International Journal on "Technical and Physical Problems of Engineering" (IJTPE)
Published by International Organization of IOTPE
ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

December 2021	Issue 49	Volume 13	Number 4	Pages 17-26

EFFECT OF SOLAR RADIATION EXPOSURE DIRECTION TO CONVERSION OF SOLAR RADIATION VALUE ON HORIZONTAL PLANE TO VALUE ON INCLINED PLANE FOR ESTIMATING ELECTRIC POWER FROM SOLAR ROOFTOP

W. Chokkuea [1]   S. Sirikaew [2]

1. Department of Physics, Faculty of Science, Mahasarakham University, Kantarawichai District, Mahasarakham, Thailand, drwutthisat@gmail.com
2. Department of Physics, Faculty of Science, Silpakorn University, Mueang Nakhonpathom District, Nakhonpathom, Thailand, sattra_20@hotmail.com

Abstract- This research proposes the effect of Solar Radiation (SR) exposure direction to the conversion of SR value on the Horizontal Plane (HP) to the value on an Inclined Plane (IP) for estimating the electric power from the solar rooftop by processing through the Microsoft Excel program. The building used for research is located in Mahasarakham University, which are A, B, D, FA, SC2, TA, and EN buildings. So, the study was divided into 4 parts: (1) estimation of roof area potential, (2) estimation of SR potential according to roof direction, (3) estimation of electric power and energy from the installation of solar panels according to roof direction, and (4) estimation of electric energy towards the installed electric power or array yield. The research results found that the roof of the building has a slope of 30° with the HP by the SR direction can be classified according to the roof direction using the surface azimuth angle in 12 directions, namely 165°, 135°, 120°, 75°, 45°, 30°, -15°, -45°, -60°, -105°, -135°, and -150°. All buildings have a roof area ranging from 2,575.79-3,974.76 m^2 and can install solar panels up to 884-1,656 panels. In addition, it has an installed electric power of 265.20-496.80 kWp. The results of the SR estimation showed that the solar energy on the annual average HP was 5.56 kWh/m^2-d. While the results from the conversion of the SR on that plane give the value on an IP along the roof direction is up to 5.82 kWh/m^2-d in -15° direction. The results of the total electric energy estimation for the whole year showed that the highest and lowest values were TA and D buildings at 816.07 and 436.63 MWh, respectively. Additionally, the highest and lowest monthly array yield were 154.20 kWh/kWp in -15° direction and 117.18 kWh/kWp in 165° direction, respectively. Moreover, it was found that the annual array yield of each building had the highest and lowest values which is D and A building, the values of 1,646.42 and 1,631.80 kWh/kWp, respectively. While TA, SC2, FA, and EN buildings, the annual array yield is the same, 1,642.65 kWh/kWp

Keywords: Solar Irradiance, Solar Irradiance Conversion, Solar Rooftop, Array Yield.

1. INTRODUCTION

Thailand is located along the equator at latitude 5-21 °N and longitude 97-106 °E [1], can receive Solar Radiation (SR) all year round with an average of 17.8 MJ/m^2-d [2]. Normally, solar energy, which is renewable energy, will be is used to produce two forms of energy: for thermal energy production (e.g. solar collector and solar drying technologies) and for electricity generation (e.g. solar cell technology and concentrating solar energy) [3-5]. Over the years, the electricity generation from solar cells soared. This is a result of efforts to decrease the use of fossil fuels and promote the use of renewable energy. Therefore, this is represented by price incentives to acquisition electricity produced from renewable energy at a fixed rate during the period of support (Feed-in Tariff: FiT) [6]. Furthermore, if it considers Alternative Energy Development Plan 2015-2036 (AEDP2015), it also found the renewable energy target in 2036 determined at 30% of the final energy use which the electricity generation from renewable energy has the highest proportion of solar energy for 6,000 MW or 30% [7].

For devices used to convert solar energy into electric energy, it is called solar cell or photovoltaic cell, which works with the photovoltaic effect [9]. Therefore, if considering the electric energy produced, it is found that it depends on 2 main factors that can be controlled: solar panel type and application installation. The solar panel installation is important to consider the principles of engineering design in determining the optimum installation location for maximum SR exposure. That is must consider the direction and incidence angle of SR exposure, so it must be installed at an inclined angle along the latitude of the area and facing the SR exposure towards the equator [3, 9]. At present, the electricity generation from solar cells includes solar farms and floating solar farms, building integrated photovoltaic (BIPV), and solar rooftop [10].

Thus, installed each such solar panels types are specific to that limited space. Since the solar rooftop is one of the most widely installed systems because the roof is an area that receives solar all day. Also, it is optimal use of the space. However, due to the limitations of the roof, an IP (inclined plane) and direction cannot be adjusted as most buildings are not designed for installed solar panels. Therefore, the electric energy generated from solar panels when installed for each building is different. For this reason, a solar potential estimation in any given SR exposure direction. Therefore, it is important to consider estimating the electric energy that will be obtained in the actual installation. A study on the electricity generation from solar cell has been found to focus on the southern SR exposure direction and utilize the latitude of the area to obtain maximum solar energy throughout the year [11-13].

In addition, the estimation of the efficiency, capacity, as well as the cost-effectiveness analysis of electricity generation systems from solar cell has also been studied extensively [14, 15]. From the said report, most studies on electric power generation from solar cell also focused on installing the panels with an inclined angle along the latitude of each area and facing the SR towards the south but solar cells that installing in the roof, this cannot be achieved with the limitations of roof plane and direction as described above. In addition, the electric energy estimation from solar cells on the rooftop must be estimated from SR according to the direction of the roof.

However, most of the SR measuring stations are equipped with a HP (horizontal plane). Consequently, this research aims to estimate SR value along the direction of the roof using SR on the HP. So that, it is said that the electric energy produced by solar cells can be estimated when it is installed for use. Then, the objective of this research is to study the effect of SR exposure direction on the conversion of SR value on the HP to the value on an IP for estimating the electric power from the solar rooftop.

2. MATERIAL AND METHOD

A study of the effect of SR exposure direction to the conversion of SR value on the HP to the value on an IP for estimating the electric power from the solar rooftop. The researchers studied by using mathematical models and processed via Microsoft Excel program by dividing the research study process into 4 parts as follows:

2.1. Area Potential Estimation

The researcher used 7 buildings inside Mahasarakham University (16°12'N and 103°16'E [1]), Mahasarakham Province, as a case study, consisting of the Academic Resource Center (A), Computer office (B), College of Politics and Governance (D), Faculty of Technology (TA), Faculty of Science (SC2), Faculty of Fine and Applied Arts (FA), and Faculty of Engineering (EN) are shown in Figure 1. By the area potential estimation of that building using data from the building blueprint analyzed with the AutoCAD program to estimate the direction, an inclined angle, and the roof area for estimating the area where solar panels can be installed. The area will be able to estimate the number of solar panels using a distance of 0.01 m between solar panels and a distance of at least 0.7 m between solar panels and roof edges.

