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A STUDY ON RELIABILITY OF MATHEMATICAL MODEL WITH MONITORING SYSTEM OF SOLAR ROOFTOP SYSTEM

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ABSTRACT

This research represented the study on reliability of mathematical model with monitoring system of solar rooftop system, case study of a plastic manufacturer in Samut Sakhon Province. The analytical areas were divided into 4 cases including: southern direction of solar radiation with roof's till angle of 5° (S1); southern direction of solar radiation with roof's tilt angle of 20° (S2); northern direction of solar radiation with roof's till angle of 5° (N1); and northern direction of solar radiation with roof's till angle of 20° (N2). Historical data on average monthly capacity of rooftop solar of 2018 was collected via monitoring system every 15 minutes for comparing to data on mathematical model. Data on research areas, direction of installation, roof's tilt angle via Google Earth Program, solar irradiance from Solar Radiation Station, Faculty of Engineering, Mahasarakham University, ambient temperature from weather station of Meteorology Station, Bangkok (Bang Khen Weather Section) of 2018, were used for analyzing on capacity before comparing to reliability of data. The results were presented in the form of root mean square difference (RMSD), mean bias difference (MBD), and coefficient of determination (R^2). The results revealed that the best reliability, RMSD, MBD, and R^2, are 60.82%, 51.49%, and 0.738 for S1, respectively, 41.87%, 35.94%, and 0.903 for S2, respectively, 44.26%, 38.77%, and 0.898 for N1, respectively, and 37.53%, 30.90%, and 0.897 for N2, respectively, while such values of the combined data are 46.39%, 38.93%, and 0.849, respectively. As a result, correlation of assessment on reliability of data tended to be value obtained from the mathematical model compared to value obtained from monitoring system.

Keywords: solar radiation, conversion of solar radiation, solar rooftop, mathematical model.

1. INTRODUCTION

Currently, solar power generation by using solar panels has been preferred increasingly [1]. Installation of solar rooftop is one of extensively preferred formats. Since rooftop area can be exposed by solar radiation throughout the day and it is often not utilized, solar rooftop is considered as another way to utilize areas for the ultimate benefit. It has been acknowledged that inclined plane installed with tilt angle that is equal to latitude of area and turned to be exposed with solar radiation, direct radiation, at equator will be able to be exposed by solar radiation in the highest level throughout the year [2]. Therefore, this principle is applied to installation of solar panels. However, with limitation of roofs that are not designed and constructed for installing solar panels, the operation of solar panels installed with tilt angle and direction of exposure to solar radiation of such roofs are inefficient. As a result, entrepreneurs in various areas install additional devices or tools to optimize and correct installation as defined in the above theory leading to better efficiency of solar panels. Moreover, evaluation on capacity of generated power or evaluation on system performance before actual installation is also considered as an important thing to be considered for using as data before making decision on investment in solar rooftop installation. The research report conducted by Suntiti *et al*. [3] evaluated performance of 3 types of solar panel on the roof in various regions of Thailand by using PSIM Program whereas such system was classified as PV grid connected system. The results revealed that monocrystalline silicon (mono-Si) and location of central region of Thailand had the highest level of appropriateness of installation in the light of solar radiance and environmental temperature affecting to generated power capacity.

Ramanan *et al*. [4] analyzed on performance and measured energy value of 2 types of solar panel on the roof by using PVsyst Program whereas such system was classified as PV grid connected system. This research was conducted under tropical wet weather of India and it was found that performance ratio of 2 types of solar panel had yearly mean of 78.48% (for polycrystalline silicon) and 86.73% (for copper indium selenium). Sandhya *et al*. [5] studied on performance of solar rooftop by using PVGIS, PVWatt, and PVsyst Programs whereas such system was classified as PV grid connected system. This research was conducted under tropical wet and dry weather of India and it was found that generated power measured from actual measurement and those 3 programs had MBE as 5.33%, 12.33%, and 30.64%, respectively, whereas NMBE was 2.95%, 7.88%, and 22.75%, respectively. Bhakta *et al*. [6] evaluated performance of solar power generating power by using solar panels measured by HOMER Pro Program whereas such system was classified as PV stand-alone system. The research was conducted under climate of Lakshadweep Island in India and the results revealed that performance ratio had yearly mean ranged from 64.22% - 65.83%.

