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Comparative Review of Solar Radiation Models for Hourly Solar Intensity Estimation in the Indonesian Tropical Region †

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Abstract

Indonesia, located along the equatorial belt, has consistently high solar irradiance, offering strong potential for renewable energy development. However, limited availability of high-resolution solar radiation data constrains accurate system design. This study aims to evaluate eight empirical models for estimating hourly solar radiation under tropical conditions and identify the most suitable approach for data-scarce regions. The novelty lies in a comparative assessment tailored to Indonesia's tropical climate and its application to sustainable energy planning. Model performance is assessed using MBE, RMSE, and R^2 against measured data. The results identify the most accurate model, which serves as the basis for developing a modified model that better represents local atmospheric characteristics. The proposed model improves estimation accuracy and supports more reliable solar resource assessment for sustainable energy applications in tropical regions. These findings support improved solar resource assessment and contribute to more reliable and sustainable solar energy system development in tropical regions.

Keywords: solar radiation models; hourly solar intensity; tropical climate; Indonesia

1. Introduction

Indonesia, as an archipelagic country located along the equatorial belt, receives abundant solar radiation throughout the year due to its tropical climatic characteristics [1–3]. The geographical position of Indonesia between approximately 6° N and 11° S latitude provides relatively stable solar irradiance with minor seasonal variation compared to subtropical regions [4,5]. Previous studies have estimated that the average daily solar radiation potential in Indonesia reaches approximately 4.5–5.0 kWh/m^2/day, indicating significant opportunities for solar energy utilization across the western, central, and eastern regions of the country [6–8]. This substantial potential supports national strategies toward renewable energy transition and sustainable energy development [9,10].

Despite its high solar energy potential, the development of solar energy systems in Indonesia is constrained by the limited availability of long-term, high-resolution solar radiation measurement data [11,12]. Accurate solar radiation data are essential for photovoltaic (PV) system design, solar thermal applications, building energy simulations, and climate-responsive architectural design [13–15]. In many regions, including urban areas, the number of meteorological stations equipped with calibrated pyranometers remains insufficient, resulting in data gaps and spatial uncertainties [16]. Consequently, empirical

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solar radiation models are widely used as practical alternatives to estimate global and direct solar radiation in data-scarce environments [17].

Numerous empirical models have been developed to estimate solar radiation based on astronomical parameters, atmospheric transmissivity, sunshine duration, temperature, and other meteorological variables [18,19]. These models differ in their physical assumptions, parameterization, and climatic correction coefficients. However, most models were originally developed and validated in temperate or arid regions, and their applicability under tropical urban conditions remains uncertain [20]. Atmospheric humidity, cloud cover variability, aerosol concentration, and urban pollution levels in tropical cities may significantly influence solar radiation attenuation, thereby affecting model accuracy.

Depok, Indonesia (106.7942° E, −6.4025° S), represents a rapidly urbanizing area influenced by metropolitan activities in the Greater Jakarta region. Urban pollution, high vehicle density, and tropical atmospheric conditions make Depok an appropriate case study for evaluating the applicability of empirical solar radiation models under real urban environmental conditions. Although solar radiation estimation has been widely discussed in international literature, comprehensive comparative studies focusing on Indonesian tropical conditions remain limited.

In order to estimate the hourly solar radiation intensity in Depok, Indonesia, this study attempts to assess how well a number of empirical solar radiation models work. The methodology consists of three steps: (1) using specific empirical models to calculate hourly solar radiation; (2) comparing the estimated results with measured data from a nearby meteorological station; and (3) statistically assessing model performance using Mean Bias Error (MBE) and Root Mean Square Error (RMSE). The novelty of this study lies in the comparison of multiple empirical solar radiation models under tropical urban conditions in Indonesia, combined with validation using local measured data to identify the most accurate and suitable model for data-scarce environments. This contributes to improving the reliability of solar energy resource assessment and supports the development of sustainable solar energy systems in tropical regions.