Figure 1. The study area [16]

2.2. SR Potential Estimation

In general, the composition of the SR on any planes can be considered as Figure 2. Therefore, the estimation of the SR on an IP in any directions of SR exposure can be estimated by converting direct SR and diffuse SR value from the sky on the HP to values on an IP in the direction of SR exposure and the effects of the reflected SR from the ground are as follows.

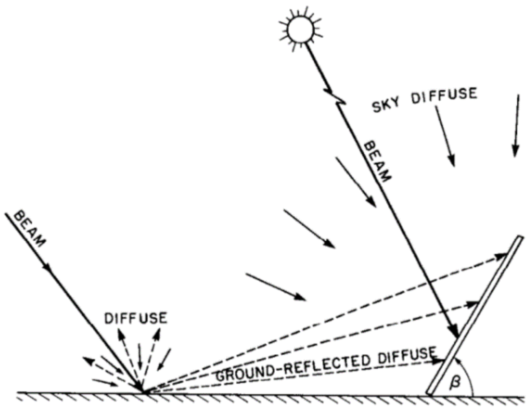


Figure 2. The composition of the SR on an IP [17]

2.2.1. Direct Radiation Incident on an Inclined Plane

Converting the direct SR value on the HP to the values on an IP is calculated as equation (1-8) [17]. For the calculation δ in the equation (3), the monthly average is determined from d_n every day 15th of the month, which is an estimate of the amount of SR that hits the roof in any directions of SR exposure, which is considered from used as the monthly average. These values are used to approximation the SR exposure throughout the month to estimate the energy received from SR throughout the year.

By converting the direct SR on the HP to the values on an IP is determined $\cos\theta > 0$ only by equation (2), it is found that $\cos\theta = 0$ when $\theta = 90$ showing that the sun is perpendicular to the SR exposure plane and $\cos\theta < 0$ when $\theta > 90$ showing that the sun located behind the SR exposure plane, at this time the direct SR on an IP is not considered.

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

$$\begin{aligned}\cos\theta &= \sin\delta\sin\varphi\cos\beta - \sin\delta\cos\varphi\sin\beta\cos\gamma + \\ &+ \cos\varphi\cos\beta\cos\omega\cos\delta + \sin\varphi\sin\beta\cos\gamma\cos\omega\cos\delta + \\ &+ \cos\delta\sin\beta\sin\gamma\sin\omega\end{aligned} \quad (2)$$

$$\delta = (0.006918 - 0.399912\cos\Gamma + 0.070257\sin\Gamma - \\ -0.006758\cos 2\Gamma + 0.000907\sin 2\Gamma - \\ -0.002697\cos 3\Gamma + 0.00148\sin 3\Gamma) \quad (3)$$

$$\omega = 15(12 - ST) \quad (4)$$

$$ST = LST + 4(L_s - L_l) + E_t \quad (5)$$

$$E_t = 229.18(0.000075 + 0.001868\cos\Gamma - \\ -0.032077\sin\Gamma - 0.014615\cos 2\Gamma - 0.040489\sin 2\Gamma) \quad (6)$$

$$\Gamma = [(d_n - 1)360/365] \quad (7)$$

$$\cos\theta_z = \sin\delta\sin\varphi + \cos\delta\cos\varphi\cos\omega \quad (8)$$

2.2.2. Sky Diffuse Radiation Incident on an Inclined Plane

Converting the diffuse SR values from the sky on the HP to values on an IP considered in the case of the anisotropic model that is calculated as equation (9) [17].

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

2.2.3. Ground-Reflected Radiation Incident on an Inclined Plane

Radiation reflected from the ground, this is because ground reflected radiation is very small when compared with direct SR and diffuse SR from the sky. Therefore, to simplify the calculation, the researcher considered the ground-reflected radiation in the situation of the even earth's surface, which is not dependent on the direction (isotropic model) calculated as equation (10) [17].

$$G_{r\beta\gamma} = (1/2)G\rho(1-\cos\beta) \quad (10)$$

Therefore, the total SR that hits the roof in any SR exposure directions. It can be calculated as equation (11) [14].

$$G_{\beta\gamma} = G_{b\beta\gamma} + G_{d\beta\gamma} + G_{r\beta\gamma} \quad (11)$$

To convert SR values on the HP to values on an IP to estimate the solar potential estimation according to the direction of the roof using monthly average SR data from the station in Faculty of Engineering, Mahasarakham University during the year 2007-2010.

2.3. Electric Power and Energy Estimation

Estimation of electric power and energy by the solar cell used in research studies is a type of mono-crystalline silicon solar cell (mono-Si), SW285-300 MONO model (5-busbar) and the technical data of such solar panels is shown in Table 1.

Table 1. Technical data of solar panels at STC [15]

Property of module	Value	Property of module	Value
P_{mp} [W]	300.00	$\alpha_{V_{oc}}$ [%/C]	-0.30
V_{oc} [V]	40.10	$\alpha_{I_{sc}}$ [%/C]	0.04
V_{mp} [V]	31.60	NOCT [C]	46.00
I_{sc} [A]	10.23	Length [m]	1.68
I_{mp} [A]	9.57	Width [m]	1.00

The solar panels are placed parallel to the roof in all directions. To estimate the electric power from a solar panel used 4 parts, there consists of part 1, the direction and slope of the roof obtained from the area potential estimation. For part 2, the SR is obtained from the estimation of the solar potential according to the direction of the roof. For part 3, it is solar panels data and part 4 is monthly average ambient temperature using data from the year 2017 from 4 of meteorological stations [18], namely (1) Tha Phra Agrometeorological Station (16°20'N and 102°49'E), (2) Northeastern Meteorological Center (Upper Part) (16°32'N and 104°43'E), (3) Roi Et Agrometeorological Station (16°03'N and 103°41'E), and (4) Roi Et Meteorological Station (16°03'N and 103°41'E).

The data from the monitoring station will show the measurements according to the UTC system at Greenwich, England, to use data to assess electric power at the same time with SR from the measuring station in the Faculty of Engineering. So, it had to convert UTC to the time zone using Thailand's longitude, which was average of 105°00'E [1]. Therefore, from all 4 parts of the data, the electric power generation by solar panels can be estimated in the condition of SR intensity, ambient temperature and the SR exposure direction is as equation (12-15) [3, 9, 19].

$$P_{pv} = I_{mp}V_{mp} \quad (12)$$

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

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

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

From equation (14), it is found that $V_{mp} > 0$ when $G_{\beta\gamma} > 1$. Therefore, the estimation of electric power will be considered at $G_{\beta\gamma} > 1$. That is, the electric energy produced by solar panels in the state of SR intensity, ambient temperature, and SR exposure direction. It can be calculated as equation (16) [9].

$$E = P_{pv}t \quad (16)$$

2.4. Array Yield Estimation

Electric energy estimation to installed electric power (array yield: Y_a) based on the international energy agency (IEA-PVPS T2-03: 2002) [20] can be calculated as equation (17).

$$Y_a = E/P_{ins} \quad (17)$$

3. RESULT AND DISCUSSION

3.1. Results of Area Potential Estimation

The results of the study presented that an inclined angle of the roof from the building blueprint, analyzed in conjunction with AutoCAD program, was 30° with the HP, an example of this analysis is shown in Figure 3 showing (A) A Building and (B) EN Building. That the 7 buildings used in the study were able to classify the SR exposure direction according to the direction of the roof using the surface azimuth angle for 12 directions, namely 165°, 135°, 120°, 75°, 45°, 30°, -15°, -45°, -60°, -105°, -135°, and -150°. The buildings with the highest total roof area are TA, FA, EN, A, B, SC2, and D with values of 3,974.76, 3,876.00, 2,880.00, 2,742.90, 2,742.90, 2,611.20, and 2,575.79 m^2, respectively. Each such building can install solar panels for the number of 1,656, 1,536, 1,048, 972, 972, 1,024, and 884 panels, respectively, and installed electric power of 496.8, 460.8, 314.4, 291.6, 291.6, 307.2, and 265.2 kWp, respectively. The results of a detailed area potential estimation are shown in Table 2.