Malvoni *et al.* [7] analyzed on performance, efficiency, and long-term energy loss of solar power generation by using solar panels measured by SAM and PVsyst Programs whereas such system was classified as

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PV grid connected system. The research was conducted under Mediterranean climate at Salento University located in the south of Italy. The results revealed that performance ratio obtained from both programs had yearly mean of 87.43% and 77.57%, respectively. In addition, the results also revealed that generated power capacity measured by the model was lower than actual measurement with value of 3.0% and 3.3%, respectively. In addition, there was the research report conducted to evaluate on performance of solar power generation by using solar panels measured by other programs, for example, PV*SOL, RETScreen, SolariusPV, HelioScope, Solar Pro, SOLARGIS, and PV F-Chart Programs, etc. [8-9]

From the above research report, it was found that most researches conducted to evaluate performance of solar power generation by using solar panels by using package software mainly required data on solar radiation from ground-based weather radar stations in such areas to gain correctness and accuracy in evaluating performance of such system. However, with limitation on measuring devices and tools, evaluation on performance of solar power generation by using solar panels calculated from mathematical model through conversion of solar irradiance on horizontal plane to be inclined plane was another method that was applied. Therefore, this research aims to analyze on reliability of evaluation on performance of solar cells.

2. METHODOLOGY

The research divided this study on reliability of mathematical model with monitoring system of solar rooftop system, the researcher into 3 parts including: (1) electric power measured by monitoring system; (2) electric power calculated from mathematical model by using conversion of solar irradiance; and (3) analysis on reliability of mathematical model, with the following details:

2.1 Electric Power Measured by Monitoring System

The researcher used a plastic manufacturer in Samut Sakhon Province (13.56 °N and 100.21 °E [10]) as the case study. The roof of such manufacturer was curved with slope from north - west. Characteristics of slope or tilted angle (β) and direction of exposure to solar radiation could be classified by using surface azimuth angle (γ) in 4 directions including: northern direction of solar radiation ($\gamma = 0$) with roof's tilt angle of 5° ($\beta = 5$) and 20° ($\beta = 20$) that was replaced by S1 and S2, respectively, and southern direction of solar radiation ($\gamma = 180$) with roof's tilt angle of 5° ($\beta = 5$) and 20° ($\beta = 20$) that was replaced by N1 and N2, respectively. The roof of such manufacturer was installed with 1,500 polycrystalline silicon solar panels in parallel manner with the roof consisted of total installed capacity of 390 kWp (technical data of solar panel as shown in Table-1). Installation of solar rooftop was shown in Figure-1 (A).

Electric power generated by solar panels was recoded every 15 minutes by using PV system list whereas 96 solar panels (24.96 kWp) were connected with 1 inverter and generated power capacity could be measured by such inverter. As a result, the researcher selected 4 sets of solar panels (covering 4 directions of roof) and each set could read generated power capacity from inverter. These sets consisted of: (1) S1 - Inverter No. 719 (2); S2 - Inverter No. 660; (3) N1 - Inverter No. 762; and (4) N2 - Inverter No. 684 as shown in Figure-1 (B).

Table-1. Technical information of solar panel at STC.

Data	Value
Panel type	poly-Si
Model	SW 260
Maximum power: Pmp)Wp(	260
Open Circuit Voltage: Voc)V(	38.4
Maximum voltage: Vmp)V(	31.4
Short-circuit current: Isc)A(	8.94
Maximum current: Imp)A(	8.37
Temperature coefficient of Voc:)%/°C(	-0.31
Temperature coefficient of Isc:)%/°C(	0.051
Panel operating temperature at NOCT (°C)	46
Width)m(	1.001
Length)m(	1.675

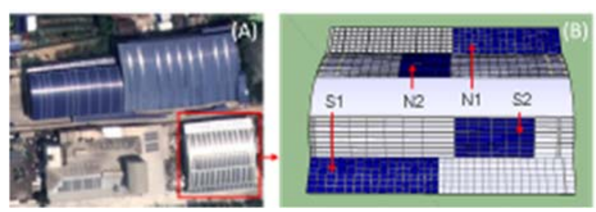

Figure-1. (a) Top view of solar panels installed on the roof of the plastics factory building, Samut Sakhon Province and (b) a set of solar panels connected to 1 inverter considered.

2.2 Electric Power Calculated from Mathematical Model

To evaluate electric power, it is necessary to evaluate from solar irradiance incident on solar panels after installation. As a result, mathematical model of generated power capacity consisted of 2 parts including: (1) mathematical model for evaluating solar irradiance; and (2) mathematical model for evaluating electric power, as follows:

2.2.1 Mathematical model for calculating solar irradiance

Generally, pyranometer at the station is installed on horizontal plane therefore this research evaluated solar irradiance on inclined plane based on direction of solar panels by converting direct irradiance from the sun and diffuse irradiance from the sky on horizontal plane to be

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inclined plane under direction of solar panels plus with ground-reflected irradiance. Procedures of conversion of solar irradiance could be explained as follows:

- Conversion of direct irradiance from the sun on horizontal plane to be inclined plane could be calculated as shown in equation (1) [11-12].

