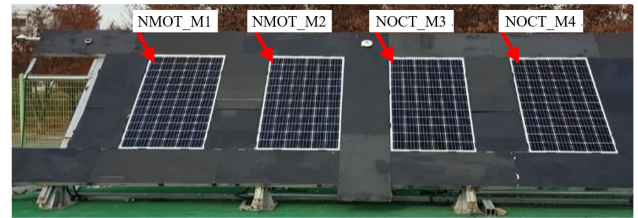

FIGURE 1. NOCT and NMOT systems were installed at the outdoor test facility. All modules were mounted in an open rack.
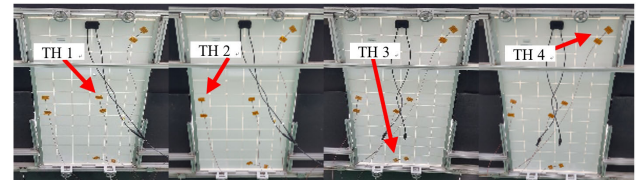

FIGURE 2. Four positions of thermocouples attached to each backside for the measurement of module temperature.

TABLE 2. Comparison the requirements NOCT and NMOT.

	NOCT (IEC 61215:2005)	NMOT (IEC 61215-2:2016)
Tilt angle	45°±5°	37.5°±2.5°
Period	4 h before local solar noon to 4 h after local solar noon	
Data acquisition	Interval of no more than 5 s	
Electrical load	Open circuit	Electric maximum power point tracker(MPPT)
Thermal sensor	Two points; Middle : 2 points	Four points ; Top : 1 point, Middle : 2 points, Bottom : 1 point
T_m	Average of 2 points	Exclude the temperature that differs most from the four-module temperature means T_m= average of 3 points
Acceptable data points	Average of the 3 different daysboth before and after solar noon	At least 10 different days and at least 10 data points both before and after solar noon
Model	$T_m - T_{amb} = u_0 + u_1 \times G$ u_0= intercept u_1= slope	$T_m - T_{amb} = \dfrac{G}{u_0 + u_1 \cdot v}$ v = 5 minutes average of wind speed G = Total solar irradiance
Regression	G against $T_m - T_{amb}$	v against $(G/(T_m - T_{amb}))$
Reject the following		
Irradiance	Below 400 W/m²	
	Max. irradiance − Min. irradiance during 10 minutes > 10% of Max. irradiance	
Wind speed	below 0.25 m/s, over 1.75 m/s	Instantaneous wind speed during 10 mins below 0.25 m/s or over 3 x wind speed during 5 minutes average
	4 m/s gust after within 10 minutes	wind speed of 5 minutes average below 1 m/s or over 8 m/s
Wind direction	±20° of east or west	Deleted
Ambient temperature	$T_{amb} \leq 5$ °C or $T_{amb} \geq 35$ °C	Deleted

A. NOCT METHOD OF CALCULATION

In NOCT, the PV module junction temperature (T_j) is a function correlated with the ambient temperature (T_{amb}) and

the irradiance (G) of an operating PV module. The difference between the ambient temperature and the module temperature can also be sought through an interpolation equation based on direct linear regression independent of the irradiance when the irradiance level is above 400 W/m^2.

In addition, the module temperature can be estimated by calibrating under the conditions of the irradiance (800 W/m^2) and the ambient temperature (20 °C), as defined in IEC 61215:2005 [3], [10].

$$T_j = \frac{G}{800}(T_m - T_{amb}) + T_{amb} + T_{correct} \qquad (1)$$

The $T_m - T_{amb}$ values with the data collected for 3 days can be estimated directly by the irradiance equation. The corresponding PV module operating temperature can be estimated by substituting the basic conditions of $G = 800$ W/m^2, $T_{amb} = 20$ °C in equation [1], [12].