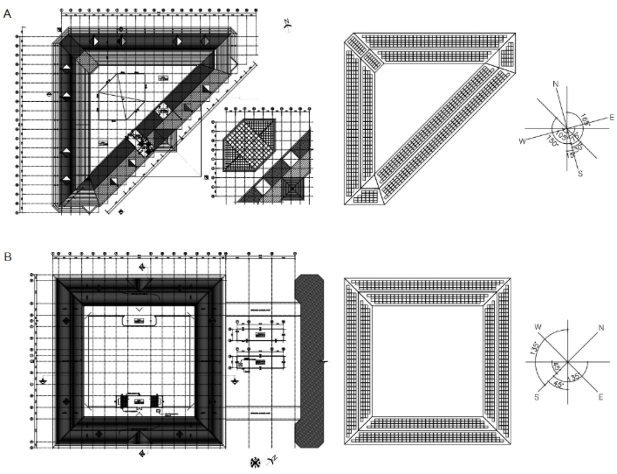


Figure 3. An example of the analysis

3.2. Results of SR Potential Estimation

3.2.1. Result of Converting the Direct Radiation Value on the HP to IP

It was found that the direction of the direct radiation value can be explained by an incidence angle of the direct radiation value (θ), in which case the values are dependent on ω, δ, and γ only (φ and β constant), so the cosine of the solar incidence angle of the direct radiation value ($\cos\theta$) according to equation (2). In each direction (γ), an example can be shown in Figure 4.

From the condition of determining the direct radiation value on an IP in any SR exposure directions, that is $0 < \cos\theta \leq 1$ by $\cos\theta \leq 0$ indicating that the sun is behind or perpendicular to the SR exposure surface which at this time the direct radiation value on an IP is not considered. Figure 4 shows the correlation among an incidence angle of the direct radiation value on an IP in the 12 SR exposure directions every day 15th of the month (A) March, (B) June, (C) September, and (D) December with the interval of 6:15 am to 6:15 pm, which is the time when the SR hits the solar probe on the HP at station of Faculty of Engineering, Mahasarakham University. It was found that in Figure 4 (B) June, (the path of the sun is at the north end), the direction has valued 165° (the SR exposure plane in the northeast), will receive direct SR during the time of 6:15 am to 6:15 pm, that is, can receive SR all day, while the direction has valued -45° will receive direct SR during the time of 7:45 am to 6:15 pm. In addition, if the case of Figure 4 (D) December (the path of the sun is at the south end), the direction has valued 165°, will receive direct SR during the time of 7:15 am to 3:30 pm, while the direction has valued -15° will be exposed to direct SR during the time of 6:15 am to 6:15 pm, that is, can receive SR all day.

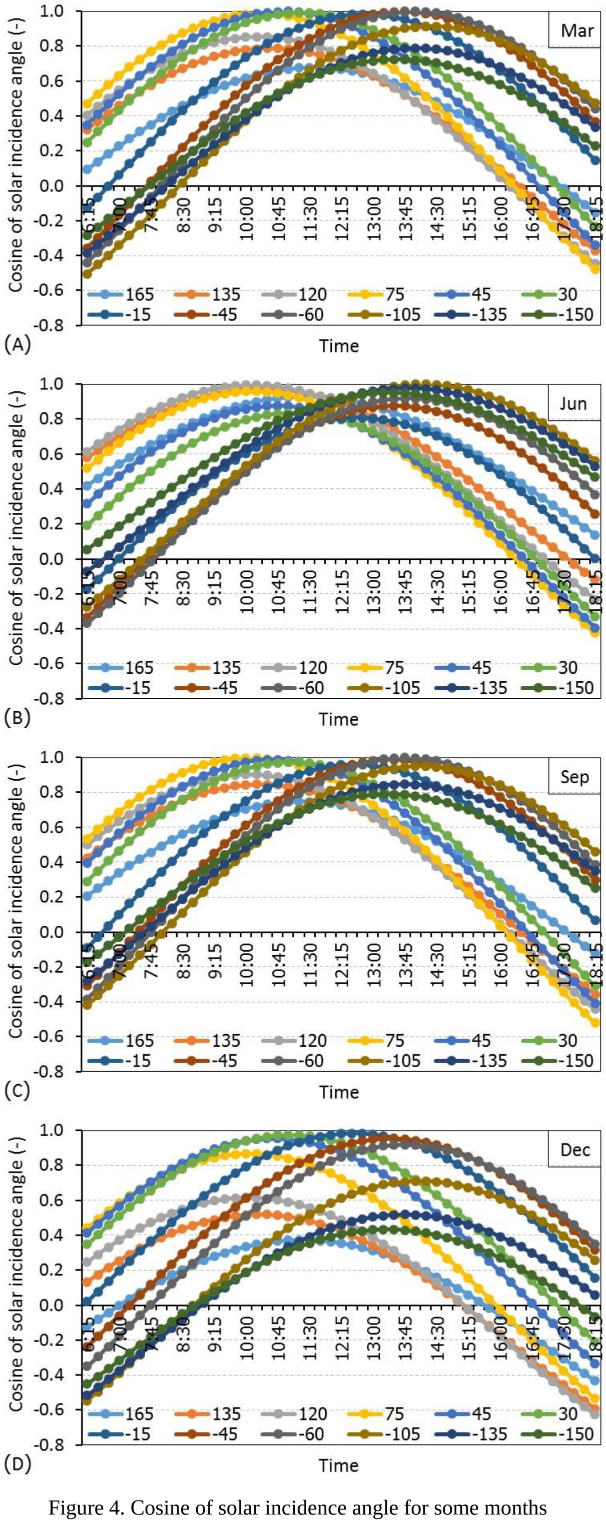


Figure 4. Cosine of solar incidence angle for some months

Therefore, Figure 4 shows that different directions are exposed to direct SR at different intervals. In addition, each month, the sun is perpendicular ($\cos\theta = 1$)) or almost perpendicular ($\cos\theta \cong 1$) to the SR exposure plane at a different time. The above effect is a result of the tilt of the earth's axis. Also, the rotation of the earth and the earth's orbit around the sun is an ellipse [17, 21]. Therefore, resulting in the direct SR on an IP in the 12 directions, according to equation (1), have different values. An example can be shown in Figure 5.