$$G_{b\beta\gamma} = G_b(\cos\theta / \cos\theta_z) \tag{1}$$

$$\begin{aligned}\cos\theta = {} & \sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\gamma + \\ & \cos\delta\cos\phi\cos\beta\cos\omega + \\ & \cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega + \\ & \cos\delta\sin\beta\sin\gamma\sin\omega\end{aligned} \tag{2}$$

$$\begin{aligned}\delta = {} & (0.006918 - 0.399912\cos\Gamma + 0.070257\sin\Gamma - \\ & 0.006758\cos 2\Gamma + 0.000907\sin 2\Gamma - \\ & 0.002697\cos 3\Gamma + 0.00148\sin 3\Gamma)\end{aligned} \tag{3}$$

$$\omega = 15(12 - ST) \tag{4}$$

$$ST = LST + 4(L_s - L_l) + E_t \tag{5}$$

$$\begin{aligned}E_t = {} & 229.18(0.000075 + 0.001868\cos\Gamma - \\ & 0.032077\sin\Gamma - 0.014615\cos 2\Gamma - \\ & 0.040489\sin 2\Gamma)\end{aligned} \tag{6}$$

$$\Gamma = [(d_n - 1)360/365] \tag{7}$$

$$\cos\theta_z = \sin\delta\sin\phi + \cos\delta\cos\phi\cos\omega \tag{8}$$

- Conversion of diffuse irradiance from the sky on horizontal plane to be inclined plane in case of uneven earth surface based on anisotropic model could be calculated as shown in equation (9) [11-12].

$$\begin{aligned}G_{d\beta\gamma} = {} & (1/2)G_d(1+\cos\beta)[1+F\sin^3(\beta/2)]\times \\ & (1+F\cos^2\theta\sin^3\theta_z)\end{aligned} \tag{9}$$

- The ground-reflected irradiance in case of uneven earth surface based on direction could be calculated as shown in equation (10) [11-12].

$$G_{r\beta\gamma} = (1/2)G\rho(1-\cos\beta)\left[1+\sin^2\left(\theta_z/2\right)\right]\left(\left|\cos\Delta\right|\right) \tag{10}$$

As a result, global irradiance incident on an inclined plane of the roof in any direction of exposure to solar radiation could be calculated as shown in equation (11) [11-12].

$$G_{\beta\gamma} = G_{b\beta\gamma} + G_{d\beta\gamma} + G_{r\beta\gamma} \tag{11}$$

The δ of conversion of direct irradiance on horizontal plane to be inclined plane could be calculated by considering on d_n on the 15th day of each month and considering on the duration when the sun was at the surface for exposing to solar radiation only. Such duration represented $\cos\theta > 0$ (equation (2)) whereas $\cos\theta = 0$ when $\theta = 90$. This represented that the sun would be perpendicular with the plane to expose to solar radiation and $\cos\theta < 0$ when $\theta > 90$ representing that the sun would be behind the plane for exposing to solar radiation. As a result, direct irradiance on inclined plane would be considered in the range of $0 \le \theta < 90$ only. Conversion of solar radiation on horizontal plane to be inclined plane would be considered every 15 minutes from 07:00 a.m. - 04:00 p.m. and it would be used as monthly mean for evaluating energy obtained from solar radiation during each month. However, since there was no station to measure solar irradiance on the same plane of the research area, this research was conducted by using data on monthly mean of solar irradiance from the station of Faculty of Engineering, Mahasarakham University (16°12'N and 103°16'E [10]) from 2007-2010 that was not quite different from solar radiation of the research area.

2.2.2 Mathematical model for calculating electric power

Calculation of electric power obtained from solar panels was conducted by using data from 3 parts including: Part 1 - solar irradiance on inclined plane under direction of solar panels (equation (11)); Part 2 - technical data of solar panel (Table-1); and Part 3 - ambient temperature. These data were monthly mean of 2018 obtained from Meteorology Station, Bangkok (Bang Khen Weather Section) therefore, from 3 parts of data, electric power generated by solar panels with any solar irradiance, ambient temperature, and direction of exposure to solar radiation could be calculated as shown in equation (12) [2, 14]

$$P_{pv} = I_{mp}V_{mp} \tag{12}$$

$$I_{mp} = I_{mp,r}\left(G_{\beta\gamma}/G_r\right)\left[1+\alpha_I\left(T_c - T_{c,r}\right)\right] \tag{13}$$

$$V_{mp} = V_{mp,r}\left(\ln G_{\beta\gamma}/\ln G_r\right)\left[1+\alpha_V\left(T_c - T_{c,r}\right)\right] \tag{14}$$

$$T_c = T_a + \left[\left(NOCT - 20\right)/800\right]G_{\beta\gamma} \tag{15}$$

2.3 Analysis on Reliability of Mathematical Model

Statistic variables used in performance test of the model were root mean square difference (RMSD), mean bias difference (MBD), and coefficient of determination (R^2) that could be calculated as shown in equations (16)-(18) [12].

