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Research article

Incorporating theoretical and practical approaches to assess the amount of sunlight captured by a tilted surface in a tropical climate

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ABSTRACT

Global solar radiation can theoretically be approximated in terms of tilt and azimuth of the surface regarding the impossibility of simultaneous measurement of solar radiation at various surface tilt and azimuth angles. Moreover, the random and anisotropic nature of diffuse radiation in a tropical climate makes it extremely difficult to estimate global solar radiation accurately as a function of surface tilt and azimuth angles. This study aims to develop a novel experimental and theoretical approach in the form of a computational network in order to determine a precise combined model integrated with global horizontal solar radiation to evaluate global tilted solar radiation in a tropical climate. Obtained results revealed that precisely estimation of the global tilted solar radiation was possible, by combining geometric factors for the tilted beam solar radiation, a combination of Gueymard and Louche models for the tilted diffuse solar radiation, and isotropic ground reflectance model for the ground reflected radiation, along with global horizontal solar radiation. It was observed that the accuracy of the model developed was higher for the partly sunny sky compared to the cloudy and rainy sky, estimates were more accurate on south-facing surfaces, and the model's accuracy declined with the increasing tilt angle of the surface. The statistical analysis exhibited excellent agreement between the measured data and simulation results, considering the value of normalized mean absolute error (nMAE %), normalized root mean squared error (nRMSE %), and mean absolute percentage error (MAPE %), which were in the ranges 0.22–0.94, 0.27–1.11, and 0.23–1.02, respectively for estimating global tilted solar radiation in various regions of Peninsular Malaysia, and they were respectively found in the range of 10.2–27.5%, 16.1–38.9%, and 6.0–17.8%, for evaluating the monthly optimum tilt angle towards the south, that leads to a loss of solar energy from 1.3 to 5.4 kWh/m2/year in Peninsular Malaysia. This search revealed that the experimental and theoretical approach employed in this study can be extended to more climatic regions.

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Nomenclature

$c_{1,}\ c_2$	acceleration coefficients
C_β	integration of the associated geometry to the diffuse irradiance on a tilted surface
F	Klucher horizon brightening correction factor
F_1	Perez's circumsolar coefficient
F_2	Perez's horizon brightness coefficient
F_{Hay}	Hay's sky-clarity factor
F_M	composite clearness function
M_{cal}	calculated result
M_{meas}	measured data
N_G	Gueymard weighting factor
P_i	best particle position
P_g	best group position
$r_{1,}\ r_2$	random numbers
r_{bt}	ratio of direct radiation
R_{do}	function of solar altitude
R_{d1}	function of tilt angle
r_{dH}	ratio of horizontal diffuse radiation
r_{dT}	ratio of tilted diffuse solar radiation
r_{rT}	ratio of ground reflected radiation
S_{bH}	horizontal direct solar radiation (Wm-^{2})
S_{bT}	global tilted solar irradiance (Wm-^{2})
S_{dH}	S_{dT} horizontal diffuse solar radiation (Wm^{-2}) tilted diffuse solar radiation (Wm-2)
S_H	global horizontal solar radiation (Wm-^{2})
S_o	solar constant (Wm-^{2})
S_{rT}	reflected solar radiation (Wm-^{2})
S_T	global tilted solar irradiance (Wm-^{2})
t	time (s)
T_M	Muneer tilt factor
v_i	velocity vector
x_i	position vector
α	solar altitude angle (^{o})
θ_i	incident angle (^{o})
β_c	tilt angle (^{o})
ρ_g	ground reflectivity
θ_z	Solar zenith angle (^{o})
Φ	latitude angle of location (^{o})
Υ	solar azimuth angle (^{o})
Υ_s	surface azimuth angle (^{o})
ω	inertia weight

1. Introduction

The increase in energy demand is mainly attributable to industrial activity and rapid population growth in developing countries. All future projections predict accelerated fossil fuel-based energy generation with a consequent destructive impact on the world and likely lead to the exhaustion of fossil fuel resources and the rapid deployment of renewables. Solar energy is a reliable source of renewable energy that can be directly transformed into useable energy through solar systems comprising solar thermal and solar photovoltaic systems. The intensity of solar radiation is linearly correlated with the efficiency of solar energy systems, meanwhile, the solar incidence as a function of solar azimuth and zenith angles as well as surface tilt and azimuth angles is a crucial factor that influences the intensity of solar radiation. Therefore, regarding the inherently intermittent and non-uniform nature of the sun, a measure of global tilted solar radiation received on the surface at various angles of tilt and azimuth is critical to determine the optimal performance of solar systems within a specific time frame [1–4]. Nevertheless, despite the numerous meteorological stations, most measurements consist of global horizontal solar radiation due to the high cost of installing gauging instruments, although limited data on tilted surfaces and random orientations are available. Accordingly, it would be desirable to provide an accurate model to estimate solar radiation received on the surface as a function of tilt and azimuth angles of the surface to investigate the performance of solar systems under specific climate regions [5–7].

Some researchers concentrated on non-parametric models obtained through predictive modeling methods with the utmost precision relative to parametric models. Talebizadeh et al. (2011) and Lucio et al. (2012) disclosed the Genetic Algorithm (GA) and

Multilayer Perceptron Algorithm (MLP) are the most accurate and reliable calculation methods for maximizing incoming solar radiation by locating the most effective tilt and azimuth angle of the surface. However, despite the high precision of predictive modeling methods, they have a variety of initial weights for forecasting algorithms and require a lot of reliable data to provide the model [8]. Moreover, they cannot provide an adequate perception of the model concerning the sky and the characteristics of the climate. In contrast, parametric models can be modified regarding influencing parameters, including geographic location, weather conditions, tilt angle, and azimuth angle. Parametric models are capable of determining the optimal tilt angle and orientation of the surface in various time intervals, which ensures the amount of sunlight received at the surface, improves the performance of the solar system and reduces the cost of the solar tracking system [9]. Hence, extensive research was directed toward developing appropriate parametric models to assess the global tilted solar radiation. Pursuing this goal, researchers have proposed a transposition model derived from mathematical and empirical models to evaluate global tilted solar radiation by correlating it with global horizontal solar radiation. In the proposed model, the tilted beam radiation can be obtained by mean of geometric optics correlation based on trigonometric relationships between horizontal and tilted surfaces, tilted diffuse radiation may be estimated using tilted diffuse fraction models, and the reflected radiation response is a function of ground reflectance [10].