B. NMOT METHOD OF CALCULATION

The NMOT test estimates the module temperature using the following equation:

$$T_j = \frac{G}{u_0 + u_1 \cdot v} + T_{amb} \qquad (2)$$

At NMOT, the PV module junction temperature is a function correlated with the ambient temperature (T_{amb}) and the irradiance (G) and the wind speed (v) of an operating PV module. Being independent of the ambient temperature, the difference between the ambient temperature and module temperature ($T_m - T_{amb}$) can be expressed as a function $u_0 + u_1 \cdot v = G/(T_m - T_{amb})$ of the wind speed based on it being proportional to the irradiance level above 400 W/m^3 [7], [11]–[14].

Using the data obtained for more than 10 days, a distributed graph of $G/(T_m - T_{amb})$ of v can be found and then only the dates with more than 10 data in the morning and afternoon were sorted, resulting in a linear regression equation, $u_0 + u_1 \cdot v$.

Accordingly, the daily junction temperature (T_j) can be obtained by substituting $T_{amb} = 20$ °C, $v = 1$ m/s, and $G = 800$ W/m^3 set from the basic conditions for the equation.

The value of its daily listing and the average temperature for three days becomes the junction temperature when the module is under operation [15], [16].

IV. RESULTS

An analysis of the data from this study is a result of filtering according to the requirements of NOCT and NMOT. Although more NMOT data existed in Table 3, to compare NOCT and NMOT directly, 8 days data is selected on the day considering both NOCT and NMOT data exist. It confirmed that the calculated value could be influenced by the wind speed and position of the temperature sensor that are used for NOCT and NMOT calculation. Moreover, non-linear curves were formed with the inclusion of the data before 10 a.m., which led to obtain the result on the relationship of the correlation coefficients.

TABLE 3. Filtered data points according to the requirements of NOCT and NMOT.

Date	NOCT	NMOT	Selected day
11/17/19	2081	3749	Day 1
11/18/19	0	0	
11/19/19	2184	3136	Day 2
11/20/19	2797	4050	Day 3
11/21/19	0	0	
11/22/19	0	4777	
11/23/19	0	3390	
11/24/19	0	0	
11/25/19	0	0	
11/26/19	1767	4161	Day 4
11/27/19	1343	2700	Day 5
11/28/19	0	0	
11/29/19	894	1876	Day 6
11/30/19	1868	4350	Day 7
12/01/19	0	0	
12/02/19	163	202	Day 8
12/03/19	0	0	
12/04/19	0	0	
12/05/19	0	0	
12/06/19	0	0	
12/07/19	0	0	
12/08/19	0	0	
12/09/19	0	3068	
12/10/19	0	4349	

A. EFFECT OF WIND SPEED

Regarding the filtering condition, NMOT has a wider range of the wind speeds from 1 m/s to 8 m/s than NOCT from 0.25 m/s to 1.75 m/s. A high wind pressure is one of the factors that affect the operating temperature of the PV module, and NOCT estimates the value from the limited range of data. In addition, the value of T_j was calculated differently depending on the filtering method of NMOT and NOCT, even with the same data. Fig. 3 revealed a difference between NMOT and NOCT based on the filtering method despite using the data derived from the same period.

A comparison of the calculation methods of the NMOT and NOCT in the Fig. 3 revealed a similar distribution. When the temperatures on each module were compared, the M1 and M2 modules were connected to the load, which dissipate the heat generated by the electronic load. Therefore, the temperatures of the M1 and M2 modules are more than 6 °C lower than those of M3 and M4, which had been tested in the open circuit in the Fig. 4.

(a)

(b)