$$RMSD = \left[\frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_{model,i} - P_{meas,i})^2}}{\frac{1}{N}\sum_{i=1}^{N}P_{meas,i}} \right] \times 100 \quad (16)$$

$$MBD = \left[\frac{\frac{1}{N}\sum_{i=1}^{N}(P_{model,i} - P_{meas,i})}{\frac{1}{N}\sum_{i=1}^{N}P_{meas,i}} \right] \times 100 \quad (17)$$

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{N}(P_{meas,i} - P_{model,i})^2}{\sum_{i=1}^{N}(P_{meas,i} - \bar{P}_{meas,i})^2} \right] \quad (18)$$

3. RESULTS

3.1 Electric Power Measured by Monitoring System

The example of electric power generated by solar panels that could be measured by inverter was shown in Figure-2. It was found that each month and each direction of exposure to solar radiation could cause solar panels to generate different power capacities, for example, the path of the sun was in the northernmost in June therefore N2 direction could generate the highest power capacity (Figure-2 (B)) whereas the path of the sun was in the southernmost in December therefore S2 direction could generate the highest power capacity (Figure-2 (D)). As a result, when considering throughout the year, it could found that electric power generated by 4 sets of solar panels, including S1, S2, N1, and N2, had the highest capacity in March, March, May, and May with value of 15.47, 15.70, 15.12, and 15.03 kW, respectively, calculated to be 61.98%, 62.91%, 60.57%, and 60.23% of installed capacity (24.96 kWp), respectively.

3.2 Electric Power Calculated from Mathematical Model

3.2.1 Solar irradiance calculated from mathematical model

The example of solar irradiance on horizontal plane measured by pyranometer and on inclined plane calculated from mathematical model was shown in Figure-3. It was found that solar irradiance on inclined plane had tendency and characteristics that were similar to solar irradiance on horizontal plane. Solar irradiance on inclined plane of each month and each direction was varied by elliptical orbit of the sun around the earth with the sun located at one focus of such elliptical orbit whereas axis of earth's rotation was in tilt angle with perpendicular line of orbital plant of the earth with angle of 23.5° [11-12]. When considering on Figure-3 (B), it was found that the path of the sun in June was in the northernmost therefore S2 direction could expose to solar radiation in the lowest level. Simultaneously, the path of the sun in December was in the southernmost therefore N2 direction could expose to solar radiation in the lowest level as well (Figure-3 (D)). Moreover, when considering on average monthly solar irradiance, it was also found that solar irradiance on horizontal plane had the highest value in April at 928.46 W/m^2 whereas direction to expose solar radiation at S1, S2, N1, and N2 had the highest value in April, February, April, and April, with value of 953.35, 943.71, 944.20, and 888.56 W/m^2, respectively.

3.2.2 Electric power calculated from mathematical model

The example of electric power calculated from mathematical model was shown in Figure-4. It was found that the highest electric capacity generated by 4 sets of solar panels, i.e., S1, S2, N1, and N2, was in April, February, April, and April (that was consistent with irradiance) with value of 21.42, 21.21, 21.20, and 19.86 kW, respectively, calculated to be 85.82%, 84.98%, 84.94%, and 79.57% of installed capacity (24.96 kWp), respectively.