The results of converting the direct SR on the HP to IP was found that direct SR on an IP had the highest value in February. It was 796.85 W/m^2 in -15° direction. While direct SR on the HP of the month was the highest at 698.46 W/m^2. In addition, it was also found that the direct SR on an IP with the highest values in February was higher than the maximum values of the direct SR on the HP (712.99 W/m^2 in April) in 83.86 W/m^2. If considering Figure 5, it is found that the direct SR on an IP in each direction has different values. It is higher than the value on the HP when an incidence angle of the direct SR on an IP is less than an incidence angle of the direct SR on the HP. Also likewise, it is lower than the value on the HP when an incidence angle of the direct SR on an IP is greater than an incidence angle of the direct SR on the HP.

3.2.2. Result of Converting the Sky Diffuse Radiation Value on the HP to IP

The result of converting the diffuse SR from the sky on the HP to the values on an IP according to equation (9), an example can be illustrated as Figure 6.

From Figure 6, it was found that the diffuse SR from the sky on an IP was the highest in June that is 290.63 W/m^2 in -120° direction. While diffuse SR from the sky on the HP for such month was the maximum value of 260.20 W/m^2. In addition, it was found that the highest value of diffuse SR from the sky on an IP in June (290.63 W/m^2 in -120° direction) was lower than the maximum value of diffuse SR on the HP in September (298.31 W/m^2) that is 7.68 W/m^2. Moreover, it was found that the diffuse SR on an IP corresponds to the diffuse SR from the sky in the HP and the path of the sun. For example, Figure 6 (D) finds that the diffuse SR from the sky on the south-facing IP is higher than the north-facing and HP because, during that month, the sun's path is at the south end.

3.2.3. Result of Ground-Reflected Radiation Incident on an Inclined Plane

The calculation of ground-reflected radiation according to equation (10) can be shown in Figure 7.

From Figure 7, it was found that the highest value of ground reflection in April was 12.44 W/m^2. While in other months, the highest value is in the range of 10.26-12.20 W/m^2. So, the global radiation received along the roof's direction according to equation (11) can be illustrated in Figure 8.

The estimation of the total radiation value on an IP was found to have the highest value in February was 979.39 W/m^2 in -15° direction. While the total radiation on the HP for the month was the highest at 860.65 W/m^2. In addition, it was also found that the total radiation on an IP with the highest value in February was higher than the maximum of the total radiation on the HP in April, 928.46 W/m^2, is 50.93 W/m^2. So that, the monthly average solar energy received in the 12 directions can be shown with a radar chart as Figure 9.

From Figure 9, it was found that SR energy (global radiation) on the HP had the highest value in May at 6.37 kWh/m^2-d and an annual average of 5.56 kWh/m^2-d. While the SR energy on an IP was highest in February was 6.52 kWh/m^2-d in -15° direction and the lowest value in December was 2.66 kWh/m^2-d in 165° direction. Further, it was also found that the annual average SR energy on an IP for the direction of 45°, 30°, -15°, -45°, and -60° were 5.57, 5.67, 5.82, 5.74, and 5.64 kWh/m^2-d, respectively, which were higher than the annual average SR energy on the HP (5.56 kWh/m^2-d).

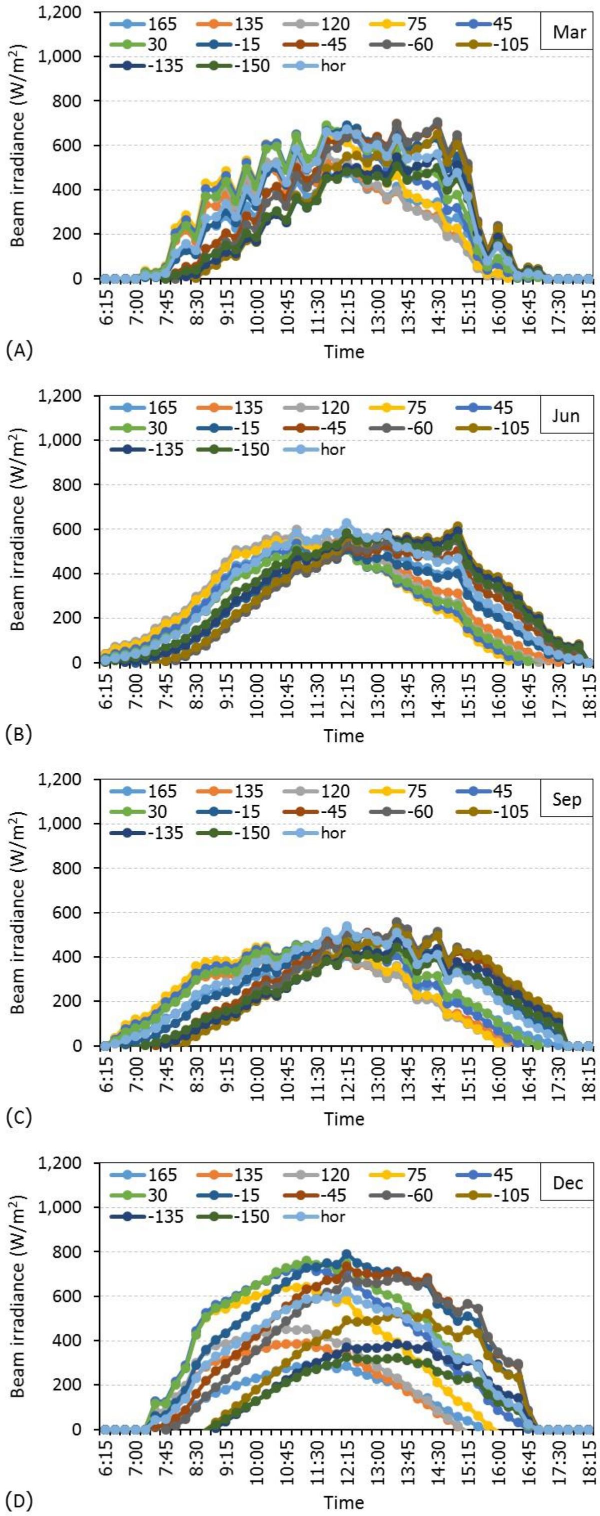


Figure 5. Result of direct irradiance conversion from the HP to IP for some months

