Hourly solar radiation in Depok, West Java, Indonesia (106.7942 Longitude, -6.4025 Latitude)

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Abstract. The objective of this paper is to predict hourly solar radiation in Faculty of Engineering, Universitas Indonesia, Depok, West Java, Indonesia (106.7942 longitude, -6.4025 latitude) as studied site. The calculation is based on several empirical models and compared to the measured data from BMKG. The comparison of theoretical data and measured data in order to know the influence of solar radiation parameters like solar irradiance condition, angstrom turbidity coefficient, and climate condition used to calculate the solar radiation at studied site. In order to evaluate the performance of solar radiation models, a statistical test was performed by using Mean Bias Error and Root Mean Square Error. The results indicate the best performance of solar radiation models that applicable in Indonesia. Therefore, Benjamin et al. model provides good performances for estimation of the hourly solar radiation.

1. Introduction
Indonesia as studied site has many potentials of solar radiation because it is located in the tropical area. Indonesia has several areas with the great solar energy potential from east until west region along the equator. The solar energy potential is considerable and it is estimated in 4.8 kWh/m² in all region [1]. The estimation of global solar radiation is essential for utilization the solar energy, design wherever appropriate observation missing, the values of solar radiation in clear skies are useful for determining the maximum performance heating and photovoltaic as well as for the design of air conditioning equipment in buildings or for determination of thermal load their solar installation.

The estimation of solar radiation has discussed in several literatures but there has not been discussing in Indonesia. The differences between several literature and this paper are the selected days, the studied site, and the parameters on the studied site. Analyzing of solar radiation intensity start with calculate the solar radiation intensity based on several empirical models, then compare the prediction data with the measurement data from BMKG, and evaluate the statically data use Mean Bias Error and Root Mean Square Error. The aim of this study is to know the solar energy power potential in Indonesia and to estimate the hourly solar radiation intensities in Depok, Indonesia by comparing solar radiation models with International Agency for Meteorology Climatology and Geophysics (BMKG) data.

2. Methodology
2.1. Date and Location Studied
The research based on recorded data from local meteorological station in Faculty of Engineering, Universitas Indonesia, Depok, Indonesia (106.7942 longitude, -6.4025 latitude) on February 20th 2014.
The measured global solar radiation shown in figure 1. The chosen of studied site based on the location of our university which has normal solar intensity and rain fall so it is good to be reference of solar radiation calculation in some places in Indonesia.

![Figure 1. The graphic of solar radiation from local meteorological station](image)

2.2. Solar Radiation Models
The research is about comparison the hourly solar radiation between the recorded solar radiations and solar radiation models. After comparing the prediction and measured data, we can conclude which model will be able to use in Indonesia based on meteorological parameters. The meteorological parameters include Earth-Sun distance \( (C_e) \), solar declination \( (\delta) \), and hour angle \( (\omega) \) and geographical parameters such as sunshine duration, mean ambient temperature, maximum and minimum ambient temperature, relative humidity, cloud cover, precipitation, latitude, longitude, altitude, and extraterrestrial radiation. The general data that we need to calculate the solar radiation is

\[
C_e = 1 + 0.034 \cos (j - 2) \quad (1)
\]

\[
\delta = 23.45 \sin (0.986 (j + 284)) \quad (2)
\]

\[
\omega = 15 (12 - T_{sv}) \quad (3)
\]

In the calculation, \( j \) is the day number of the year, ranging from 1-365 days on 1 January until 31 December. \( T_{sv} \) (h) is the true solar time at a given position.

2.3.1. Bird and Hulstrom Model. The Bird and Hulstrom model \cite{2}, the direct solar radiation \( (W/m^2) \) as in (4) and the diffuse solar radiation \( (W/m^2) \) as in (5) are calculated using the following equation:

\[
I = \cos \theta_z \cdot I_n \quad (4)
\]

\[
D = D_r \cdot D_a \cdot D_m \quad (5)
\]

The \( \theta_z \) (degrees) is the zenith angle and the horizontal diffuse irradiance \( D(W/m^2) \) at ground level is a combination of three individual components corresponding to the Rayleigh scattering after the first pass through the atmosphere \( D_r (W/m^2) \); the aerosols scattering and the multiple-reflection process between the ground and sky.
2.3.2. Model 2 ASHRAE. As recommended by ASHRAE [3], global solar radiation \((G)\), beam solar radiation in the direction of rays \((I_n)\), and diffuse solar radiation \((D)\) on the horizontal surface on a clear day are calculated using as the following equation:

\[
G = I_n \cos \Theta_x + D \tag{6}
\]

\[
I_n = A. \exp(-B/ \cos \Theta_x) \tag{7}
\]

\[
D = C. I_n \tag{8}
\]

A, B, and C values according to ASHRAE Model for solar irradiance calculation is provided on ASHRAE table. A \((W/m^2)\) is direct solar radiation values, B and C is dimensionless values that all parameters depends on date in a year.