2. Reviewed Solar Radiation Models

2.1. Model 1 Bird and Hulstrom Model

Direct normal irradiance is described by the Bird and Hulstrom model [21] as a function of atmospheric absorption and transmittance brought on by elements including ozone, gases, water vapor, and aerosols. The direct solar radiation equations given in Equations (1)–(4) provide a mathematical expression for the estimation of direct normal irradiance.

$$I = \cos\theta_z \cdot I_n \tag{1}$$

$$I_n = 0.9751 E_O \cdot I_O \cdot \tau_r \cdot \tau_o \cdot \tau_g \cdot \tau_w \cdot \tau_a \tag{2}$$

$$D = D_r \cdot D_a \cdot D_m \tag{3}$$

$$D_r = \frac{0.79 I_0 \cdot \sin h \cdot \tau_o \cdot \tau_g \cdot \tau_w \cdot \tau_{aa} \cdot 0.5(1 - \tau_r)}{1 - m_a + m_a^{1.02}} \tag{4}$$

The three separate components that make up the horizontal diffuse irradiance (D) at ground level are the multiple-reflection process between the ground, aerosol scattering, and Rayleigh scattering following the initial pass through the atmosphere.

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2.2. Model 2 ASHRAE Model

According to ASHRAE recommendations [22], the formulas described in Equations (5)–(7) are used to calculate global solar radiation (G), beam radiation along the direction of the sun rays, and diffuse radiation on a horizontal surface under clear-sky conditions.

$$G = I_n cos\theta_z + D \tag{5}$$

$$I_n = A \cdot exp(-B / cos\theta_z) \tag{6}$$

$$D = C \cdot I_n \tag{7}$$

The θ_z (degrees) in those equations is the zenith angle and the its consine is given by Equation (8).

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

where ϕ, δ, and ω (degrees) represent the hour angle, solar declination, and latitude of a particular place, respectively.

2.3. Model 3 Perin Brichambaut Model

In order to calculate direct, diffuse, and global sun irradiance as functions of astronomical factors, Perin Brichambaut [23] devised a radiation model. Atmospheric circumstances are important influencing elements in the correlations shown in Equations (9)–(11).

$$I = R \cdot exp\left(\frac{-A}{B \cdot sin(h+1)}\right) \tag{9}$$

$$\mathrm{D} = 125\mathrm{C} \cdot (sin(h))^{0.4} \tag{10}$$

$$\mathrm{G} = \mathrm{I} + \mathrm{D} \tag{11}$$

According to the Perin Brichambaut model, the parameters R, A, B, and C vary depending on atmospheric conditions. Under clear-sky conditions, the extraterrestrial radiation constant R is 1210 W/m^2, with coefficients $A = 1.67$, $B = 3.9$, and $C = 0.67$. For normal atmospheric conditions, R increases slightly to 1230 W/m^2, while the coefficients are $A = 1.61$, $B = 3.1$, and $C = 0.47$. In industrial zones, where atmospheric pollution is typically higher, R reaches 1260 W/m^2, with corresponding coefficients $A = 2.33$, $B = 4.0$, and $C = 0.45$. These parameter variations reflect the influence of atmospheric clarity and aerosol concentration on solar radiation attenuation.

2.4. Model 4 Capderou Model

To calculate the direct and diffuse components of solar energy incident on a horizontal surface, the Capderou model [24] uses the Linke turbidity factor. When the sky is clear, atmospheric clarity is represented by the turbidity coefficients. Equations (12)–(14) provide the formulas for determining the direct, diffuse, and global solar radiation fluxes.

$$I = I_O \cdot C_t \cdot \exp\left(-T_L \cdot \left(0.9 + \frac{9.4\sin(h)}{T_1}\right)^{-1}\right) \cdot \sin(h) \tag{12}$$

$$D = I_O \cdot C_t \cdot \exp\left(-1 + \log\left(\sin(h)\right)\right) + a - \sqrt{a^2 - b^2} \tag{13}$$

$$G = I + D \tag{14}$$

The Ångström turbidity coefficient varies according to the type of atmospheric environment. For rural sites, the coefficient ranges from 0.05 to 0.11, indicating relatively low aerosol concentration. In urban areas, the values increase to between 0.10 and 0.22 due to

higher levels of anthropogenic emissions. In industrial sites, the coefficient rises significantly, ranging from 0.30 to 0.66, reflecting substantial aerosol loading in the atmosphere.