Isotropic models, i.e., Liu and Jordan, Korokanis, and Badescu, assumed uniformity in the distribution and intensity of diffuse radiation over the Skydome and ignored the circumsolar and horizon brightening parts [11]. In contrast, Bugler, Temps & Coulson, and Klucher developed Liu and Jordan's model by adding contributions of diffuse radiation from circumsolar and the rest of the sky based on the angular height of the sun over the horizon and the fraction of cloud cover [12]. Hay and Davies identified linearity contributions of the isotropic and circumsolar to the diffuse solar radiation on a tilted surface by developing an isotropic model based on the sky-clarity factor, whereas the horizon brightening part is assumed to be zero and Willmott later upgraded this model by integrating an anisotropy reduction factor for the tilted surface [13,14]. Hay & Davies model was modified in the Ma & Iqbal model by substituting Hay's sky-clarity factor with a more clearness index by improving the accuracy of predicting diffuse radiation at a high tilt angle, low altitude angle, and cloudy sky [15]. In Skartveit and Olseth's model, Hay & Davies's model was modified by adding barriers blocking the horizon and the zenith correcting factor to account the brightness anisotropy of the sky both in cloudless and overcast conditions [16]. Muneer et al. estimated diffuse solar radiation by considering the effects of overcast weather conditions for both the shaded and un-shaded surfaces. In this model, a composite clearness function was defined in terms of the specific sky and azimuthal terms. This function is assumed to be zero for shaded and sun-facing surfaces under overcast sky conditions, while it is equal to Hay's sky-clarity factor for clear sky and partly cloudy sky conditions. Furthermore, Muneer's tilt factor is defined as a function of the radiation distribution index of the sky brightness with functional dependence on the sky and azimuthal conditions as well as the location [11]. The Perez model comprehensively analyzed diffuse solar radiation based on the incident and azimuth angles. Empirically-defined coefficients in this model exhibit functional dependence on the zenith angle, clearness index, and the sky brightness parameter based on the air mass, extraterrestrial and diffuse solar radiation, circumsolar brightening, and horizon brightening [14,17]. Gueymard proposed that the radiation from a partly cloudy sky can be a weighted sum of circumsolar and hemispherical components that could be modeled with a polynomial regression based on the tilt angle, solar azimuth, and solar altitude along with the overcast sky radiation [11]. In addition, Hay & Davies model was further improved in Reindl models by integrating a horizon brightening correction factor from the Klucher model [14]. Some researchers suggested combining anisotropic models to enhance the estimation accuracy of global tilted solar radiation under different climatic conditions and obtained the composite HDKR model by combining Hay & Davies, Klucher, and Reindl models [18].

By virtue of the randomness and anisotropy of diffuse radiation, the determination of an accurate diffuse fraction model consistent with the measured data leads to the development of the most accurate model to estimate the global tilted solar radiation. Therefore, the researchers attempted to identify the appropriate model as a function of influencing parameters, including weather characteristics, tilt, and azimuth angle of the surface, by comparing the accuracy of the isotropic and anisotropic models. Marion Eliza et al. (2021) revealed that Tian isotropic model was more accurate compared to the isotropic models of Liu and Jordan, Koronakis, and Badescu for determining the optimal tilt angle and orientation of photovoltaic modules in the tropical climate of Sabah, Malaysia, while Herlambang et al. (2016) indicated that the Liu and Jordan isotropic models were suitable and adequate for the tropical climate of Taiwan. In contrast, the Perez model was optimal in mostly cloudy conditions. Khalil et al. (2016) reported that the Perez model was more accurate for estimating tilted diffuse solar radiation for multiple locations in Egypt with an arid climate. On the other hand, statistical analysis showed that neither model can accurately predict diffuse radiation for all skies and that their performance changes significantly depending on the tilt and azimuth angle. Li et al. (2017) found that the Muneer anisotropic model was more accurate for predicting tilted diffuse solar radiation under a clear and intermediate clear sky in Beijing, China, while the accuracy of Skartveit and Olseth's model was superior to the rest of the models for a cloudy sky.

Wattan et al. (2016) examined the precision of diffuse fraction models as a function of tilt angle and concluded that the model's accuracy was reduced with increasing tilt angle. Hence, some researchers developed a precise model by modifying or integrating the parametric models in an effort to address this concern. Takilalte et al. (2020) established a parametric model for estimating incoming solar radiation based on transposition and Liu and Jordan models and considering specific direct and diffuse cloudiness factors for tilted surfaces for different types of sky, from mostly cloudy to mostly clear sky. García et al. (2021) observed that the precision of the modified Perez model concerning the sky and circumsolar view factors is higher than that of the modified Liu and Jordan model and the modified Haye and Davies model for estimating tilted diffuse solar radiation located in an urban canyon in the continental climate of Pamplona, Spain. Demain et al. (2013) exhibited the highest accuracy by integrating Perez, Willmott, and Bugler models to estimate tilted diffuse solar radiation under clear, partly clear, partly cloudy, cloudy, and overcast conditions in Brussels, Belgium. Araneo et al. (2014) reported that combining the Miguel model with the Perez model allows for accurate estimation of horizontal and tilted diffuse radiation in the Mediterranean climate of Rome, Italy.

Given its proximity to the equator, Malaysia has plenty of solar radiation with a significant level of diffuse radiation and an average of 12 h of daylight for the entire year [3]. The optimal tilt angle and orientation of the surface for different time intervals of the year with respect to the tropical climate and various seasons in Malaysia is a key factor to receive maximum solar radiation to optimize the performance of solar systems. In order to determine the optimal tilt angle and orientation of the surface in the tropics with a significant level of diffuse radiation which leads to the randomly-distributed directional solar radiation, the solar radiation received on the surface should be accurately estimated at different tilt and azimuth angles [19]. Although some Malaysian scholars have written about solar radiation models to report the correlation between the optimum angle and orientation of the surface with the tropical climate of Malaysia, they have mainly concentrated on isotropic models for estimating solar radiation and optimal tilt angle only for south-oriented surfaces [6,20–22]. Therefore, the global tilted solar radiation received on the surface should be investigated with regard to the different angles of tilt and azimuth of the surface to ensure the optimal efficiency of solar energy systems.

Determining the optimal tilt angle and orientation requires simultaneous measurement of the global solar radiation received on the surface at several tilt angles and azimuths for different time intervals, while it needs several measuring instruments and equipment, which is practically impossible considering the costs, calibration, maintenance, etc. Hence, the principal theme of this research is to develop an integrated experimental and theoretical framework in the form of a multi-layer computational network to discover a precise combined model based on a combination of regression and parametric models and simultaneous global solar radiation measurement data for the horizontal surface as a reference and tilted surfaces facing north, south, west and east at two tilt angles of 7° and 15° with respect to the optimal angles obtained for tilted surfaces in Peninsular Malaysia, in order to minimize random anisotropic variations of solar radiation in the tropical climate of Malaysia and estimate the global tilted solar radiation and its components at any arbitrary slope angle and orientation of the surface.