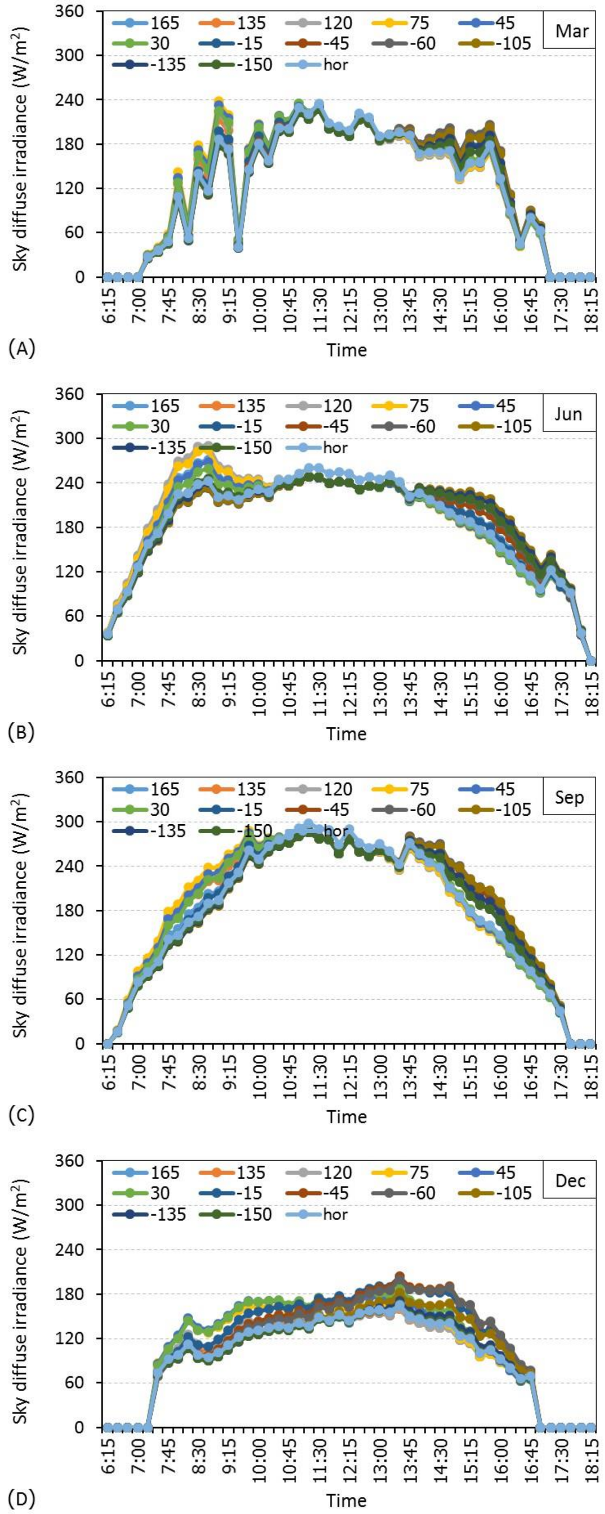


Figure 6. Result of sky diffuse irradiance conversion from the HP to IP for some months

3.3. Result of Electric Power and Energy Estimation

The result of converting the ambient temperature from 4 stations from the UTC system to the time zone in Thailand, which is UTC+7 (105 deg / 15 h/deg), found that the highest and lowest values in April and December were 34.72 and 17.91 C, respectively, or the annual average value was 28.75 C. So, the electric power estimation results, it was found that the electric power produced from one solar panel in the 12 SR exposure directions every day 15th of the month can be illustrated as Figure 10. From Figure 10, 300 Wp can generate its maximum electric power in February (at 12:30 pm) is 266.28 W in -15° direction, and the maximum with the lowest value in December (at 11:30 am) is 113.03 W in 165° direction. It was also found that the electric power produced in each of these directions corresponds to the SR obtained by converting the value on the HP to the value on an IP in the direction of SR exposure.

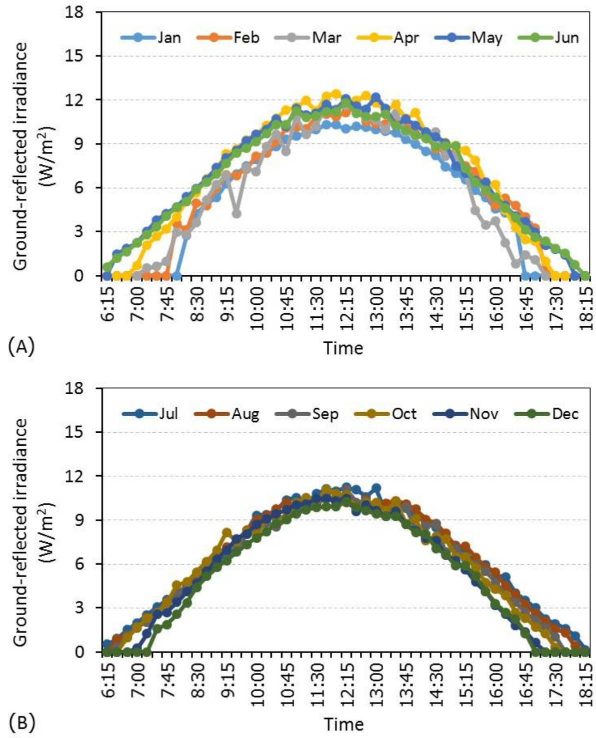
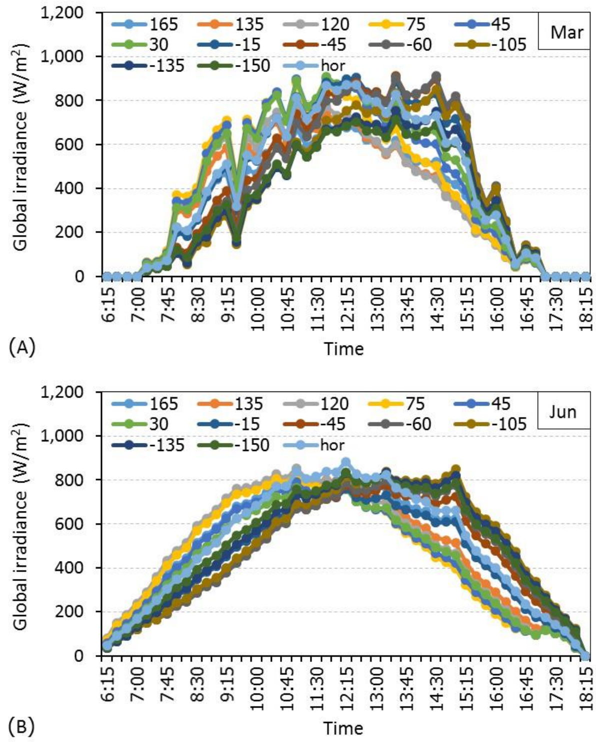