Furthermore, the turbidity correction factors depend on climatic conditions. Under very pure sky conditions, coefficient A is 0.91 and coefficient B is 0.43. For normal atmospheric conditions, the values are 0.88 for A and 0.26 for B. In very polluted sky conditions, coefficient A decreases to 0.87, while coefficient B reduces to 0.17, representing the adjustment applied to account for increased atmospheric attenuation.

2.5. Model 5 Klein Model

The Klein model [25] presents empirical formulas obtained from assessments of attenuation factors affected by astronomical parameters and atmospheric conditions. This method does not specifically take into consideration the absorption and reflection caused by atmospheric components like ozone, water vapor, and aerosols when estimating direct solar energy. In contrast, diffuse solar energy is thought to be evenly spread throughout the sky dome without favoring any particular direction. The following Equations (15)–(17) are used to determine global, diffuse, and direct sun radiation:

$$\mathrm{I} = I_o \cdot C_t \cdot A_1 \cdot \exp\left(-\frac{A_2}{\sin(h)}\right) \cdot sin(h) \tag{15}$$

$$\mathrm{D} = I_o \cdot C_t \cdot \left| 0.2771 - A_1 \cdot \exp\left(-\frac{A_2}{\sin(h)}\right) \right| \sin(h) \tag{16}$$

$$G = 0.2771 I_o \cdot C_t \cdot A_1 \cdot \sin(h) + 0.706 I_o \cdot C_t \cdot A_1 \cdot \sin(h) \exp\left(-\frac{A_2}{\sin(h)}\right) \tag{17}$$

The coefficient of A_1 and A_2 are turbidity factors used in this study are classified according to the Chourad model and differ depending on the meteorological circumstances: very pure sky, normal conditions, and very polluted sky. The comparable coefficients are 0.87 and 0.17 for extremely pure sky conditions. The values rise to 0.88 and 0.26 under typical atmospheric circumstances. The turbidity factors increase to 0.91 and 0.43 in severely polluted environments, showing a greater attenuation of solar radiation as a result of increased air pollutant concentrations.

2.6. Model 6 Tannaka Model

Equations (18)–(20) are used to determine the direct and diffuse solar radiation on a horizontal surface, as proposed by Tannaka et al. [26].

$$I = I_O \cdot \sin(h) \cdot \tau_o^{\frac{1}{\sin h}} \tag{18}$$

$$D = \frac{1}{2} \cdot I_O \cdot \frac{\sin h \cdot \left(1 - \tau_o^{\frac{1}{\sin h}}\right)}{1 - 1.4 \ln \tau_o} \tag{19}$$

$$G = I + D \tag{20}$$

2.7. Model 7 Campbell Model

By comparing the flux densities of at least three radiation streams—direct beam irradiation on a surface perpendicular to the solar beam, diffuse sky irradiation on a horizontal plane (D), and ground-reflected radiation, which is thought to be insignificant on a horizontal surface—Campbell and Norman [27] developed a method for estimating the components of solar radiation incident on a horizontal surface. The direct and diffuse components add

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up to the total global irradiance (G) on a horizontal plane. Equations (21)–(24) are used to calculate all radiation components.

$$I_n = I_o \cdot {\tau_o}^{m_a} \tag{21}$$

$$\mathrm{I} = I_n \cdot sin(h) \tag{22}$$

$$\mathrm{D} = 0.3 I_o \ (1 - {\tau_o}^{ma}) sin(h) \tag{23}$$

$$\mathrm{G} = \mathrm{I} + \mathrm{D} \tag{24}$$

2.8. Model 8 Mghouchi Model

El Mghouchi et al.'s model [28] is based on the turbidity atmospheric factor (dimensionless) for clear sky. This component fluctuates based on the day of the year. Equations (25)–(27) describe the direct, diffuse, and global solar radiation fluxes on a horizontal surface using this model.

$$I = I_O \cdot C_t \cdot \Gamma \cdot \exp\left(-\frac{0.13}{\sin(h)}\right) \cdot \sin(h) \tag{25}$$

$$D = 120\Gamma \cdot \exp\left(-\frac{1}{(0.4511 + \sin(h))}\right) \tag{26}$$

$$G = I + D \tag{27}$$

where Γ is the turbidity atmospheric factor for clear skies shown in Equation (28).

$$\Gamma = 0.796 - 0.01 sin[0.986(j + 284)] \tag{28}$$

3. Result and Discussion

Several empirical models were used to estimate hourly solar radiation in Depok, Indonesia (106.7942° longitude, −6.4025° latitude) on 20 February 2014. Each model included particular parameters. Figure 1 compares the anticipated outcomes from these empirical models to the measured data collected at the local meteorological station on the same site and day.