There are three steps in the process. The first step discovers the precise combined model based on experimental data to assess global solar radiation as a function of tilt and azimuth angle of the surface in a tropical climate. In this step, the quality control procedures are applied to validate experimental data to compare with theoretical results for determining the accurate model with the least error in terms of statistical analysis methods. In the second step, the accuracy of the combined model is evaluated using statistical analysis to estimate solar radiation in various sky and weather conditions attributed to the tropical climate. Finally, the accuracy of the combined model is assessed for various regions of Peninsular Malaysia through statistical analysis in estimating global tilted solar irradiation and optimal inclination angles.

2. Methodology

The primary purpose of this study relates to developing integrated experimental and theoretical procedures to figure out the most precise model for estimating global tilted solar radiation as a function of the tilt and azimuth angle of the surface to determine the optimal tilt angle and orientation of the surface concerning Malaysia tropical climate. The research methodology used is categorized into three phases:

The first phase describes the global solar radiation acquisition by setting up the measurement system and using official meteorological data sources to derive global horizontal and tilted solar radiation at specific locations and time intervals to validate the developed model. The second phase illustrates the experimental-theoretical approach for developing an accurate solar radiation model that should be identified through the analytical, computational network for determining global solar radiation on the randomly oriented tilted surface concerning the climate zone. Finally, the last phase focuses on validating the developed novel model against the

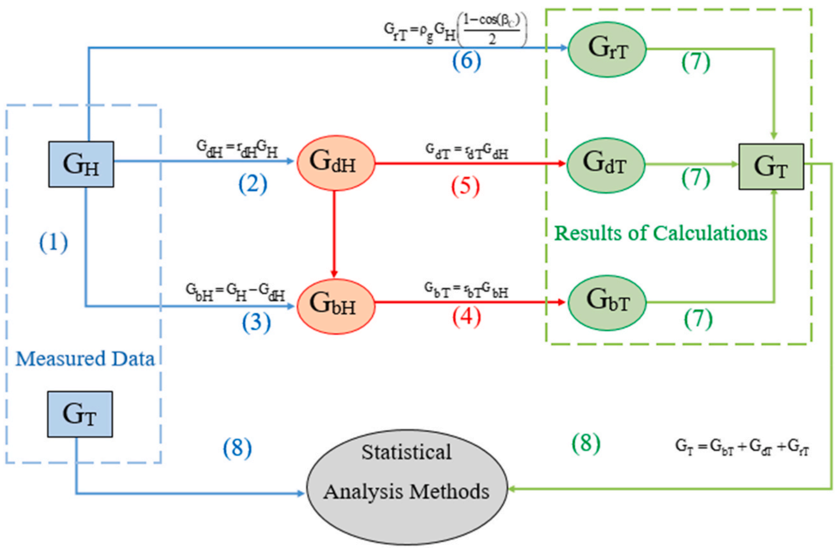

Fig. 1. A comprehensive, in-depth, descriptive flowchart of the study's approach.

data obtained from the solar radiation measurements by performing statistical analysis.

The sequence of primary activities based on the research methodology is given in the following steps (Fig. 1).

1. Global horizontal and tilted solar radiation was measured using measurement instruments arranged on surfaces at varying tilt and azimuth angles.
2. Horizontal diffuse solar radiation was obtained using measured global horizontal solar radiation (step 1) and horizontal diffuse fraction models (Table 2) by considering the average of the clearness index.
3. Horizontal beam solar radiation was obtained using measured global horizontal solar radiation (step 1), and the horizontal diffuse solar radiation was obtained in step 2.
4. The tilted beam solar radiation was estimated by considering the geometric factor and using the horizontal beam solar radiation obtained in step 3.
5. The tilted diffuse solar radiation was determined using tilted diffuse fraction models (Table 1), and the horizontal diffuse solar radiation results were obtained in step 2.
6. Reflected solar radiation was determined using measured horizontal solar radiation (step 1) and ground reflectance with regard to the tilt angle,
7. The tilted solar radiation components (beam from step 4, diffuse from step 5, and reflected from step 6) were used for estimating the global tilted solar radiation,
8. Theoretically calculated global tilted solar radiation (step 7) and the experimental data (step 1) are compared through statistical analysis to discover the appropriate model.

2.1. Experimental Setup

2.1.1. Measurement of global solar radiation

According to the principal theme of this study, an extensive outdoor experiment was conducted to gauge the incident solar radiation at the tilted surface to obtain a precise model as a function of tilt and azimuth angle. These measurements were carried out at the National University of Malaysia in Bandar Baru Bangi (2.9°N and 101.7°E). The measurement site was free of shadows or obstructions along the sight line of the sun. The solar radiation measurements were recorded at 10-s increments using an indirect measurement method consisting of a reliable mathematical model and solar reference cells to achieve global horizontal and tilted solar radiation at various tilt and azimuth angles. Fig. 2 illustrates the experimental configuration employed in this study. The measurements were recorded in the morning, afternoon, and evening, using monocrystalline silicon solar reference cells for the horizontal surface as the reference and tilted surfaces toward east, west, south, and north at two tilt angles of approximately 7° and 15° with regards to the optimum angles obtained from the literature review which is between 7° and 12° for Peninsular Malaysia [9].

The monocrystalline silicon solar reference cell provides a low-cost, high-precision instrument for solar irradiance measurement. To assess performance and accuracy, the manufacturer calibrates solar reference cells through standardized tests and secondary calibration under conditions close to reality [19]. In this study, the calibrated Apogee SP-110 pyranometer was used to carry out the secondary calibration of solar reference cells.

The National Aeronautics and Space Administration's (NASA) meteorological data together with the Meteonorm software database for five regions, namely the south, north, east, and west of Peninsular Malaysia, were used to compare and assist in simulation work and evaluate the accuracy of models in various locations.

2.1.2. Data quality control procedure

Although instruments to measure solar radiation are critical for advancing research and evaluating the performance of solar systems, their sensitive function response to the intensity of solar radiation is influenced by the tilt and azimuth angle of the surface

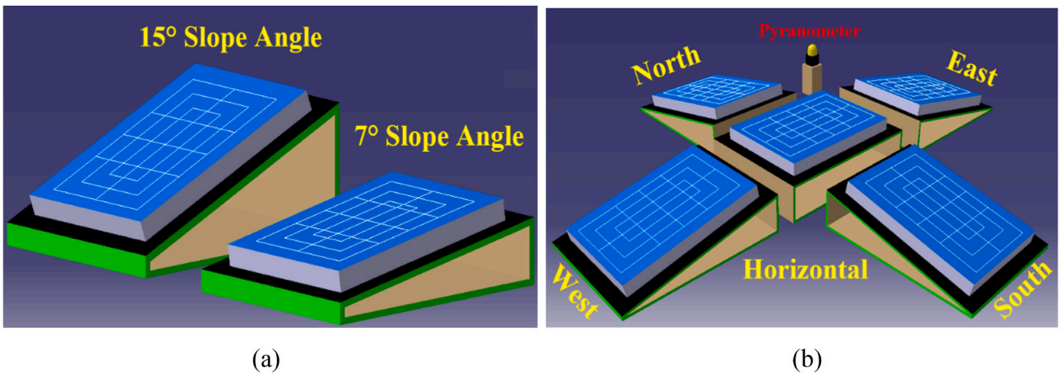

Fig. 2. Experiment set up using solar reference cells to measure global solar radiation as function of (a) tilt angles and (b) orientation.