FIGURE 4. Comparison of the NMOT and NOCT on a load or in open circuit: (a) NMOT_M1: On load vs. NOCT_M3: Open circuit, (b) NMOT_M2: On load vs. NOCT_M4: Open circuit.
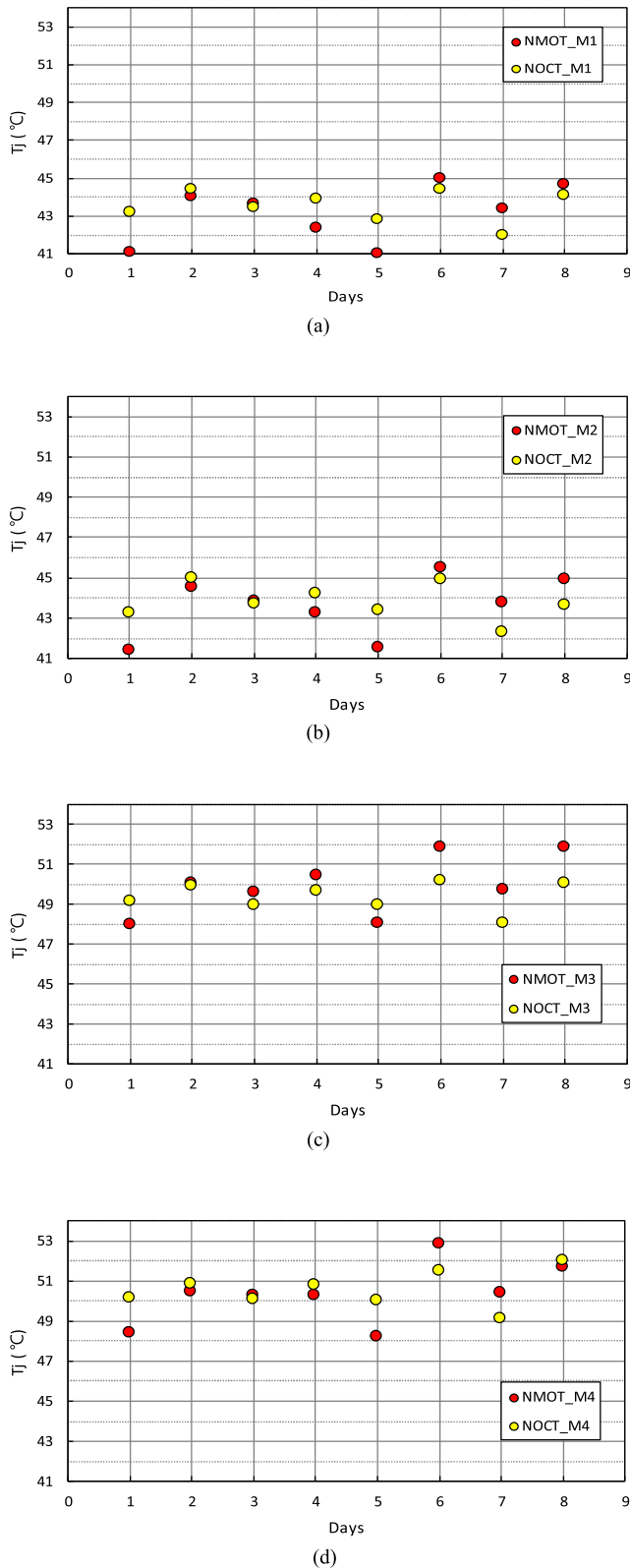

(a)

(b)

(c)

(d)

FIGURE 3. Comparison of NMOT and NOCT based on the filtering method: (a) NMOT vs. NOCT_M1: On load, (b) NMOT vs. NOCT_ M2: On load, (c) NMOT vs. NOCT_M3: Open circuit, (d) NMOT vs. NOCT_M4: Open circuit.
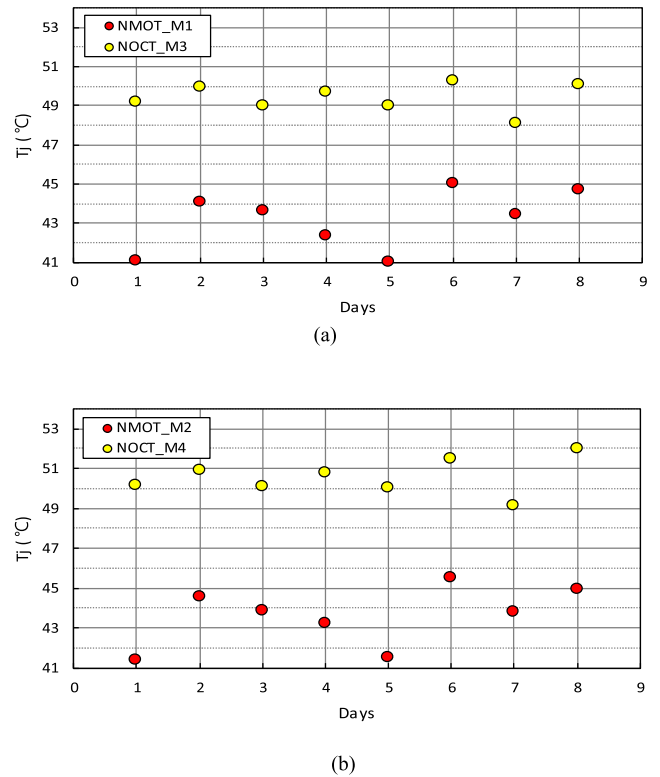
B. INFLUENCE BY THE ATTACHED POSITION OF THE TEMPERATURE SENSOR