Figure 7. Ground-reflected irradiance on an IP



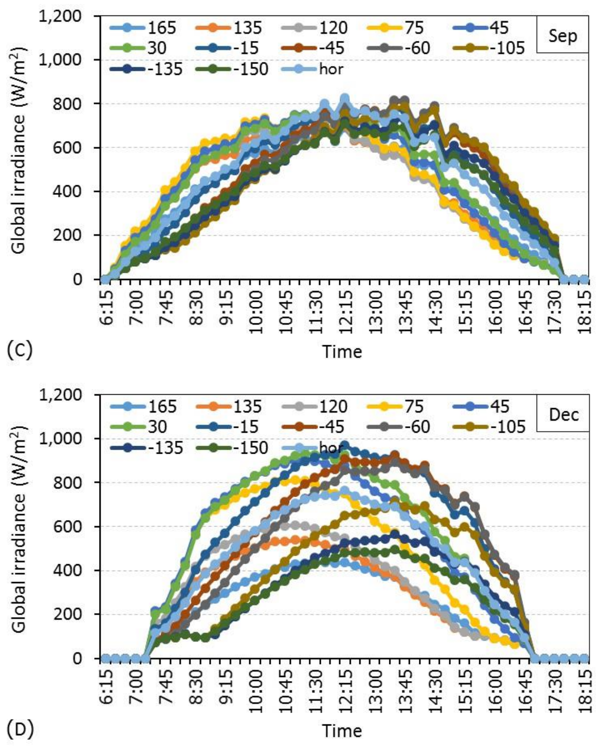


Figure 8. Global irradiance on an IP for some months

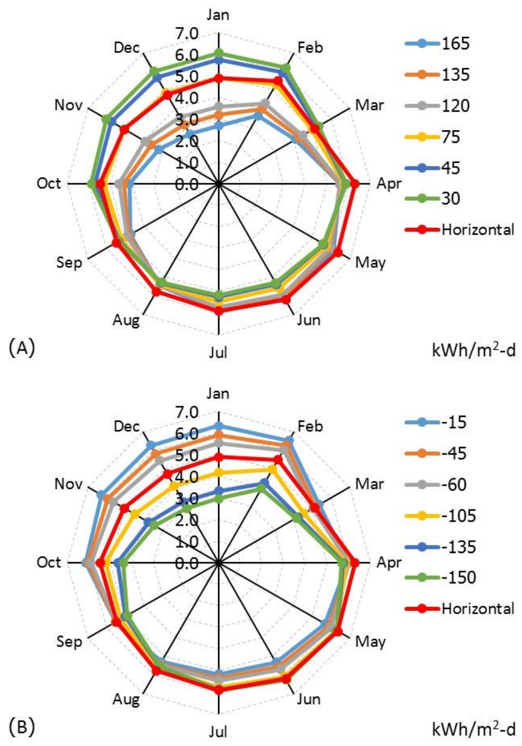


Figure 9. Monthly average global radiation on an IP

The results of the electric energy estimation from N solar panels according to the roof direction of each building, it was found that the highest and lowest annual electricity produced at TA and D buildings were 816.07 and 436.63 MWh, respectively. By the monthly generated electricity for each building can be shown in Table 3.

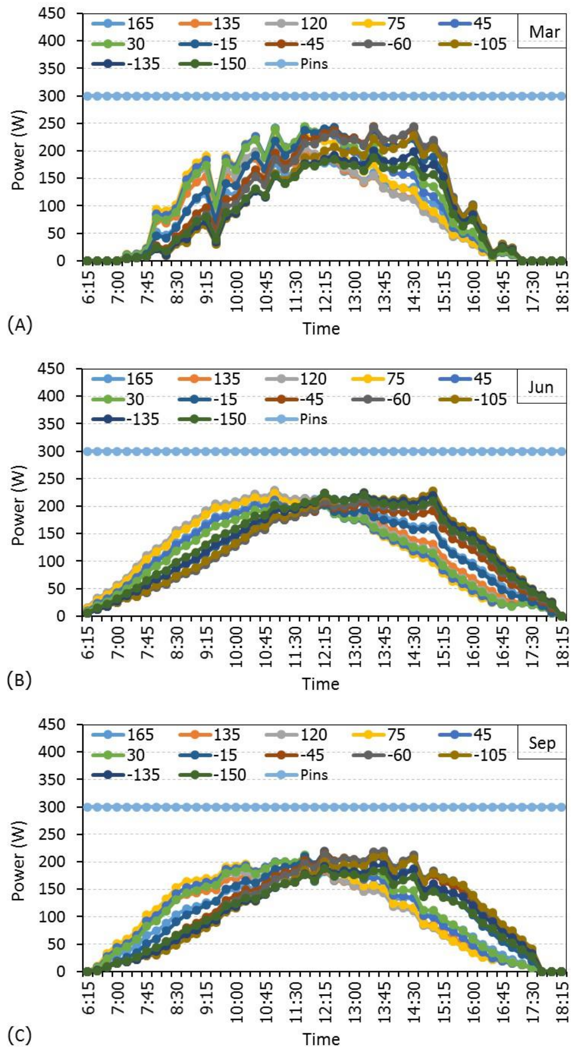
3.4. Result of Array Yield Estimation

Evaluation of electric energy against installed electric power (or array yield estimation), it was found that the highest and lowest values of an annual average array yield were 154.20 kWh/kWp in -15° direction and 117.18 kWh/kWp in 165° direction, respectively. By the monthly array yield of each SR exposure direction can be shown as shown in Table 4. In addition, the annual array yield of each building can be shown in Figure 11.

From Figure 11, it was found that the highest and lowest values of the annual array yield were D and A building that were 1,646.42 and 1,631.80 kWh/kWp, respectively. While TA, SC2, FA, and EN buildings have the same values at 1,642.65 kWh/kWp. As a result of the above 4 buildings, the SR exposure direction and the number of SR exposure directions were equal.

4. CONCLUSIONS

The building used in the study has a roof slope of 30° with the HP and can be classify the SR exposure direction according to the roof direction using the surfacer azimuth angle for 12 directions. The roof of each building has area ranging from 2,575.79-3,974.76 m^2, capable of installing solar panels of 884-1,656 panels and having an installed electric power of 265.20-496.80 kWp. However, due to the limitations of the roof area and the conditions for installing panels, some areas are not considered installation. As a result, the ratio of the roof area to the number of panels installed in each building is different.



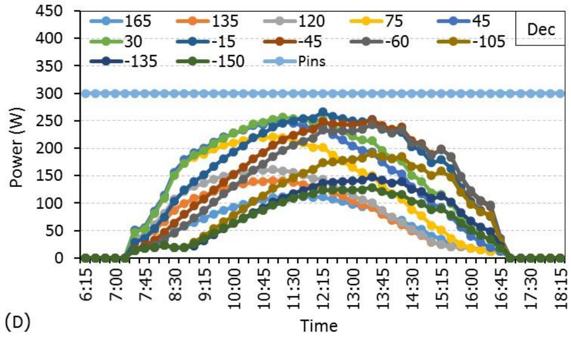


Figure 10. Electric power from one panel according to each direction for some months

The buildings used for the study were not designed to install solar panels. Therefore, the SR exposure direction and roof slope are unsuitable for solar panel installation. The converting the SR value on the HP to the value on an IP in the direction of the roof, it was found that SR energy on the HP had an annual average of 5.56 kWh/m^2-d. While on an IP, it is 5.82 kWh/m^2-d in -15° direction. Therefore, the SR received is specific on each direction, allowing each direction to receive solar energy in time and amount that different.

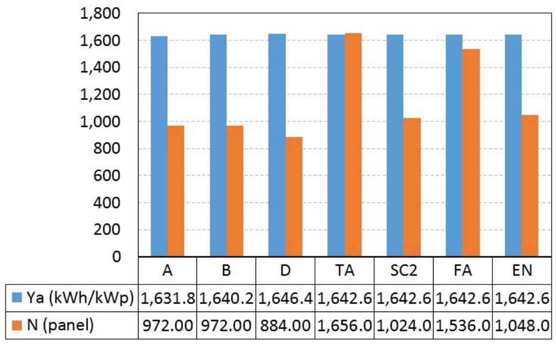


Figure 11. Annual array yield of each building

The electric power generation by solar panels is different depending on the SR exposure direction and the time in each day. In addition, that direction and the number of panels affect the electric energy that is produced. The results of the estimation of total electricity produced throughout the year showed that the buildings that produce the highest and lowest electric energy were TA and D buildings at 816.07 and 436.63 MWh, respectively.