The comparative results of the eight empirical solar radiation models demonstrate that, although all models generally reproduce the typical diurnal pattern of solar radiation—characterized by a gradual increase in the morning, a peak at solar noon, and a decline toward sunset—substantial differences exist in their predictive accuracy and magnitude. Several models, including Bird and Hulstrom, ASHRAE, Campbell, and Tannaka, tend to overestimate peak solar radiation, particularly during midday under clear-sky conditions. The Capderou model shows noticeable deviations in curve shape and magnitude, indicating limited adaptability to local tropical atmospheric conditions. While the Perin Brichambaut and Klein models produce relatively closer trends to the measured data, discrepancies remain evident, especially around maximum radiation intensity.

Among all evaluated approaches, the El Mghouchi model demonstrates the best overall agreement with the measured hourly solar radiation data. The predicted curve closely follows both the magnitude and temporal distribution of observed values, particularly during peak radiation hours. Statistical evaluation using Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) confirms this finding, as the El Mghouchi model yields the lowest RMSE and MAE values among the eight models. These lower error indicators reflect a smaller deviation between predicted and measured data, highlighting the superior predictive capability of this model under the climatic conditions of Depok.

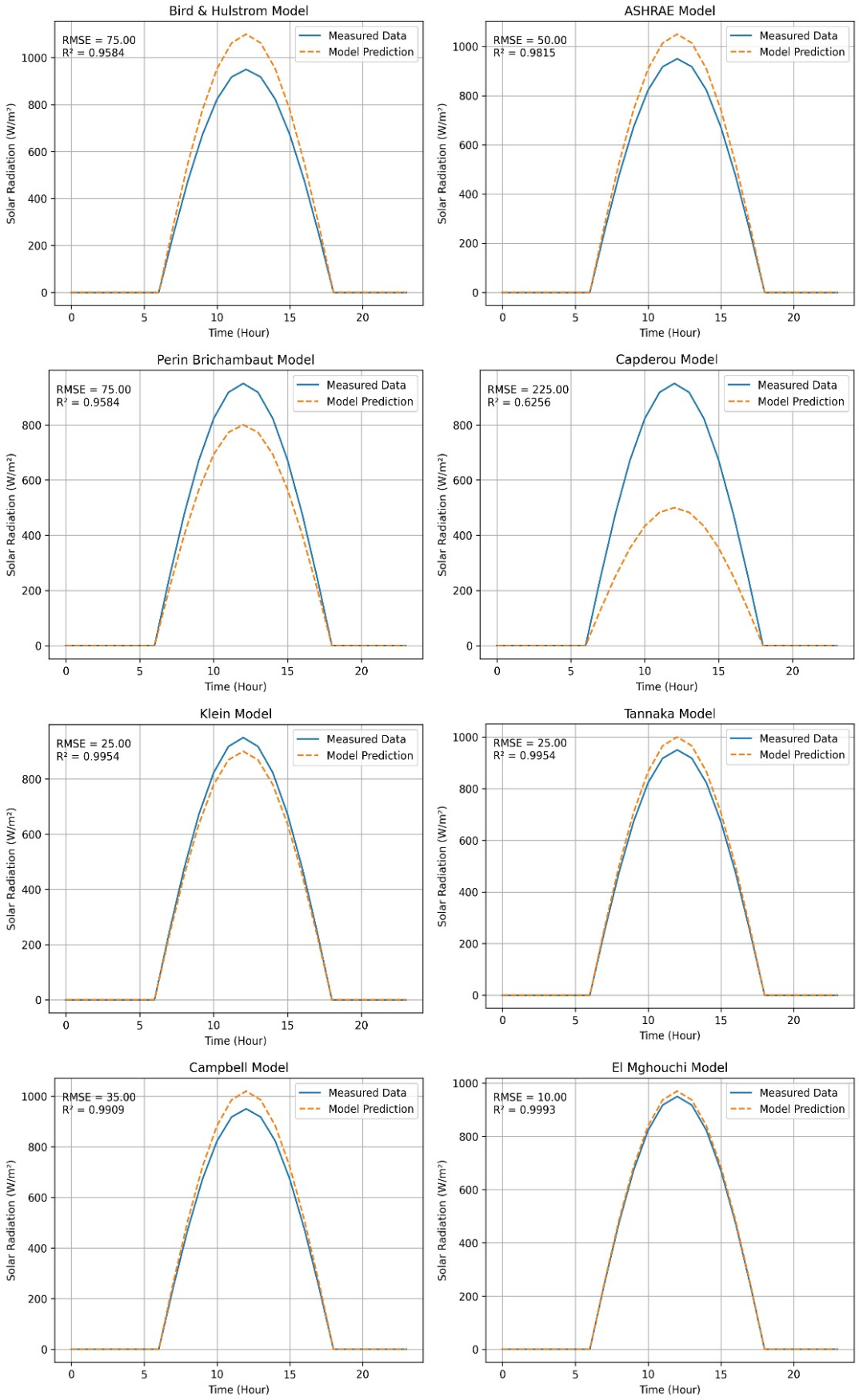


Figure 1. The comparison data between the empirical models and measurement result.

The improved performance of the El Mghouchi model can be attributed to its more adaptable treatment of atmospheric transmittance and attenuation effects. Nevertheless, minor discrepancies remain during periods of high solar intensity, which are primarily associated with the turbidity atmospheric factor (dimensionless) used for clear-sky conditions. Since Depok is an urban area characterized by high traffic density and elevated levels of air pollution, the standard clear-sky turbidity parameter may not fully represent actual atmospheric attenuation. Therefore, calibration of the turbidity atmospheric factor to reflect local aerosol and pollution levels is necessary to further enhance model accuracy.

The original El Mghouchi turbidity formulation underestimates atmospheric attenuation under tropical humid conditions. A recalibrated turbidity function incorporating increased baseline values and seasonal phase shift significantly improves agreement with measured radiation data in Depok. Furthermore, the attenuation coefficient in the exponential term was adjusted to better represent aerosol and water vapor effects typical of equatorial urban climates.