In NMOT, the temperature value was obtained from temperature sensors with four attached spots. In addition, the module temperature T_m was calculated based on the average of the temperature from four sensors after excluding the temperature of one sensor, which shows the greatest deviation from the temperature average of four sensors.

The calculated average temperature and the gap of the excluded sensor at this time confirmed that the deviation of the temperature on each sensor increased with increasing wind speed. In particular, in Table 4 the temperature sensor #4 installed at the top of the module showed a higher exclusion rate than the other three temperature sensors, suggesting that the wind pressure had a strong effect on the upper part of the module. This confirms indirectly that the wind speed influences the operating temperature.

C. NMOT ESTIMATE WITH VARIABLE WIND SPEED

Regarding the data for linear regression, NMOT uses $G/(T_m - T_{amb})$ the wind speed (v) while NOCT uses $T_m - T_{amb}$ the irradiance (G). Comparing NMOT equation (2) and NOCT equation (1), wind speed is a parameter only for NMOT equation (2) not for NOCT equation (1). NOCT is

TABLE 4. Exclusion rate of each temperature sensor.

		TH1	TH2	TH3	TH4	SUM
M1	Number (#) of samples	8408	1420	6601	42988	59417
	Exclusion rate	14.2 %	2.4%	11.1%	72.3%	100%
M2	Number (#) of samples	1559	2040	12605	43208	59412
	Exclusion rate	2.6%	3.4%	21.2%	72.7%	100%
M3	Number (#) of samples	1397	11721	22132	24162	59412
	Exclusion rate	2.4%	19.7%	37.2%	40.7%	100%
M4	Number (#) of samples	385	15090	12991	30947	59413
	Exclusion rate	0.6%	25.4%	21.9%	52.1%	100%

* Exclusion rate is the ratio of the corresponding channel to the total number of samples.

TABLE 5. Calculating the temperature coefficient of NMOT according to the wind speed from 1 m/s to 5 m/s.

Wind speed (m/s)	1.0	2.0	3.0	4.0	5.0
M1_NMOT (℃)	45.0	40.6	37.5	35.2	33.5
M2_NMOT (℃)	45.7	40.6	37.2	34.8	33.0

TABLE 6. NOCT and NMOT daily correlation coefficient squared (R^2).

NOCT correlation coefficient squared (R^2)			
	M1	M2	M3	M4
Day 1	0.892	0.901	0.911	0.917
Day 2	0.941	0.930	0.901	0.929
Day 3	0.890	0.911	0.915	0.930
Day 4	0.951	0.933	0.946	0.967
Day 5	0.893	0.886	0.914	0.923
Day 6	0.947	0.934	0.850	0.901
Day 7	0.791	0.772	0.855	0.874
Day 8	0.985	0.983	0.979	0.984

NMOT correlation coefficient squared (R^2)			
	M1	M2	M3	M4
Day 1	0.024	0.013	0.004	0.003
Day 2	0.012	0.050	0.025	0.013
Day 3	0.373	0.355	0.352	0.365
Day 4	0.004	0.066	0.311	0.071
Day 5	0.023	0.046	0.113	0.027
Day 6	0.359	0.357	0.043	0.419
Day 7	0.744	0.766	0.680	0.721
Day 8	0.140	0.064	0.060	0.468

a simple process by estimating the operating temperature directly from the irradiance (G) but uses the wind speed only as a filtering condition, not as a decisive factor in determining the operating temperature.

