The Estimation of Hourly Solar Radiation on tilted Surfaces using Artificial Neural Network: A Case Study of Surabaya

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Abstract. This study aims to generate an accurate model for estimating the radiation of solar panels on different inclination angles. The output of this model is useful for determining the optimal installation angle of the solar panel either on land or on the ships. Furthermore, the amount of the hourly direct and diffuse radiation on the horizontal surface is estimated using Artificial Neural Networks (ANN), which were trained with the monthly radiation data of Surabaya from 2018 to 2019. Subsequently, the radiation on the inclined surface is estimated using a mathematical model. Also, the ANN accuracy was validated with a regression value higher than 99% for either direct or diffuse radiation estimate. A full-year evaluation based on the proposed model suggests an inclination angle of 25° for the solar panel installed in Surabaya. Meanwhile, the evaluation gives different angles for each month with the advantage compared with the fixed angle installation.

1. Introduction
The abundant potential of solar energy has drawn the attention of the Indonesia government in recent years. In 2017, the government launched a rooftop solar initiative program slated to be completed in 2020 with the sea and river occupying more than half of its territory. Furthermore, solar-powered, or at least solar-assisted marine vessels should also be used like other countries where the energies are less compared with Indonesia [1]. However, one problem that should be addressed to effectively use the solar energy systems is to install the panels at their optimal inclination angles. This is important to obtain most of the generated energy, which significantly increases the reception of radiation compared with the horizontal position as shown by several studies [2], [3]. Furthermore, an investigation of solar panels installed on ship in Japan showed that a monthly adjustment of the panels angle to their optimal position increases the reception of solar radiation by at least 21% [4].

To determine the optimal angle, a comparison between the hourly solar radiation on the horizontal and various inclined angles is required. However, in contrast to the horizontal position, the amount of solar radiation on the inclined angles is not continuously measured by the meteorological agencies. Consequently, estimation must be carried out to obtain information on solar radiation on various angles of inclination. However, estimating solar radiation on inclined angles is more difficult than the horizontal. Furthermore, the addition of ground-reflected radiation when the panels are tilted increases the complexity of the estimation.

On locations where the hourly solar radiation on horizontal position is continuously measured, models were proposed in previous studies to estimate the solar radiation received on tilted position.
Most of these studies adopted empirical models [5]–[7] while some used machine learning such as the Artificial Neural Network (ANN) [8]. However, the meteorological, climatological, and geophysical agency (BMKG) in Indonesia does not measure the hourly radiation in horizontal position.

This study proposed a model to estimate the solar radiation on tilted surface in Indonesia and uses the ANN-based estimator to overcome the problem of limited information on the hourly solar radiation. This is because several studies have shown that ANN gives accurate estimates on horizontal position [9], [10]. Subsequently, the estimate of the hourly solar radiation on tilted position is performed using the empirical model. Furthermore, the output of this study will be utilized as a basis to design the optimal solar energy systems in the country.

2. Research method
To estimate the hourly solar radiation on tilted surfaces, the horizontal is first estimated using the ANN. Its input comprises of locations, local times, and the daily average global solar radiation in horizontal position. The architecture of the proposed method is shown in Figure 1. Two ANNs were built to estimate hourly direct and diffuse radiation separately and were trained using 2018 and 2019 data of the Surabaya City, Indonesia. Furthermore, a strong correlation between the input and output is indicated by regression value (R) higher than 99% for each ANN as shown in Figure 2.

In the Figure 1, \( G_m \) is the Daily average global solar radiation on horizontal position, \( \varphi \) and \( \rho \) are the latitude and longitude of the panel location respectively, \( n \) is the day number in the year, and \( t_h \) is time of evaluation.

The output of the ANN is then used to estimate the global solar radiation on the inclined surface, which is proportional to the electric energy generated by the panels. Furthermore, the total amount of the global solar radiation is the summation of the direct, diffuse, and ground-reflected as shown in Figure 3, and defined as

\[
G_T = G_{Tb} + G_{Td} + G_{Tr}
\]  

(1)

The amount of direct, diffuse, and ground-reflected radiation on tilted surface are defined as follows [3], [11]

\[
G_{Tb} = G_b \frac{\cos \theta}{\cos \theta_z}
\]  

(2)

\[
G_{Td} = G_d \frac{1 + \cos \beta}{2}
\]  

(3)

\[
G_{Tr} = \frac{g \left(1 - \cos \beta \right)}{2}
\]  

(4)

where \( G_T \) is the hourly global solar radiation on tilted position, \( G_{Tb}, G_{Td}, \) and \( G_{Tr} \) are the hourly direct, diffuse, and ground-reflected solar radiation on an inclined surface respectively, \( G_b \) and \( G_d \) are the hourly direct and diffuse solar radiation on horizontal surface respectively, \( \theta \) is the solar incidence angle on an inclined surface, \( \theta_z \) is the solar incidence angle, \( \beta \) is the panel inclination angle, and \( r_g \) is the surface reflectivity constant.
Figure 1. The architecture of the proposed method.