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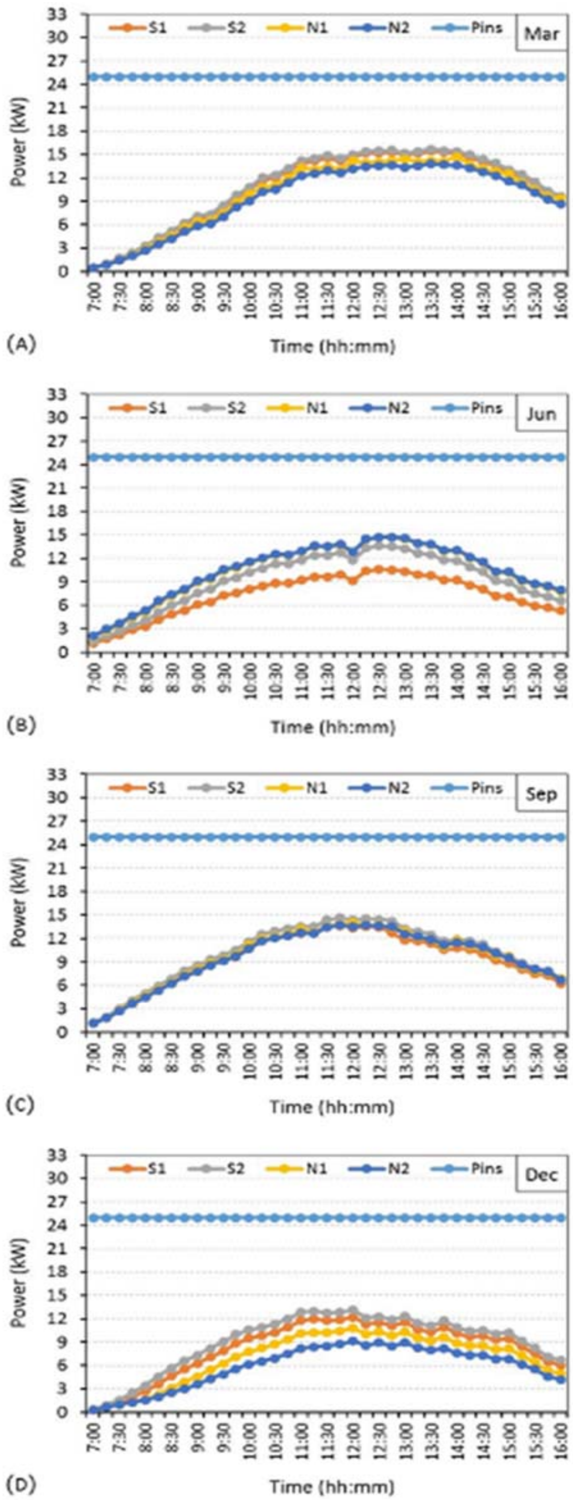

Figure-2. Electric power measured by monitoring system for the (A) March, (B) June, (C) September, and (D) December.

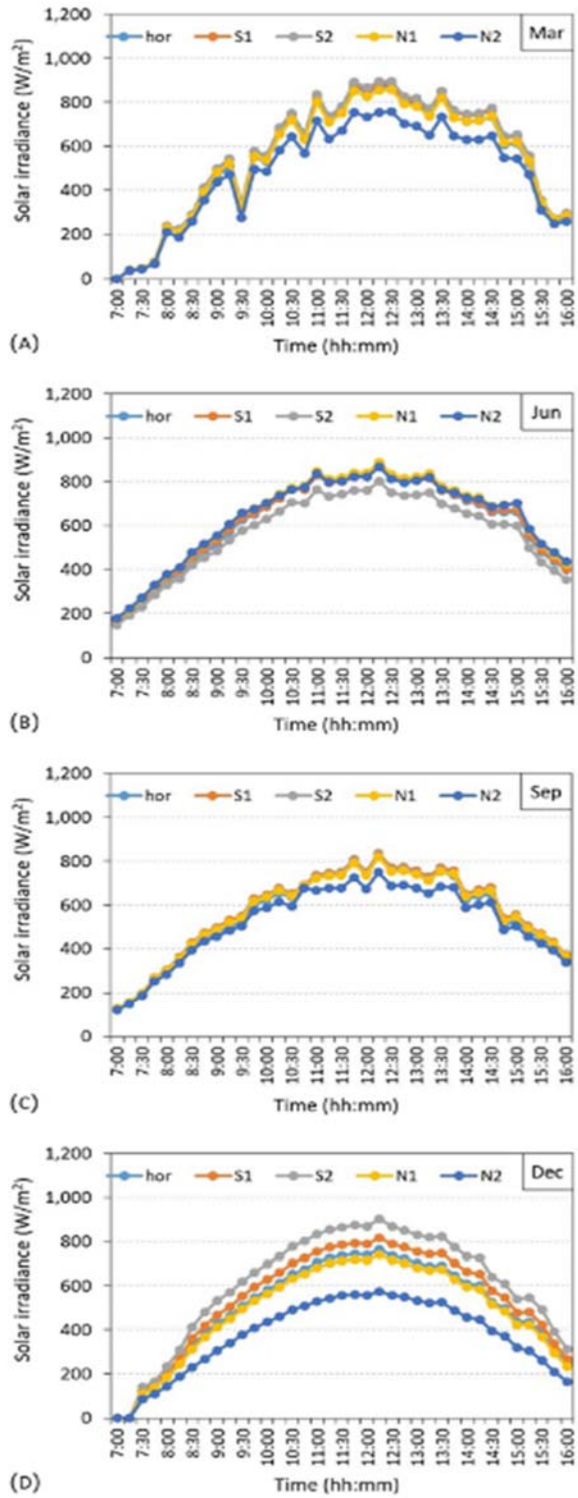

Figure-3. Total solar irradiance on the horizontal plane from pyranometer and global solar irradiance on an inclined plane from a mathematical model for the (A) March, (B) June, (C) September, and (D) December.