The array yield depends on the SR exposure direction only. By the results of the estimation found that the monthly average array yield throughout the year has the highest and lowest values are -15° and 165° direction, respectively. So, the SR exposure direction suitable for installing solar panels under roof slope up 30° is -15°, -45°, 30°, -60°, 45°, 75°, -105°, 120°, -135°, 135°, -150°, and 165°, respectively. Furthermore, an annual array yield of each building has the highest and lowest values are D and A buildings, respectively. While TA, SC2, FA, and EN buildings, an annual array yield is the same. Therefore, if we install the solar panels in such cases, we consider the number of panels to receive the highest array yield with the lowest solar panels. The above results can be used as a basis for considering the investment in installing solar panels in the next opportunity.

NOMENCLATURES

1. Acronyms

HP Horizontal Plane
IP Inclined Plane
SR Solar Radiation
STC Standard Test Conditions

2. Symbols / Parameters

A_r : The roof area [m^2]
d_n : The day number of the year or Julian day [days]
E : The electric energy [Wh]
E_t : The equation of time [min]
F : The modulating function given by $1-(G_d/G)^2$ [-]
FF : The fill factor [-]
G : The total SR incident on the HP [W/m^2]
G_b : The direct SR incident on the HP [W/m^2]
$G_{b\beta\gamma}$: The direct SR incident on an IP [W/m^2]
G_d : The diffuse SR incident on the HP [W/m^2]
$G_{d\beta\gamma}$: The diffuse SR incident on an IP [W/m^2]
G_r : The SR at STC [W/m^2] (It is equal to 1,000 W/m^2)
$G_{r\beta\gamma}$: The ground-reflected SR incident on an IP [W/m^2]
$G_{\beta\gamma}$: The global SR incident on an IP [W/m^2]
I_{mp} : The maximum current of solar panel at P_{mp} [A]
$I_{mp,r}$: The current of solar panel at STC [A]
I_{sc} : The short circuit current of solar panel [A]
L_l : The local longitude [deg]
L_s : The standard longitude [deg]
LST : The local standard time [deg]
N_{pv} : The number of PV panels [panels]
$NOCT$: The nominal operating cell temperature [C]
P_{ins} : The installed electric power [W]
P_{mp} : The maximum power of solar panel [W]
P_{pv} : The power of solar panel [W]
ST : The solar time [hour: min in eq. 5 and min in eq. 4]
t : The time [hour]
T_a : The ambient temperature [C]
T_c : The solar panel temperature [C]
$T_{c,r}$: The solar panel temperature at STC [C]
V_{mp} : The maximum voltage of solar panel at P_{mp} [V]
$V_{mp,r}$: The voltage of solar panel at STC [V]
V_{oc} : The open circuit voltage of solar panel [V]
Y_a : The array yield [Wh/Wp]
$\alpha_{I_{sc}}$: The temperature coefficient of I_{sc} [%/C]
$\alpha_{V_{oc}}$: The temperature coefficient of V_{oc} [%/C]

β : The inclination of a surface from the HP [deg]

θ : The incidence angle [deg]

θ_z : The zenith angle [deg]

ρ : The ground albedo (In this study, ρ is equal to 0.2.)

φ : The geographic latitude angle [deg]

γ : The surface azimuth angle [deg]

δ : The declination angle [deg]

Γ : The day angle [deg]

ω : The hour angle [deg]

Table 2. Evaluation of roof area and installed electric power potential

Building	List	Surface azimuth angle						Total
		165°	75°	30°	-15°	-105°	-150°	
A	A_r (m^2)	465.00	395.23	556.31	395.23	465.00	466.13	2,742.90
	N_{pv} (panels)	173.00	133.00	188.00	133.00	173.00	172.00	972.00
	P_{ins} (kWp)	51.90	39.90	56.40	39.90	51.90	51.60	291.60
Building	List	Surface azimuth angle						Total
		165°	120°	75°	-15°	-60°	-105°	
B	A_r (m^2)	465.00	466.13	465.00	395.23	556.31	395.23	2,742.90
	N_{pv} (panels)	173.00	172.00	173.00	133.00	188.00	133.00	972.00
	P_{ins} (kWp)	51.90	51.60	51.90	39.90	56.40	39.90	291.60
D	A_r (m^2)	389.43	505.20	389.43	415.75	460.23	415.75	2,575.79
	N_{pv} (panels)	127.00	186.00	127.00	136.00	172.00	136.00	884.00
	P_{ins} (kWp)	38.10	55.80	38.10	40.80	51.60	40.80	265.20
Building	List	Surface azimuth angle						Total
		135°	45°	-45°	-135°	-	-	
TA	A_r (m^2)	993.69	993.69	993.69	993.69	-	-	3,974.76
	N_{pv} (panels)	414.00	414.00	414.00	414.00	-	-	1,656.00
	P_{ins} (kWp)	124.20	124.20	124.20	124.20	-	-	496.80
SC2	A_r (m^2)	652.80	652.80	652.80	652.80	-	-	2,611.20
	N_{pv} (panels)	256.00	256.00	256.00	256.00	-	-	1,024.00
	P_{ins} (kWp)	76.80	76.80	76.80	76.80	-	-	307.20
FA	A_r (m^2)	969.00	969.00	969.00	969.00	-	-	3,876.00
	N_{pv} (panels)	384.00	384.00	384.00	384.00	-	-	1,536.00
	P_{ins} (kWp)	115.20	115.20	115.20	115.20	-	-	460.80
EN	A_r (m^2)	720.00	720.00	720.00	720.00	-	-	2,880.00
	N_{pv} (panels)	262.00	262.00	262.00	262.00	-	-	1,048.00
	P_{ins} (kWp)	78.60	78.60	78.60	78.60	-	-	314.40

Table 3. Electric energy of each building (MWh)

Month	Building							Total
	A	B	D	TA	SC2	FA	EN	
Jan	35.08	35.40	32.54	60.95	37.69	56.54	38.57	296.77
Feb	35.94	36.25	33.24	62.07	38.38	57.57	39.28	302.73
Mar	36.67	36.85	33.60	62.87	38.87	58.31	39.79	306.96
Apr	44.04	44.16	40.21	75.15	46.47	69.71	47.56	367.29
May	46.56	46.58	42.37	79.20	48.97	73.46	50.12	387.27
Jun	43.74	43.76	39.75	74.33	45.97	68.95	47.04	363.55
Jul	43.25	43.33	39.36	73.57	45.49	68.24	46.56	359.82
Aug	41.96	42.11	38.31	71.54	44.24	66.36	45.28	349.79
Sep	38.50	38.72	35.31	65.89	40.75	61.12	41.70	321.98
Oct	40.19	40.56	37.12	69.22	42.80	64.20	43.80	337.89
Nov	35.38	35.71	32.76	61.25	37.87	56.81	38.76	298.54
Dec	34.54	34.87	32.05	60.02	37.11	55.67	37.98	292.25
Average	39.65	39.86	36.39	68.01	42.05	63.08	43.04	332.07
Total	475.83	478.29	436.63	816.07	504.62	756.93	516.45	3,984.83