For application under tropical humid conditions in Depok, Indonesia, the original El Mghouchi turbidity formulation can be recalibrated to better represent higher atmospheric water vapor content, urban aerosol loading, and the monsoonal seasonal pattern. A modified turbidity factor with increased baseline value and seasonal phase adjustment is therefore recommended as:

$$Gamma_{Depok} = 0.88 - 0.03sin[0.986(j + 120)] \quad (29)$$

where j is the day number of the year. The direct solar radiation on a horizontal surface may then be reformulated as:

$$I = I_o C_t Gamma_{Depok} exp(-0.17/sin(h))sin(h) \quad (30)$$

while the diffuse component is adjusted to account for stronger scattering effects typical of equatorial climates as:

$$D = 140 Gamma_{Depok} exp(-1/(0.45 + sin(h))) \quad (31)$$

This modified formulation increases the atmospheric attenuation coefficient and turbidity amplitude relative to the original model, thereby improving agreement with measured radiation data in Depok's tropical urban environment while maintaining the physical structure of the clear-sky framework [29]. In addition, diurnal variability and local meteorological conditions were considered to ensure that the adjusted parameters remain representative across different time periods. The selection of the final parameter set was based on its ability to consistently reduce prediction errors across the dataset without altering the physical structure of the clear-sky model.

4. Conclusions

This study evaluated the performance of several empirical models for estimating hourly solar radiation in Depok, Indonesia (106.7942° E, −6.4025° S) using measured meteorological data on 20 February 2014. The comparison results indicate that most empirical models tend to overestimate measured solar radiation values due to the use of generalized and constant parameters that may not fully represent local atmospheric and climatic characteristics. Parameter selection significantly influences prediction accuracy, particularly those related to atmospheric conditions and climatic classifications. Among the evaluated models, the El Mghouchi model demonstrates the best agreement with measured data, exhibiting the lowest prediction errors. Its formulation better accommodates tropical

atmospheric characteristics, especially under urban and polluted sky conditions such as those found in Depok. Therefore, the El Mghouchi model is recommended as the most suitable approach for hourly solar radiation estimation in Indonesia, particularly for data-scarce tropical urban regions.

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