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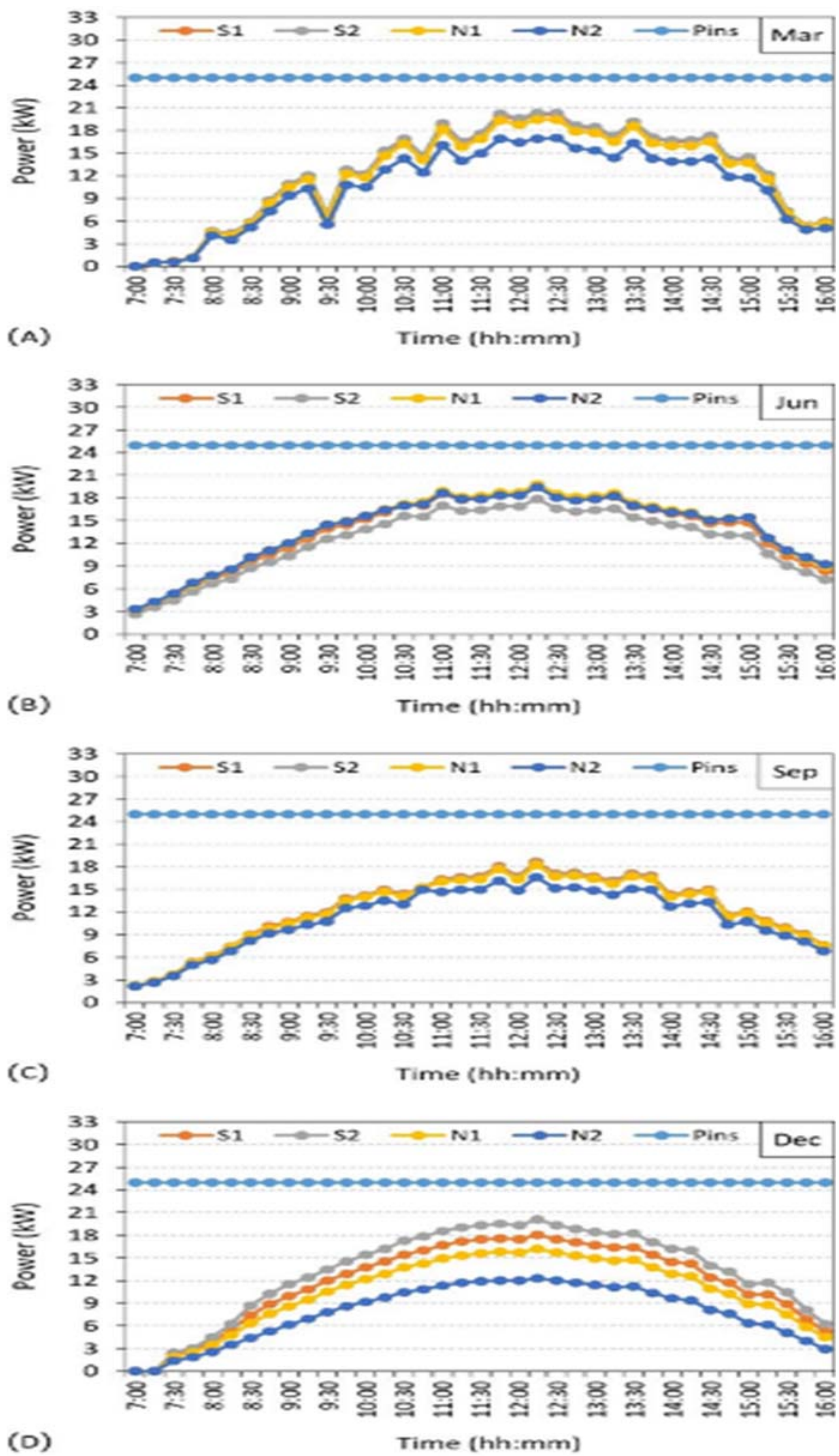

Figure-4. Electric power calculated from a mathematical model for the (A) March, (B) June, (C) September, and (D) December.

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3.3 Results of Analysis on Reliability of Mathematical Model

Reliability of mathematical model for evaluating generated power capacity of each direction throughout the year (S1 Direction was not considered in July and N1 Direction was not considered in January due to errors of monitoring system of such directions in those months hindering measuring results recording) with value of RMSD, MBD, and R^2 as shown in Table-2 and Figure-5.

Table-2. Results of the model reliability analysis.