In contrast, NMOT uses the wind speed in the estimation equation of the linear curves. This can lead to a regionally and environmentally customized operating temperature by varying the wind speed according to the environment under the test conditions setting a default wind speed of 1 m/s.

As shown in Table 5, the temperature coefficient of the different wind speed can be calculated according to the conditions from 1 m/s to 5 m/s.

D. NON-LINEAR DATA IN THE MORNING

Although NMOT can use the wind speed as an independent variable, daily deviations exist, and non-linear curves are shown in the filtered data. This explains the problem raised by the prerequisite of NMOT in that the data of $G/(T_m - T_{amb})$ for the wind speed (v) is linearly proportional to the estimated junction temperature (T_j), which affects the reliability of NMOT.

This problem is caused by the formation of non-linear data for one to two hours after the start of solar irradiation. Although IEC 61853-2:2016 [7] suggests the data from four hours before and after 12:00 p.m., as a center point,

be obtained, it can be assumed that non-linear temperature distribution is shown immediately after the beginning of solar irradiation and linear distribution only after a certain time. Therefore, it will be necessary to exclude the non-linear data for the time before a module is activated.

In the filtering conditions, NMOT can use more data for the estimation, such as the exclusion of the wind direction and the wider condition of the wind speed than NOCT, but some uncertainties could include in appropriate data.

As shown in Table 6, the R^2 value of the NOCT ranged from 0.772 to 0.985, whereas that of NMOT was relatively low, ranging from 0.003 to 0.766. This is because the coefficients of NMOT using $G/(T_m - T_{amb})$ for the wind speed are approximately to zero. In addition, there is the low correlation coefficient despite the normal linear distribution. This suggests a problem in the correlation of linear regression suggested by NMOT.

Thus, to exclude the non-linear curve from the non-linear data, the data before 10 a.m.were deleted from the existing data, and the operating temperature was estimated. As a result, after excluding the morning data, regardless of the module number, as shown in Fig. 5, the correlation

TABLE 7. Change in the correlation coefficient with/without the data before 10 a.m. (a) Including the data before 10 a.m. (b) Excluding the data before 10 a.m.

(a) Including the data before 10 a.m.

	NMOT correlation coefficient squared (R^2)			
	M1	M2	M3	M4
Day 1	0.024	0.019	0.004	0.003
Day 2	0.012	0.024	0.025	0.013
Day 3	0.373	0.313	0.352	0.365
Day 4	0.004	0.048	0.311	0.071
Day 5	0.023	0.037	0.113	0.027
Day 6	0.359	0.329	0.043	0.419
Day 7	0.744	0.718	0.680	0.721
Day 8	0.140	0.078	0.060	0.468

(b) Excluding the data before 10 a.m.

	NMOT correlation coefficient squared (R^2)			
	M1	M2	M3	M4
Day 1	0.376	0.354	0.212	0.296
Day 2	0.068	0.168	0.130	0.092
Day 3	0.457	0.367	0.335	0.372
Day 4	0.569	0.605	0.614	0.642
Day 5	0.893	0.895	0.827	0.859
Day 6	0.310	0.295	0.013	0.366
Day 7	0.781	0.763	0.725	0.773
Day 8	0.140	0.078	0.060	0.468

(a)

(b)

FIGURE 5. Day 1 Improved graph (M1) with a deletion of the data before 10 a.m.: (a) The graph including the data before 10 a.m., (b) The graph excluding the data before 10 a.m.

TABLE 8. Temperature and correlation coefficient (M1) when summing up NMOT values with the data before 10 a.m. from Days 1 to 8.