Table 4. Array yield of each surface azimuth angle (kWh/kWp)

Month	Surface azimuth angle											
	165°	135°	120°	75°	45°	30°	-15°	-45°	-60°	-105°	-135°	-150°
Jan	68.25	83.24	94.45	133.61	158.28	167.65	175.68	162.96	152.13	111.82	86.29	76.25
Feb	85.38	95.59	103.65	130.78	147.25	154.14	162.07	155.17	148.49	121.24	101.75	93.69
Mar	107.45	113.90	118.60	133.85	141.54	143.98	144.34	139.06	135.14	120.85	111.69	108.46
Apr	144.71	145.82	147.20	151.53	153.16	153.83	155.89	156.69	156.72	153.56	149.41	147.53
May	164.90	161.10	159.37	153.89	149.86	148.54	151.02	157.30	160.82	168.37	169.42	169.00
Jun	160.95	156.60	153.88	144.36	137.84	135.47	135.90	142.42	146.55	157.53	161.64	162.63
Jul	157.23	154.42	152.60	145.18	139.25	136.87	136.33	141.62	145.05	153.94	157.08	157.91
Aug	144.34	144.11	144.36	143.60	141.23	140.15	140.52	143.72	145.51	148.05	146.96	146.16
Sep	119.86	122.74	125.55	133.90	137.48	138.85	142.11	142.55	141.92	135.18	127.77	124.38
Oct	107.58	115.51	121.99	143.10	154.90	159.66	167.13	163.79	159.78	139.65	123.10	115.90
Nov	78.64	90.96	100.28	132.22	151.54	159.04	166.09	156.44	148.02	115.66	94.20	85.67
Dec	66.92	82.07	93.26	132.36	156.58	165.80	173.34	160.36	149.50	109.42	84.25	74.39
Average	117.18	122.17	126.27	139.86	147.41	150.33	154.20	151.84	149.13	136.27	126.13	121.83

REFERENCES

[1] C. Infobase, "Thailand Latitude and Longitude Map", www.mapsofworld.com/lat_long/thailand-lat-long.html (accessed on 5 May 2020).

[2] Department of Alternative Energy Development and Efficiency, "Thailand Alternative Energy Situation 2019". Ministry of Energy, 2019.

[3] J.A. Duffie, W.A. Beckman, "Solar Engineering of Thermal Processes", John Wiley & Sons, New York, The United State, 2013.

[4] A.Sh. Abdinov, R.F. Babayeva, "Flexible Photocells based on Layered $A^{iii} B^{vi}$ Semiconductor Compounds", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 40, Vol. 11, No. 3, pp. 23-27, September 2019.

[5] N.I. Babashova, N.F. Rajabli, R.B. Rustamov. "Review on the Challenges and the Future of Solar Cell for Space Applications", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 44, Vol. 12, No. 3, pp. 36-40, September 2020.

[6] Energy Policy and Planning Office. "Policies on Purchasing Electricity from Renewable Energy". http//:www.eppo.go.th/index.php/th/electricity/plan-buy-renewenergy (accessed on 5 May 2020) (in Thai).

[7] Department of Alternative Energy Development and Efficiency. "Alternative Energy Development Plan: AEDP2015", Ministry of Energy, 2015.

[8] A. Luque, S. Hegedus, "Handbook of Photovoltaic Science and Engineering", John Wiley & Sons, New York. The United State, 2011.

[9] International Energy Agency, "Annual Report 2016", IEA Photovoltaic Power Systems Programme (PVPS), 2017.

[10] L.M. Ayompe, A. Duffy, S.J. McCormack, M. Conlon, "Measured Performance of a 1.72 kW Rooftop Grid Connected Photovoltaic System in Ireland", Energy Conversion and Management, Vol. 52, No 2, pp. 816-825, 2011.

[11] V. Sharma, S.S. Chandel, "Performance Analysis of a 190 kWp Grid Interactive Solar Photovoltaic Power Plant in India", Energy, Vol. 55, pp. 476-485, 2013.

[12] E. Kymakis, S. Kalykakis, T.M. Papazoglou. "Performance Analysis of a Grid Connected Photovoltaic Park on the Island of Crete", Energy Conversion and Management, Vol. 50, No. 3, pp. 433-438, 2009.

[13] N. Suwanasang, S. Tongsopit, "An Assessment of the Technical and Economic Potential of Rooftop Solar Systems on Chulalongkorn University's Buildings", Journal of Energy Research, Vol. 12, No. 2, pp. 59-74, 2015 (in Thai).

[14] P. Chinnavornrangsee, S. Songtrai, N. Udomdachanut, S. Kittisontirak, A. Hongsingthong, T. Krajangsang, J. Sritharathikhun, K. Sriprapha, "Evaluation of Rooftop Solar PV Performance of Different PV Module Technologies Operating in Thailand", Ladkrabang Engineering Journal, Vol. 32, No. 2, pp. 19-24, 2015 (in Thai).

[15] Mahasarakham University. "MSU@SY2014-2015". https//:inter.msu.ac.th/news_detail-610-msu-sy-2014-2015.html (accessed on 11 September 2020).

[16] M. Iqbal, "An Introduction to Solar Radiation", Academic Press, Ontario, Canada, 1983.

[17] Eco Direct, "300 Watt Mono Solar Panel", www.ecodirect.com/SolarWorld-SW300-Plus-Mono-5BB-300W-Mono-Panel-p/solarworld-sw300-plus-mono-5bb.html (accessed on 13 September 2017).

[18] Thai Meteorological Department. "Weather Classified by City", www.aws-observation.tmd.go.th (accessed on 3 January 2018).

[19] V. Quaschning, "Understanding Renewable Energy Systems", Earthscan, London, The United State, 2005.

[20] International Energy Agency, "Operational Performance, Reliability and Promotion of Photovoltaic Systems", IEA Photovoltaic Power Systems Programme (PVPS), 2001.

[21] S. Janjai, "Solar Radiation", Phetkasem Printing Grou. Nakhon Pathom, Thailand, 2017 (in Thai).

BIOGRAPHIES

Wutthisat Chokkuea was born in Mahasarakham, Thailand, in 1979. He received the Ph.D. degree in Mechanical Engineering from Mahasarakham University, Thailand in 2014. Currently, he is an Assistant Professor at the Department of Physics, Mahasarakham University, Mahasarakham, Thailand. His research interests are in the renewable energy, energy conservation and energy modeling.

Sattra Sirikaew was born in Mahasarakham, Thailand, 1993. He received the B.Sc. degree in Applied Physics from Mahasarakham University, Thailand, and the M.Sc. degree in Physics from the same university. Currently, he is a Ph.D. student at Faculty of Science, Silpakorn University, Nakhon Pathom, Thailand.