Installation and direction of solar radiation exposure	RMSD)%(	MBD)%(	R^2
S1: Tilt angle of 5° from horizontal plane and face the solar radiation south	60.82	51.49	0.738
S2: Tilt angle of 20° from horizontal plane and face the solar radiation south	41.87	35.94	0.903
N1: Tilt angle of 5° from horizontal plane and facing the solar radiation north	44.26	38.77	0.898
N2: Tilt angle of 20° from horizontal plane and face the solar radiation north	37.53	30.90	0.897
Combined data	46.39	38.93	0.849

From Table-2, it was found that RMSD was in the lowest level in installation of N2, S2, N1, and S1 with value of 37.53%, 41.87%, 44.26%, and 60.82%, respectively, whereas the lowest value of MBD was found in such installation with value of 30.90%, 35.94%, 38.77%, and 51.49%, respectively. Consequently, R^2 was 0.897, 0.903, 0.898, and 0.738, respectively, whereas RMSD, MBD, and R^2 of the combined data was 46.39%, 38.93%, and 0.849, respectively. This represented that reliability of mathematical model was in moderate level.

4. CONCLUSIONS

From the study on reliability of mathematical model of solar rooftop by comparing with electric power generated by installed solar panels, it was found that solar panels were installed with 4 formats, i.e., direction of exposure to solar radiation in the south with tilt angle of 5° and 20° from horizontal plane represented by S1 and S2, respectively; and direction of exposure to solar radiation in the north with tilt angle of 5° and 20° from horizontal plane represented by N1 and N2, respectively. Each format of installation contained 96 solar panels with installed capacity of 24.96 kWp. The results revealed that the highest electric capacity generated by 4 formats of installation calculated to be 61.98%, 62.91%, 60.57%, and 60.23% of installed capacity, respectively, whereas electric power calculated from mathematical model considered from conversion of solar irradiance on horizontal plane to be inclined plane under direction of exposure to the sun revealed that solar irradiance of installation of S1, S2, and N1 had higher value

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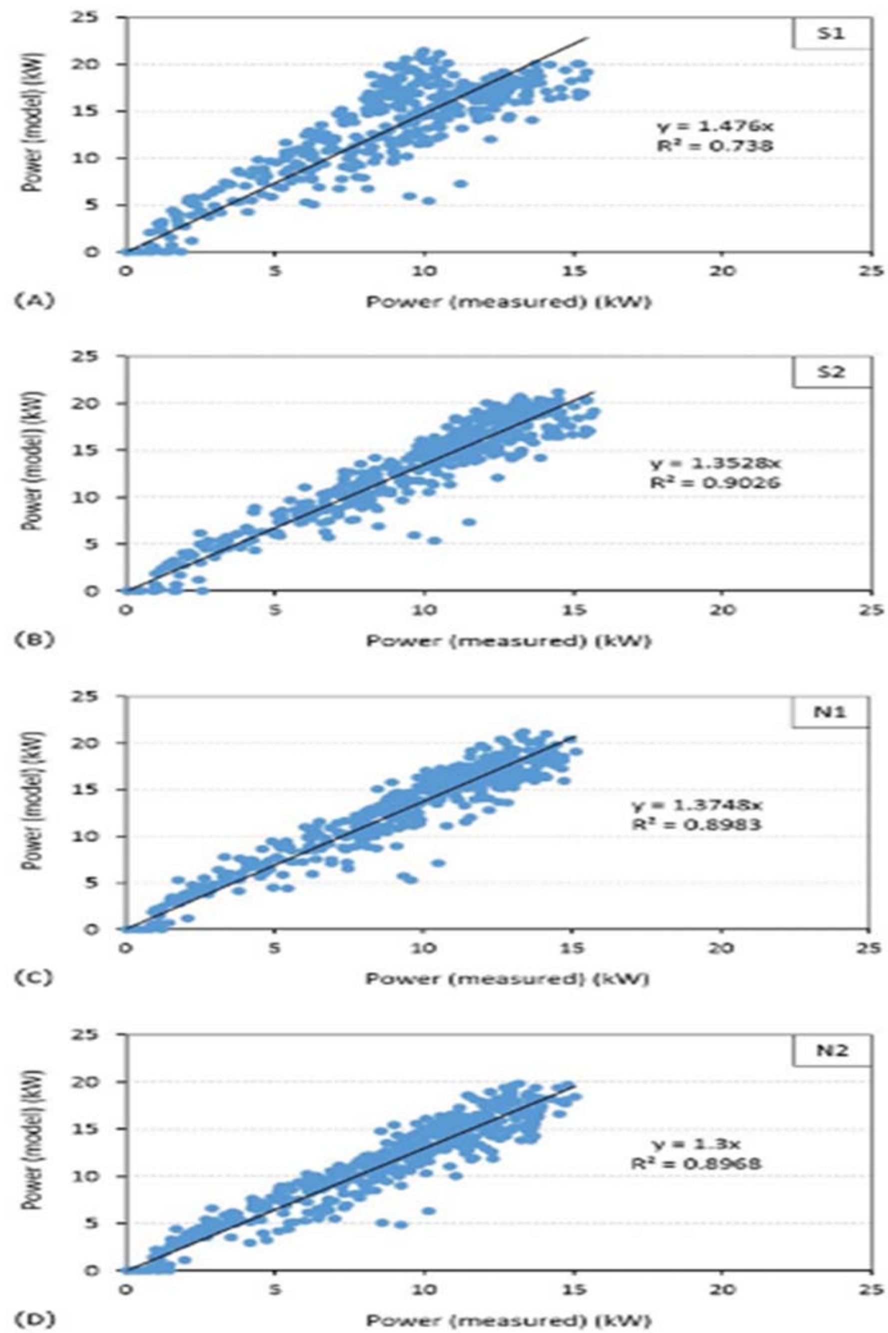