2.3.3. Cooper Model. The solar radiation arriving on a horizontal surface under cloudless skies has two components; the direct component \(I \,(W/m^2)\), and the diffuse component \(D \,(W/m^2)\), forming the global solar radiation flux \(G \,(W/m^2)\). The direct solar radiation flux does not take into account the absorbed and the reflected portions by the atmospheric constituents (water vapor, aerosols, ozone, etc.), it depends only on the Sun direction. The diffuse solar radiation flux comes from all space and it has not of a preferred condition. The empirical formulas for this model [4] are;

\[
I = I_o . \sin h \tag{9}
\]

\[
D = 125 . (\sin(h))^{0.4} \tag{10}
\]

2.3.4. Perin Brichambaut Model. In 1975 Perin Brichambaut [5] proposed a model which is designed to find direct, diffuse, and global radiation with relating to the astronomical parameters. The relationships between those formulas is the atmospheric condition:

\[
I = R \cdot \exp\left(\frac{-A}{B \cdot \sin(h+1)}\right) \tag{11}
\]

\[
D = 125 \cdot (\sin(h))^{0.4} \tag{12}
\]

Table 1. R, A, B, and C values according to Perin Brichambaut Model

| Atmospheric condition   | R \(W/m^2\) | A    | B    | C    |
|-------------------------|-------------|------|------|------|
| Clear skies             | 1210        | 1.67 | 3.9  | 0.67 |
| Normal condition        | 1230        | 1.61 | 3.1  | 0.47 |
| Industrial zones        | 1260        | 2.33 | 4    | 0.45 |

2.3.5. Capderou Model. The Capderou [6] model uses the Linke turbidity factor to calculate the direct and diffuse solar radiation components received on horizontal plane. Several turbidity factors provided on table 3 and table 4. The factors value to determine the solar radiation for clear skies. The calculation of direct, diffuse, and global solar radiation flux is

\[
I = I_o \cdot C_t \cdot \exp\left(-T_k \cdot (0.9 + \frac{0.4 \sin(h)}{T_1})^{-1}\right) \cdot \sin(h) \tag{13}
\]

\[
D = I_o \cdot C_t \cdot \exp(-1 + \log(\sin(h))) + a - \sqrt{a^2 - b^2} \tag{14}
\]
Table 2. Angstrom Turbidity Coefficient and 

| Atmospheric condition | $\beta_A$ | $\alpha_A$ |
|-----------------------|-----------|-----------|
| Rural site            | 0.05      | 0.11      |
| Urban site            | 0.10      | 0.22      |
| Industrial site       | 0.30      | 0.66      |

Table 3. Turbidity factor correction depending of climatic condition

| Climatic conditions          | Sky very pure | Normal condition | Sky very polluted |
|------------------------------|---------------|------------------|-------------------|
| $A$                          | 0.91          | 0.88             | 0.87              |
| $B$                          | 0.43          | 0.26             | 0.17              |

2.3.6. Chourad et al. Model Chourad et al. [7] model proposed empirical formulas which are based on the disturbing factor evaluations depending on the atmospheric conditions and astronomical parameters. The direct solar radiation by this model does not take into account the absorbed and reflected solar flux by the atmospheric components (water vapor, aerosols, ozone, etc). The diffuse solar radiation concern to all space and has no privilege area. The calculation of direct, diffuse, and global solar radiation as follows:

\[ I = I_0 . C_t . A_1 . \exp \left( - \frac{A_2}{\sin(h)} \right) . \sin(h) \]  (15)

\[ D = I_0 . C_t . \left| 0.2771 - A_1 . \exp \left( - \frac{A_2}{\sin(h)} \right) \right| . \sin(h) \]  (16)

\[ G = 0.2771 I_0 . C_t . A_1 . \sin(h) + 0.706 I_0 . C_t . A_1 . \sin(h) . \exp \left( - \frac{A_2}{\sin(h)} \right) \]  (17)

Table 4. Turbidity factors depending according to Chourad Model

| Climatic Condition | Sky very pure | Normal conditions | Sky very polluted |
|--------------------|---------------|-------------------|-------------------|
| $A_1$              | 0.87          | 0.88              | 0.91              |
| $A_2$              | 0.17          | 0.26              | 0.43              |

2.3.7. Tannaka model. Tannaka et al. [8] proposed the direct and the diffuse solar radiation on horizontal surface and they are calculated by the following equation;

\[ I = I_o . \sin(h) . \frac{1}{\tau_o^{\sin h}} \]  (18)

\[ D = \frac{1}{2} . I_o . \sin h . \left( 1 - \frac{\tau_o^{\sin h}}{1.41 \ln \tau_o} \right) \]  (19)