Figure 2. Regression value of the ANNs (a) Direct estimate (b) Diffuse estimate

Figure 3. Component of global solar radiation
The amount of solar radiation on inclined surface is highly related to the panel inclination angle \( \beta \). The inclination angle is described as the smallest angle between the panel and the ground as shown in Figure 4.

![Figure 4. Panel related angle](image)

3. Results and discussion
The proposed model was used to calculate the hourly solar radiation in Surabaya. The daily average of each month was calculated for the entire year to compare the reception of solar radiation on various inclination angles, which is assumed to be the same for the days in each month. Furthermore, the inclination angle from 0° to 90° was calculated with an interval of 5°. However, the solar radiation reception decreases continuously when the angle is further increased above the optimum. Figure 5 showed a comparison, which is only performed for the inclination angle up to 45°.

![Figure 5. Comparison of \( G_m \) of Surabaya on various inclination angles](image)

When the panel is installed on a fixed position for the entire year, the optimum angle to yield the maximum solar radiation is 15°. However, in comparison with the horizontal position, there is only a 1.57% increase in solar radiation is only. Furthermore, Indonesia is located on the equator, this results in the high trajectory angle of the sun for the entire year, causing small differences of solar radiation
reception for various inclination angles. Also, there is a significant increase in the difference in the solar radiation reception when the panels are adjusted to their optimal inclination angles every month. This method increases the reception to 6.77% compared with the horizontal position. A detailed $G_m$ reception on various inclination angles are shown in Table 1.

| Table 1. Value of $G_m$ in Surabaya for various inclination angles (in Wh/m²) |
|---|---|---|---|---|---|---|---|---|---|---|
| m | 0° | 5° | 10° | 15° | 20° | 25° | 30° | 35° | 40° | 45° | Monthly Optimal |
| 1 | 10,652 | 10,774 | 10,836 | **10,839** | 10,781 | 10,663 | 10,253 | 9,964 | 9,621 | 10,839 |
| 2 | **10,652** | 10,641 | 10,570 | 10,442 | 10,256 | 10,015 | 9,721 | 9,375 | 8,979 | 10,652 |
| 3 | 10,653 | **10,676** | 10,640 | 10,545 | 10,392 | 10,183 | 9,731 | 9,381 | 8,982 | 10,676 |
| 4 | 10,643 | **10,686** | 10,670 | 10,596 | 10,464 | 10,275 | 10,030 | 9,731 | 9,381 | 10,686 |
| 5 | 10,629 | 10,696 | **10,704** | 10,652 | 10,464 | 10,275 | 10,030 | 9,731 | 9,381 | 10,704 |
| 6 | 10,616 | 10,823 | 10,970 | 11,057 | **11,082** | 11,045 | 10,946 | 10,787 | 10,569 | 11,082 |
| 7 | 10,602 | 10,933 | 11,204 | 11,412 | 11,556 | **11,634** | **11,646** | 11,593 | 11,474 | 11,290 |
| 8 | 10,587 | 10,719 | 10,792 | **10,806** | 10,760 | 10,655 | 10,491 | 10,270 | 9,994 | 10,806 |
| 9 | 10,572 | **10,586** | 10,542 | 10,441 | 10,283 | 10,069 | 9,801 | 9,481 | 9,112 | 10,586 |
| 10 | 10,557 | 10,799 | 10,982 | 11,104 | **11,164** | 11,161 | 11,097 | 10,970 | 10,783 | 11,164 |
| 11 | 10,556 | 10,606 | 10,495 | **10,850** | 10,115 | 10,280 | 10,336 | 10,274 | 10,089 | 10,850 |
| 12 | 10,563 | 10,287 | **10,948** | 10,540 | 10,059 | 10,502 | 10,864 | 10,144 | 10,339 | 10,948 |
| Total | 127,283 | 127,680 | 129,353 | 129,283 | 126,856 | 125,489 | 122,353 | 119,458 | 116,819 | 130,638 |

4. Conclusions
This study proposes a model to estimate the solar radiation on inclined angles. Also, the limited information about the hourly solar radiation on horizontal position is addressed by ANNs-based estimator with 99% regression value. Subsequently, the hourly solar radiation on inclined position was estimates with mathematic model based on the ANNs output. The result showed that setting the solar panels to their fixed optimal angles throughout the year increases the solar radiation reception but not significantly. Furthermore, adjusting the angles on monthly basis enhances the solar radiation reception by the panels.

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