along with the weather and environmental conditions. Occasionally, the quality of the recorded data is low because of strong fluctuations in the measurements, whereby the evaluation of solar radiation and its components would not be feasible. Hence, quality control procedures can be applied to validate experimental data obtained through solar radiation measurements by identifying errors caused by the experiment and eliminating poor-quality data. In this study, the Gueymard and Ruiz-Arias altitude filter and Baseline Surface Radiation Network (BSRN) procedure provided by Long and Dutton, including physically possible limits test (PPL) and extremely rare limits test (ERL), were used for quality control of the measurement data of horizontal solar radiation. The PPL procedure may detect significant errors in the measured data, whereas limitations presented by the ERL test are more stringent, and errors are identified more precisely [1,23,24]. The PPL and ERL tests are for the quality control of horizontal solar radiation measurement data, including in Eqs. (1)–(3):

Altitude filter:

$$\theta_z < 85^{o} \tag{1}$$

Physically possible limits (PPL):

$$-4 \leq S_H \leq 1.5 \times S_o \times (\cos(\theta_z))^{1.2} + 100 \tag{2}$$

Extremely rare limits (ERL):

$$-4 \leq S_H \leq 1.5 \times S_o \times (\cos(\theta_z))^{1.2} + 50 \tag{3}$$

The altitude filter, PPL, and ERL have been developed for the theory of shadow proposed by Hiroshi Tanaka based on the geometric relationship between horizontal and tilted surfaces at different orientations, taking into account the solar zenith and azimuth angles [25]. Following the shadow theory, shadow prepared by the tilted surface on the horizontal plane is directly related to sunlight received on the tilted surface which may be obtained by multiplying the shading zone within the horizontal solar radiation intensity. The developed tests are given in Eqs. (4)–(8):

Developed altitude filter:

$$(\theta_z + \beta_c) < 85 \tag{4}$$

Developed physically possible limits (DPPL):

$$S_{T(SN)} \leq \frac{\left[1.5 \times S_o \times (\cos(\theta_z))^{1.2} + 100\right]}{[\cos(\beta_c) \pm \sin(\beta_c).\tan(\theta_z).\cos(\lambda)]^{-1}} \tag{5}$$

$$S_{T(EW)} \leq \frac{\left[1.5 \times S_o \times (\cos(\theta_z))^{1.2} + 100\right]}{[\cos(\beta_c) \pm \sin(\beta_c).\tan(\theta_z).\sin(\lambda)]^{-1}} \tag{6}$$

Developed extremely rare limits (DERL):

$$S_{T(SN)} \leq \frac{\left[1.5 \times S_o \times (\cos(\theta_z))^{1.2} + 50\right]}{[\cos(\beta_c) \pm \sin(\beta_c).\tan(\theta_z).\cos(\lambda)]^{-1}} \tag{7}$$

$$S_{T(EW)} \leq \frac{\left[1.5 \times S_o \times (\cos(\theta_z))^{1.2} + 50\right]}{[\cos(\beta_c) \pm \sin(\beta_c).\tan(\theta_z).\sin(\lambda)]^{-1}} \tag{8}$$

With.

plus sign (+): south-facing tilted surface, east-facing tilted surface before the solar noon, and west-facing tilted surface past the solar noon, minus sign (−): north-facing tilted surface, SN: south and north oriented
EW: east and west-oriented.

2.2. Model development

2.2.1. Solar radiation model

This section provides a theoretical method based on mathematical and empirical models to approximate the global tilted solar radiation, the global tilted solar radiation can be assumed as the sum of (a) tilted beam radiation, (b) tilted diffuse radiation, and (c) reflected radiation. as in Eq. (9) [7]:

$$G_T = G_{bT} + G_{dT} + G_{rT} \tag{9}$$

G_{bT}, G_{dT}, G_{rT} are tilted beam, tilted diffuse, and reflected solar radiations, respectively. Tilted beam solar radiation is presented in Eq. (10) [7]:

$$G_{bT} = r_{bT} G_{bH} \tag{10}$$

G_{bH} is the horizontal beam solar radiation and r_{bT} is the geometric factor and is expressed in Eq. (11) [3]:

$$r_{bT} = \begin{cases} \dfrac{\cos(\theta_i)}{\cos(\theta_z)} & \text{If } \tan(\alpha) + \tan(\beta_c)\cos(\gamma - \gamma_s) < 0 \\ 0 & \text{otherwise} \end{cases} \tag{11}$$

θ_i = incidence angle, θ_z = solar zenith angle, β_c = tilt angle, α = solar altitude angle, γ_s and γ = azimuth angle of the sun and surface and tilted diffuse solar radiation can be expressed in Eq. (12) [13]:

$$G_{dT} = r_{dT} G_{dH} \tag{12}$$

G_{dH} is the horizontal diffuse solar radiation and r_{dT} is the tilted diffuse fraction model and can be functionally described by isotropic or anisotropic models described in Table 1. The reflected solar radiations from the ground and surroundings can be expressed in Eq. (13) [10]:

$$G_{rT} = \rho_g r_{rT} G_H \tag{13}$$

The term represents ground reflectivity.

According to the global tilted solar radiation equations, estimating the components of horizontal solar radiation is crucial. Although measured data of global horizontal solar radiation is available in most regions, measured data of horizontal diffuse solar radiation is not readily available, which has led to the development of correlation models by considering the hourly clearness index (kt) using available measured data of diffuse solar radiation, as shown in Table 2 [1]. Many researchers observed that the correlation models developed are efficient relative to widely used models and can be used to estimate the components of global solar radiation [29]. Horizontal diffuse solar radiation can be obtained using the quantified horizontal solar radiation and horizontal diffuse fraction model (r_{dH}) as in Eq. (14) [3]:

$$G_{dH} = r_{dH} G_H \tag{14}$$

It is assumed that the horizontal beam solar radiation on a horizontal surface is obtained by subtracting the global solar radiation on the horizontal surface and diffuse solar, as described in Eq. (15) [7]:

$$G_{bH} = G_H - G_{dH} \tag{15}$$

Assumption.

1 Regarding experiment location, a reflection of surrounding buildings and obstacles is assumed to be negligible
2 It is assumed that the solar radiation reflected by the ground is much lower than the sum of the beam and diffuse solar radiation so that an isotropic model can be employed for the estimation of the ground albedo:

Table 1
Tilted diffuse fraction models.