2.3.8. Campbell model. The Campbell model [9] developed a computation of solar radiation components on a horizontal surface requires estimates of flux densities for at least three radiation streams; direct irradiance on a surface perpendicular to the beam ($I_n$), diffuse sky irradiance on a horizontal plane ($D$), reflected radiation from the ground that supposed null for an horizontal plane and the total irradiance ($G$) on the horizontal (direct plus diffuse). All the components are evaluated as;

\[ I = I_n . \sin(h) \]  (20)

\[ D = 0.3 I_n (1 - \tau_o ma) \sin(h) \]  (21)
2.3.9. El Mghouchi Y, et al. model. In 2014, El Mghouchi model [10] based in the the turbidity atmospheric factor $\Gamma$ (dimensionless) for clear skies. This factor varies depending on the day number of the year. The direct, diffuse, and global solar radiation fluxes on an horizontal surface according to this model are given by the following formulas:

$$ I = I_0 . C_t . \Gamma . \exp\left( - \frac{0.13}{\sin(h)} \right) . \sin(h) $$  

(22)

$$ D = 120 \Gamma . \exp\left( - \frac{1}{(0.4511+\sin(h))} \right) $$  

(23)

2.3.10. Benjamin et al. model. The Benjamin et.al. [11] model proposed the direct and the diffuse solar radiation fluxes in a horizontal surface which depends on the direct and diffuse atmospheric transmittances are given by the following formulas

$$ I = I_o . \sin(h) . \tau_{dir} $$  

(24)

$$ D = I_o . C_t . \sin(h) . \tau_{dif} $$  

(25)

The calculation for global solar radiation is the sum of direct and diffuse solar radiation fluxes.

2.4. Data Analyze Methods

In order to evaluate the calculation result from the developed models, the performance of the prediction data assed from the following well established statically test of Mean Bias Error (MBE) and Root Mean Square Error (RMSE). These indicators are calculated as:

$$ MBE = \frac{1}{K} \sum \left( I_{estimated}^i - I_{measured}^i \right) $$  

(26)

$$ RMSE = \left( \frac{1}{K} \sum \left( I_{estimated}^i - I_{measured}^i \right)^2 \right)^{1/2} $$  

(27)

3. Results and discussion

The estimation of hourly solar radiation has calculated using several empirical models from literature and several parameters provide in each model with the location in Depok, Indonesia (106.7942 longitude, -6.4025 latitude) and on February 20th 2014 as selected days. Figure 3 shows the comparison data between the empirical models and the measurement data from BMKG in studied site and selected days. The measurement data is lower than the several empirical models, it is because the empirical models have several parameters that constant and able to every location studied site. Indonesia has several parameters that will impact to the calculation like solar irradiance, atmospheric condition, and climatic condition. The chosen of the best performance models based on the closest graphic model to graphic measured data. It indicates that the solar radiation prediction of the model will be able to use in the studied site and date. Figure 3 shows several solar radiation models is close to measured data like Perin Brichambaut model, Chourad Model, and Benjamin model. After comparing the prediction data to measurement data, we should calculate the errors of each model with statistical test by MBE and RMSE in order to know the performance of each prediction model.
Table 5 shows the results of statically indicators of all the empirical models and we can conclude that Tannaka model (Model 7), El. Mghouchi model (Model 9), and Benjamin model (Model 10) has lower MBE and RMSE than the other models. The lowest of MBE and RMSE will defines as the best comparing the statically errors data and it is applicable to estimate the solar radiation intensity. Model 10 that proposed by Benjamin et al. [11] is the lowest one with the MBE and RMSE value is 55 (W/m²) and 273.6 (W/m²), respectively.

Table 5. Results of Statically Indicators

| Model | MBE (W/m²) | RMSE (W/m²) |
|-------|------------|-------------|
| Model 1 | 102.6234 | 502.7499 |
| Model 2 | 116.6215 | 571.3263 |
| Model 3 | 120.138 | 588.5534 |
| Model 4 | 142.1679 | 696.4776 |
| Model 5 | 138.6846 | 679.4132 |
| Model 6 | 332.417 | 1628.504 |
| Model 7 | 62.65497 | 306.9454 |
| Model 8 | 106.3244 | 520.8813 |
| Model 9 | 88.87161 | 435.3802 |
| Model 10 | 55.84997 | 273.6079 |

4. Conclusion
The study of the solar radiation is the starting point of any investigation for a new energy. Several parameters of solar radiation calculation are very important of measuring the direct, diffuse, and global solar radiation. The measured data based on meteorological station since 2014 until 2016 collected every hour. The comparison between all the empirical models and measurement data from
local meteorological station has calculated and has assessed by the statistical indicators. Benjamin et al. [11] model are the best performance for the estimation of hourly solar radiation intensity because they provides small statistical errors than the other empirical models.

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