Figure-5. Comparison of electric power from the mathematical model and monitoring system for the (A) S1, (B) S2, (C) N1, and (D) N2.

than the highest value on horizontal plane calculated to be 2.68%, 1.64%, and 1.70%, respectively. Simultaneously, installation of N2 had lower value than the highest value on horizontal plane calculated to be 4.30%. When calculating generated power capacity by using such solar irradiance on inclined plane, it was found that those 4 formats of installation had higher value than electric power measured by monitoring system calculated to be 38.46%, 35.08%, 40.22%, and 32.10%, respectively. The results of analysis on reliability of mathematic model with RMSD, MBD, and R^2 of the combined data were 46.39%, 38.93%, and 0.849, respectively. To make this analysis more reliable and accurate, solar irradiance on horizontal plane measured by measuring tool at the location of such solar panel installation should be used for converting such value to be value on inclined plane.

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NOMENCLATURE AND GREEK SYMBOLS

d_n	day number of the year or Julian day)since 1 January( ]days[
E_t	equation of time]min[
F	modulating function given by $1-(G_d/G)^2$]dimensionless[
G	total solar irradiance incident on a horizontal surface]W/m²[
G_b	direct solar irradiance incident on a horizontal surface]W/m²[
$G_{b\beta\gamma}$	direct solar irradiance incident on an inclined surface]W/m²[
G_d	diffuse solar irradiance incident on a horizontal surface]W/m²[
$G_{d\beta\gamma}$	diffuse solar irradiance incident on an inclined surface]W/m²[
G_r	solar irradiance at standard test condition)STC( ]W/m²[ )It is equal to 1,000 W/m²(
$G_{r\beta\gamma}$	ground-reflected solar irradiance incident on an inclined surface]W/m²[
$G_{\beta\gamma}$	global solar irradiance incident on an inclined surface]W/m²[
I_{mp}	maximum current of solar panel at P_{mp}]A[
$I_{mp,r}$	current of solar panel at STC]A[
I_{sc}	short circuit current of solar panel]A[
L_l	local longitude]degree[
L_s	standard longitude]degree[
LST	local standard time]degree[
MBD	mean bias difference]%[

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N amount of data
NOCT nominal operating cell temperature]°C[
P_{ins} installed power]W[
P_{mp} maximum power of solar panel]W[
P_{pv} photovoltaic power output]W[
$P_{meas,i}$ photovoltaic power output from the measurement
$\overline{P}_{meas,i}$ average photovoltaic power output from the measurement
$P_{model,i}$ photovoltaic power output from the model
R^2 coefficient of determination]dimensionless[
RMSD root mean square difference]%[
ST solar time]hour:min in equation 5 and min in equation 4[
T_a ambient temperature]°C[
T_c solar panel temperature]°C[
$T_{c,r}$ solar panel temperature at STC]°C[
V_{mp} maximum voltage of solar panel at P_{mp}]V[
$V_{mp,r}$ voltage of solar panel at STC]V[
V_{oc} open circuit voltage of solar panel]V[
α_I temperature coefficient of I_{sc}]%/°C[
α_V temperature coefficient of V_{oc}]%/°C[
β inclination of a surface from the horizontal position]degree[
θ angle of incidence for an arbitrarily oriented surface]degree[
θ_z zenith angle]degree[
ρ ground albedo]dimensionless[ )In this study, ρ is equal to 0.2(
ϕ geographic latitude angle]degree[
γ surface azimuth angle]degree[
δ declination angle]degree[
Γ day angle]degree[
ω hour angle]degree[
Δ azimuth of the tilted surface with respect to that of the sun]degree[