MODELS	Diffuse Fraction (R_{dT})	Ref.
Liu and Jordan [3,6,7,8–13,17,26–28,21]	$\frac{1}{2}(1+\cos(\beta_c))$	(17)
Koronakis [3,6,7,10,11,12,13,14,15,19,25]	$\frac{1}{3}(2+\cos(\beta_c))$	(18)
Badescu [6,7,10,11,12,13,14,19,25]	$\frac{1}{4}(3+\cos(2\beta_c))$	(19)
Bugler [7,11–13,27]	$\left(\frac{1+\cos(\beta_c)}{2}\left(1+0.05\frac{I_{bT}}{I_d.\cos(\theta_z)}\right)\right)+0.05\frac{I_{bT}}{I_d}\cos(\theta_i)$	(20)
Temps and Coulson [7,8,9,11–13,15]	$\left(\frac{1+\cos(\beta_c)}{2}\right)\left[1+\sin\left(\beta_c/2\right)\right]\left(1+\cos^2(\theta_i).\sin^3(\theta_z)\right)$	(21)
Klucher [7,8,10–13,17,27]	$\left(\frac{1+\cos(\beta_c)}{2}\right)\left[1+F.\sin^3\left(\beta_c/2\right)\right]\left(1+F.\cos^2(\theta_i).\sin^3(\theta_z)\right)$	(22)
Hay and Davies [3,7,8–11,13,17,28,21]	$F_{Hay}.R_b+C_\beta(1-F_{Hay})\left(\frac{1+\cos(\beta_c)}{2}\right)$	(23)
Willmot [7,8,11–13]	$F_{Hay}.R_b+C_\beta(1-F_{Hay})$	(24)
Ma and Iqbal [7,8,11,15]	$K_t.R_b+C_\beta(1-K_t)\left(\frac{1+\cos(\beta_c)}{2}\right)$	(25)
Skartveit and Olseth [7,8–13,27]	$F_{Hay}.R_b+C_\beta(1-Z-F_{Hay})\left(\frac{1+\cos(\beta_c)}{2}\right)-S(\omega,\Omega i)$	(26)
Muneer [7,8,11,13,15,27]	$F_M.R_b+T_M(1-F_M)\ p$	(27)
Perez [7,8,9,11–13,15,17,26–28]	$F_1\frac{a}{b}+(1-F_1)\left(\frac{1+\cos(\beta_c)}{2}\right)+F_2\sin(\beta_c)$	(28)
Gueymard [7,8,9,11,13]	$(1-N_G)R_{d0}+N_G R_{d1}$	(29)
Reindl [3,7,8,10–13,17]	$F_{Hay}.R_b+C_\beta(1-F_{Hay})\left(\frac{1+\cos(\beta_c)}{2}\right)\left[1+F.\sin^3\left(\beta_c/2\right)\right]$	(30)
HDKR [9,12,18,26]	$(1-F_{Hay})\left(\frac{1+\cos(\beta_c)}{2}\right)\left[1+F.\sin^3\left(\beta_c/2\right)\right]$	(31)

Table 2
Horizontal diffuse fraction models.

Model	Diffuse Fraction (R_{dH})	Ref.
Spencer [3]	$(0.94 + 0.0118\|\varphi\|) - (1.185 + 0.0135\|\varphi\|)K_t$	(32)
Erbs [3,9,12]	$0.9511 - 0.1604K_t + 4.388K_t^2 - 16.638K_t^3 + 12.336K_t^4$	(33)
Hawlader [3,9,12]	$1.135 - 0.9422K_t - 0.387K_t^2$	(34)
Muneer [3]	$0.9698 + 0.4353K_t - 4.4499K_t^2 + 2.1888K_t^3$	(35)
Reindl [3,9,12]	$1.45 - 1.67K_t$	(36)
Louche [3]	$0.98 - 0.059K_t - 0.99K_t^2 + 5.205K_t^3 - 15.307K_t^4 + 10.676K_t^5$	(37)
Chandrasekaran and Kumar [3,12]	$0.9686 + 0.1325K_t + 1.4183K_t^2 - 10.1862K_t^3 + 8.3733K_t^4$	(38)
Lam and Li [3,12]	$1.237 - 1.36K_t$	(39)
Orgill and Hollands [3,12]	$1.577 - 1.84K_t$	(40)
Miguel [3,12,17]	$0.724 + 2.738K_t - 8.32K_t^2 + 4.967K_t^3$	(41)
Blond [3,12]	$[1 + \exp(7.997(K_t - 0.586))]^{-1}$	(42)
Oliveira [3,9,12]	$0.97 + 0.8K_t - 3K_t^2 - 3.1K_t^3 + 5.2K_t^4$	(43)
Karatasou [3,12]	$0.9995 - 0.05K_t - 2.4156K_t^2 + 1.4926K_t^3$	(44)
Soares [3,12]	$0.9 + 1.1K_t - 4.5K_t^2 - 0.01K_t^3 + 3.14K_t^4$	(45)
Jacovides [3,12]	$0.94 + 0.937K_t - 5.01K_t^2 + 3.32K_t^3$	(46)

Considering the above assumptions and from equations (9)–(15), the global tilted solar radiation can be estimated as in Eq. (16) [17]:

$$G_T = G_H\left[r_{bT}(1 - r_{dH}) + r_{dT}r_{dH} + \rho_g\left(\frac{1 - \cos(\beta_c)}{2}\right)\right] \tag{16}$$

This model is derived from the combination of five key components: (a) geometric factor, (b) tilted diffuse fraction model, including isotropic and anisotropic models (Table 1), (c) horizontal diffuse fraction model (Table 2), (d) reflected solar radiations from the ground and (e) global horizontal solar radiation.

2.2.2. Computational network

This section presents the experimental and theoretical approach based on Eq. (16) in the form of a computational network to develop a precise combined model to assess the global tilted solar radiation with regard to climate region. As shown in Fig. 3, three parts of the computational network, i.e., (a) input data, (b) processor, and (c) output. The input data includes measured data of