Date	Slope	y-intercept	correlation coefficient squared (R^2)	NMOT
Day 1	-3.0425	41.0358	0.0238	41.06
Day 2	0.7537	32.5647	0.0121	44.01
Day 3	5.0465	28.8433	0.3732	43.61
Day 4	0.7991	35.0095	0.0043	42.34
Day 5	2.2092	35.8733	0.0230	41.01
Day 6	3.2099	28.8185	0.3589	44.98
Day 7	4.8962	29.3316	0.7435	43.37
Day 8	3.3730	29.0320	0.1396	44.69
	mean			43.13

Date	Slope	y-intercept	correlation coefficient squared(R^2)	NMOT
Day 1 to Day8	3.1952	31.5938	0.0748	43.00

coefficients increased, and the graph became close to a linear shape in most cases.

And in the case of Day 8, although more data before 10 a.m. existed, there's no before 10 a.m. data after filtering according to the requirements of NOCT and NMOT.

Non-linear curves are improved like Fig.5 by excluding the data before 10 a.m.. The result makes correlation coefficient in Table 7 larger and deviation of NMOT in Fig. 6 smaller, which can improve the reliability of the operating temperature.

E. SUM OF THE CALCULATED INDIVIDUAL NMOT VALUES

According to the standards of IEC 61215:2005 [3] and IEC 61215-2:2016 [6], when estimating the operating temperature, the data should first be filtered based on NOCT and NMOT conditions, and the resulting daily result value can be calculated. NOCT was found by averaging the data of three appropriate days from the daily result value. On the other hand, there can be large differences occurring according to the date, and the selection of specific dates should be dependent on the judgment of the researcher.

Using the same filtering process, a more reliable value can be obtained if the value is estimated through linear regression of the total data by combining the filtered results.
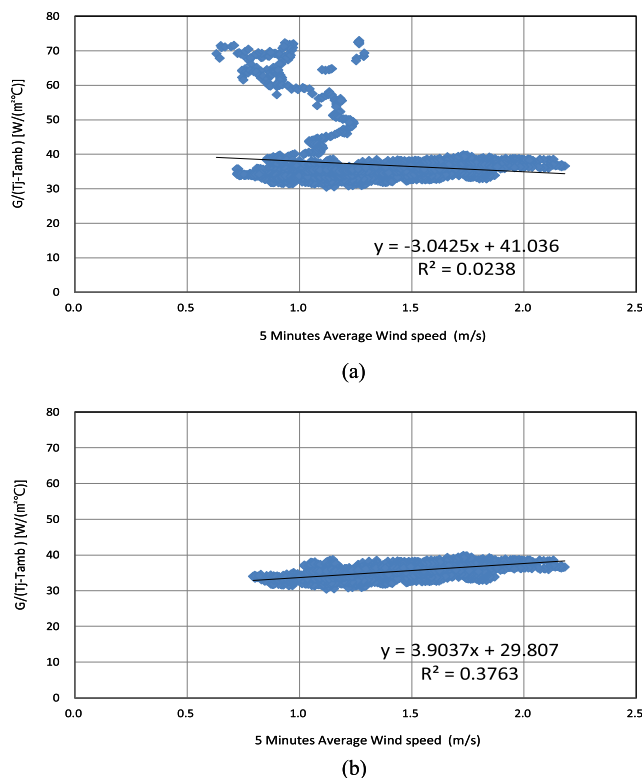
When combining the filtered data from Days 1 to 8, Fig. 7 can be obtained, and NMOT value can be derived

FIGURE 7. Summed NMOT graph (M1) including the data before 10 a.m. from Days 1 to 8.

TABLE 9. Temperature and correlation coefficient (M1) when summing up NMOT values without the data before 10 a.m. from Day 1 to Day 8.

Date	Slope	y-intercept	correlation coefficient squared (R^2)	NMOT
Day 1	3.904	29.807	0.376	43.73
Day 2	1.883	30.846	0.068	44.44
Day 3	5.552	27.605	0.457	44.13
Day 4	4.894	28.042	0.569	44.29
Day 5	5.498	28.142	0.893	43.78
Day 6	2.732	29.125	0.310	45.11
Day 7	5.886	27.482	0.781	43.98
Day 8	3.373	29.032	0.140	44.69
	mean			44.27

Date	Slope	y-intercept	correlation coefficient squared (R^2)	NMOT
Day 1 to Day8	5.6098	27.2293	0.6376	43.97