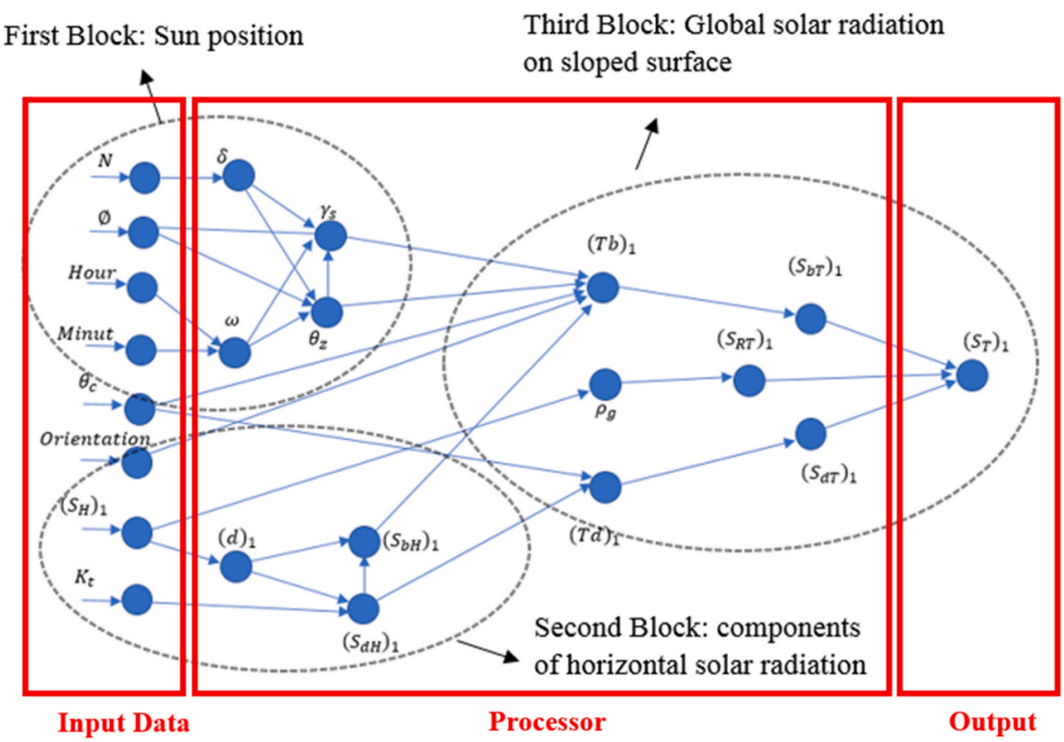

Fig. 3. Network computation of solar radiation on a tilted surface.

horizontal solar radiation, clearness index, tilt and azimuth angle of the surface, the latitude of the location, time, and day of the year. The processor then calculates the global tilted solar radiation. The processor consists of three calculation blocks: The first block determines the sun's position in the sky from the declination, hour, solar azimuth, and zenith angles concerning the time, day of the year, and the latitude of the location. The second block estimated the horizontal beam and diffuse solar radiation using measured global horizontal solar radiation and horizontal diffuse fraction model by considering the average clearness index. The global tilted solar radiation and components are then obtained in the third block using a horizontal beam and diffuse solar radiation, geometric factor, diffuse fraction model on a tilted surface, and ground reflectance.

Fig. 3 shows the steps that lead to the estimation of global tilted solar radiation based on one horizontal diffuse fraction model and one tilted diffuse fraction model. The above steps must be repeated as often as available horizontal diffuse fraction models for each tilted diffuse fraction model. According to the fifteen tilted diffuse fraction models (Eqs. 17–31) and fifteen horizontal diffuse fraction models (Eqs 32–46) considered for this study, the appropriate solar radiation model with the least error in terms of statistical analysis is obtained among 225 combined models by comparing the output results with the gauged solar radiation on a tilted surface. The computational network with (N) number of horizontal solar radiation as input data, (M) horizontal diffuse fraction models in the first hidden layer, and (Q) isotropic and anisotropic models used at the second hidden layer (Fig. 4).

2.3. Statistical analysis

The statistical analysis assesses the precision of the proposed combined models by comparing the measured and estimated global tilted solar radiation. The statistical indicators for an ideal model must indicate the lowest values, which are caused by a distribution of errors with an evenly or small variance in samples. The following statistical tools used for this analysis: (1) normalized mean absolute error (nMAE), (2) normalized root mean squared error (nRMSE), and (3) mean absolute percentage error (MAPE), as in Eqs. (47)–(49) [1,5]:

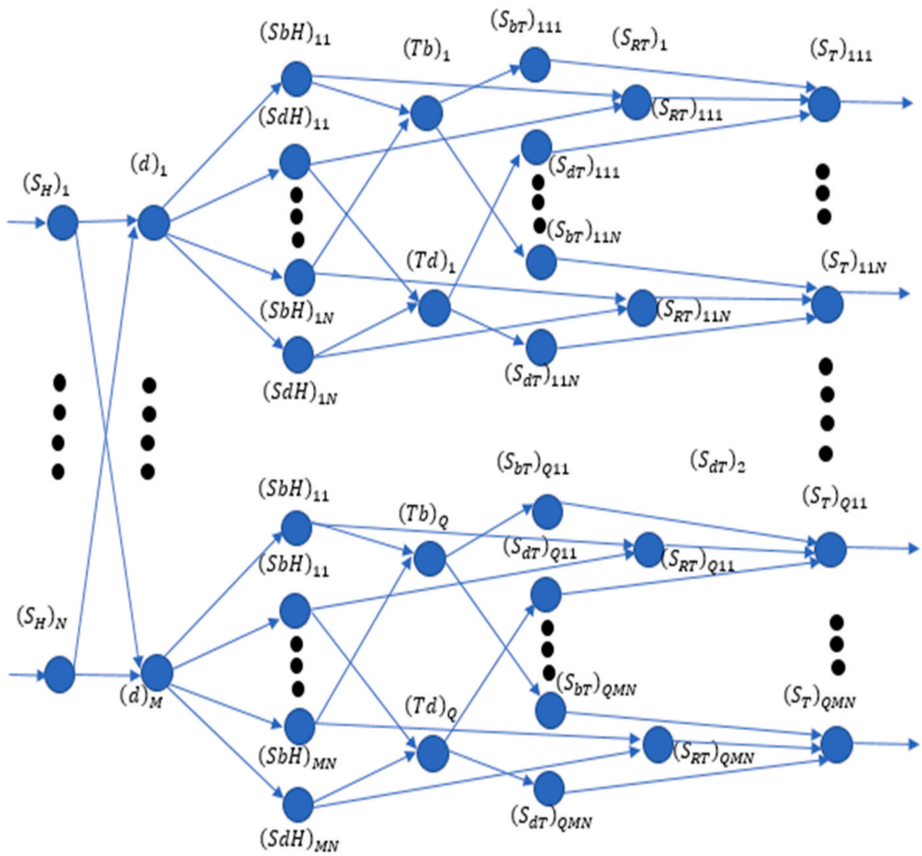

Fig. 4. Network computation for (N) horizontal solar radiation as input data, (M) horizontal diffuse fraction models, and (Q) tilted diffuse fraction models in the first hidden layer.

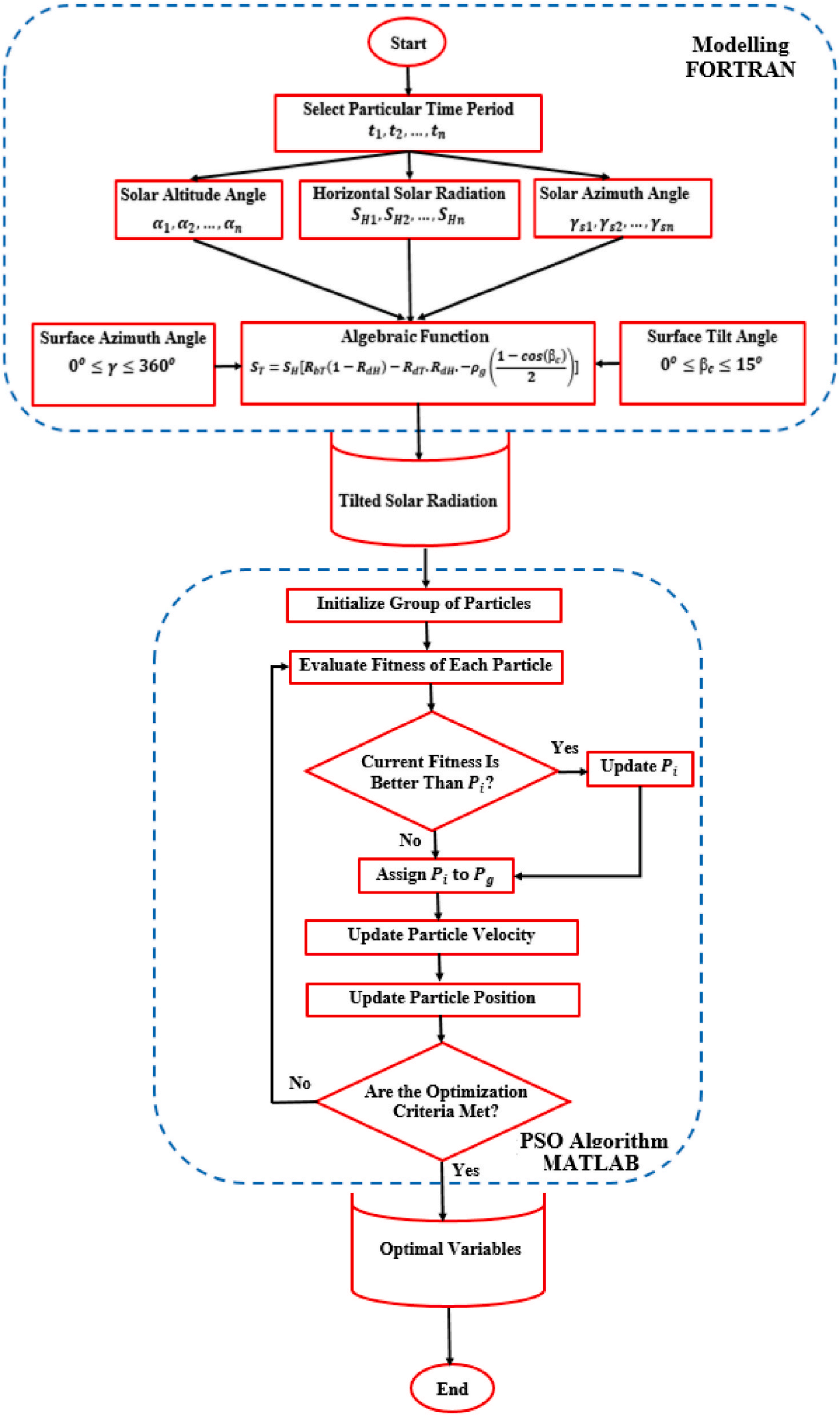

Fig. 5. Schematic of the optimization approach.

$$\mathrm{nMAE}(\%)=\frac{\sum_{i=1}^{n}\left|M_{cal}-M_{meas}\right|}{\sum_{i=1}^{n}M_{meas}}\times 100 \tag{47}$$

$$\mathrm{nMAE}(\%)=\frac{\sum_{i=1}^{n}\left|M_{cal}-M_{meas}\right|}{\sum_{i=1}^{n}M_{meas}}\times 100 \tag{48}$$

$$\mathrm{MAPE}(\%)=\frac{1}{n}\sum_{i=1}^{n}\left|\frac{M_{cal}-M_{meas}}{M_{meas}}\right|\times 100 \tag{49}$$

2.4. Single-objective optimization

The principal aim of developing the precise combined model is to enhance the incident solar radiation and, consequently, optimize the performance of solar systems by determining the optimum tilt and azimuth angle in relation to the site location and the climatic zone. Hence, the model-based simulation and single-objective optimization technique were employed as a realistic approach for analyzing global solar radiation as an objective function regarding the tilt and azimuth angle of the surface as an optimization variable. As shown in Fig. 5, the parametric model-based transient simulation implemented using the FORTRAN program linked to MATLAB includes a particular period, horizontal solar radiation, and feasible region of the variables, and the algebraic function includes the accurate combined model. Moreover, the single-objective optimization technique includes a particle swarm optimization (PSO) algorithm implemented in MATLAB on an iterative update strategy with particle position, which is more efficient than other optimization algorithms in the absence of accurate solar radiation data [30].

PSO optimizes a problem by iteratively trying to find the optimal result through particle trajectories regulated by stochastic and deterministic components and leading to the optimal solution in each iteration. Every iteration, the particle (i) with its position vector (xi) and velocity vector (vi), changes its position according to the new velocity as in Eqs (50) and (51) [31]:

$$v_i^{t+1}=\omega v_i^t+c_1 r_1\left(P_i^t-x_i^t\right)+c_2 r_2\left(P_g^t-x_i^t\right) \tag{50}$$

$$x_i^{t+1}=x_i^t+v_i^t.t \tag{51}$$

Where P_i and P_g are respectively the best particle position and best group position, ω is the inertia weight, c1, and c2 are acceleration coefficients, and r1 and r2 are random numbers between 0 and 1.

3. Results and discussions

The results obtained are analyzed through experiment and modelling in three steps: (1) determining the most precise combined model for estimating global tilted solar radiation; (2) investigating the precision of the superior combined model for estimating tilted solar radiation in variable weather conditions attributed to the tropical climate; (3) Assess the accuracy of the superior combined model for estimating solar irradiation and determining the optimum tilt angle for Peninsular Malaysia.

Table 3
Statistical analysis models for diffuse radiation.