FIGURE 6. Change in the graph with/without the data before 10 a.m.: (a) NMOT: With the data before 10 a.m. vs. NMOT: Without the data before 10 a.m._M1, (b) NMOT: With the data before 10 a.m. vs. NMOT: Without the data before 10 a.m._M2, (c) NMOT: With the data before 10 a.m. vs. NMOT: Without the data before a.m._M3, (d) NMOT: With the data before 10 a.m. vs. NMOT: Without the data before 10 a.m._M4.
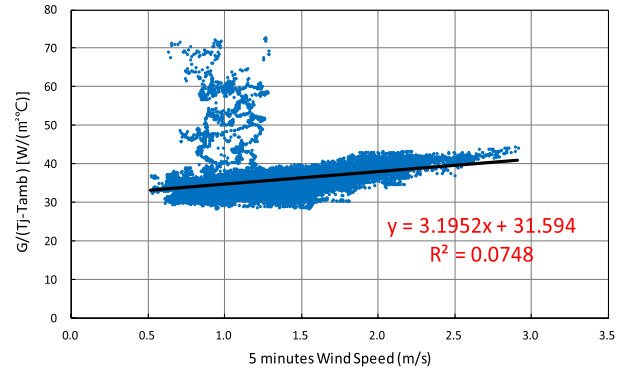
through the linear estimation equation from that graph and data. As shown in Fig. 7, the linear curve was maintained even when the data were combined, confirming that low correlation coefficient data does not impair the trend of the data.

In IEC 61215-2:2016 [6], the temperature was calculated from an average of three days among the eight days, but the temperature can vary widely depending on the dates selected. Their specific values can be found in Table 8. When comparing the result with the summed data, each value is 43.13 °C
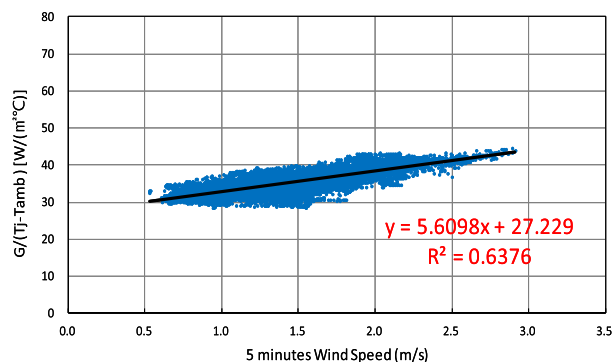
FIGURE 8. Summed NMOT graph (M1) excluding the data after 10 a.m. from Day 1 to Day 8.

and 43.00 °C, which can confirm that the summed value came out at a similar level to the average of all eight days.

On the other hand, as in Fig. 7, the data which is out of linear graph decreases correction coefficient to $R^2 = 0.0748$ of Table 8. To solve this problem, the data before 10 a.m. was excluded and only the data after 10 a.m. is gathered.

The result can be verified in Table 9, which shows that the overall correlation coefficient increased compared to Table 8, and the $R^2 = 0.0748$ on the summed graph in Table 8 was increased to 0.6376 in Table 9. In addition, non-linear data were excluded, as shown in Fig. 8. This can overcome the disadvantages of NMOT and expand its use to estimating the effects of the wind speed.

V. CONCLUSION

In this paper, NMOT and NOCT were calculated based on IEC 61215:2005 [3] and IEC 61215-2:2016 [6], and the results and the main differences were compared. In particular, the factors that caused the difference in the operating temperature between NOCT and NMOT were divided into two: wind speed and the attaching spots of the temperature sensors. To utilize NMOT and include the wind speed as an independent variable, the disadvantages of NMOT first need to be improved. In addition, there are non-linear clusters and skewed data. To improve them, some data in the morning were deleted considering the period of module operation. A method was designed to reduce the correlation and deviation of NMOT by summing up the daily data for the calculation. Therefore, as the operating temperature of the PV module can be calculated more accurately through the results of this paper, it may be a useful indicator for predicting the energy yield of a PV generation system.

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