Diffuse fraction models on a tilted surface	Diffuse fraction models on a Horizontal surface	nMAE (%)	nRMSE (%)	MAPE (%)
Badescu	Louche	2.71	7.79	2.75
Bugler	Kumar	0.77	1.62	1.52
Gueymard	Louche	0.47	1.45	1.45
Hay and Davies	Louche	0.65	1.65	1.59
HDKR	Louche	7.07	8.39	6.35
Ma and Iqbal	Louche	0.94	3.63	4.02
Klucher	Louche	2.08	2.66	3.05
Korokanis	Louche	0.32	1.40	1.45
Liu and Jordan	Louche	0.21	1.44	1.54
Muneer	Louche	0.54	1.58	1.56
Perez	Louche	0.94	3.99	3.87
Reindle	Louche	0.62	1.63	1.58
Skartveit and Olseth	Erbs	0.76	1.72	1.61
Temps and Coulson	Louche	2.88	5.42	5.91
Willmot	Louche	0.33	1.84	1.67

3.1. Appropriate solar radiation model

The results of 225 combined models were evaluated with the experimental records to determine the superior combined model with the least statistical analysis errors to estimate the global tilted solar radiation. In this study, the monthly mean daily clearness index of Malaysia was used and combined models are presented under diffuse fraction models due to the same geometric factor and ground reflectance in all combined models.

3.1.1. Assessing the accuracy of combined models

This section reports on the analysis conducted to investigate the precision of the combined models for tilt angles up to 15° in all cardinal orientations. Table 3 shows the combination of diffuse fraction models in combined models for assessing the tilted diffuse solar radiation, including the tilted diffuse fraction models and appropriate horizontal diffuse fraction models for each isotropic and anisotropic model. Statistical analysis reveals that through extensive comparison of the experimental data and theoretical results, combined models consisting of Gueymard, Korokanis, and Liu and Jordan models as tilted diffuse fraction models in combination with Louche model as horizontal diffuse fraction model are the most accurate for estimating global tilted solar radiation in the tropical climate of Malaysia. At the same time, the lowest accuracy belongs to combined models, including Badescu, HDKR, and Temps and

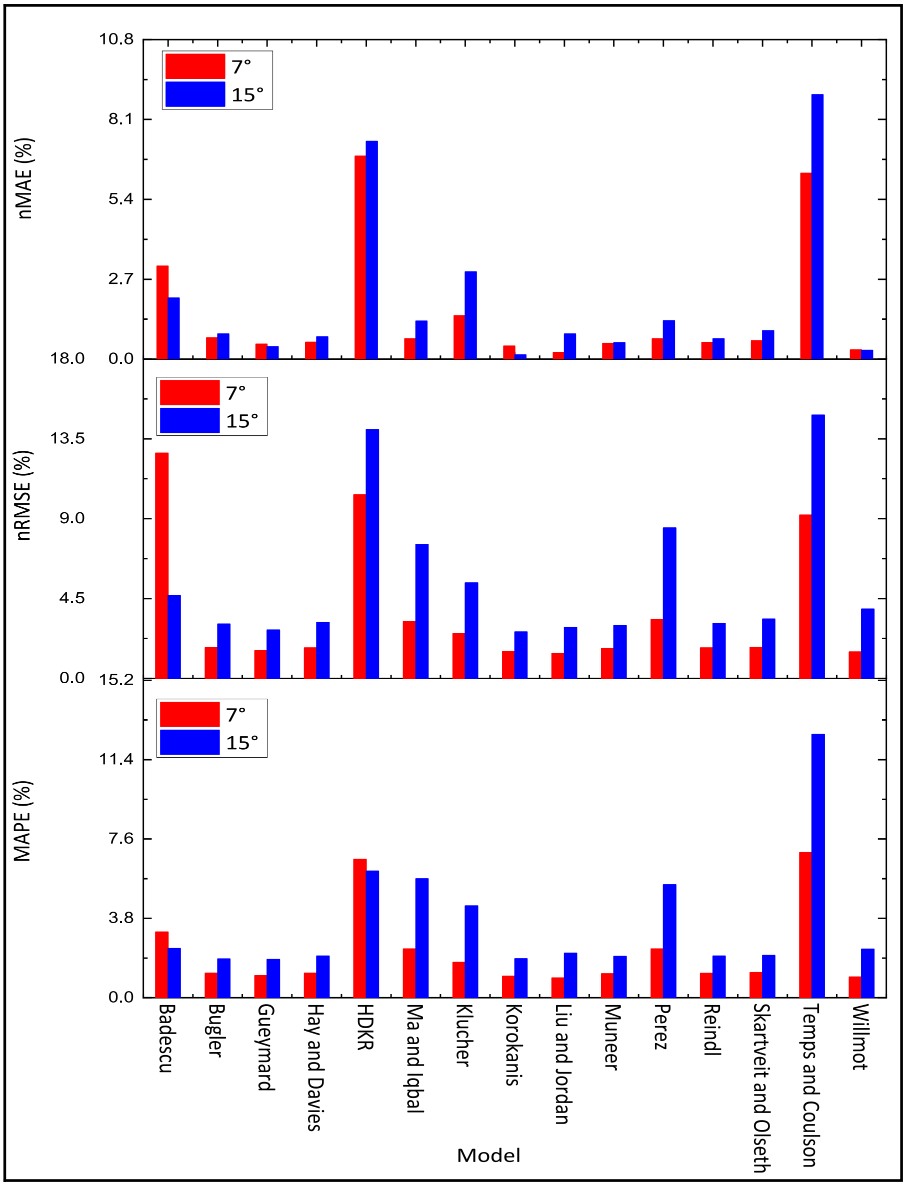

Fig. 6. The results of the statistical analysis methods nMAE (%), nRMSE (%), and MAPE (%) for 7° and 15° tilt angles.

Coulson models.

3.1.2. Assessing the precision of combined models at various tilt angles

Fig. 6 shows the precision of combined models to evaluate global solar radiation at tilt angles of 7° and 15° was analyzed by Liu, Kourokanis, Gueymard, and Louche models as in Table 3. The combined models reported the lowest accuracy, including the HDKR and the Time and Coulson models. Additionally, statistical analysis reveals that the accuracy of all combined models, except for the combined models including the Badescu and HDKR models, decreases as the tilt angle increases due to the consideration of the uniform distribution of the isotropic part of diffuse radiation for all orientations, whereas the combined model includes Gueymard and Louche models showed the smallest variation with an increasing tilt angle.

3.1.3. Assessing the precision of combined models in various azimuth angles

The accuracy of combined models to estimate global tilted solar radiation for cardinal orientations was discussed. As shown in Fig. 7, the combined models, including Reindl, Gueymard, Willmot, and Gueymard, along with the Louche model as regards the findings in Table 3, are more accurate for estimating global tilted solar radiation toward the south, north, west, and east directions, respectively. Meanwhile, the combined models comprising HDKR and Temps and Coulson have lower precision. In addition, the estimation of all the combined models for the tilted surfaces toward the south is higher than in other directions, except for combined models, including HDKR and Temps and Coulson models.

Statistical analysis results suggested that the combined model, including Gueymard and Louche diffuse models, is superior for estimating global tilted solar radiation for common tropical weather conditions. By a combination of Gueymard and Louche models as

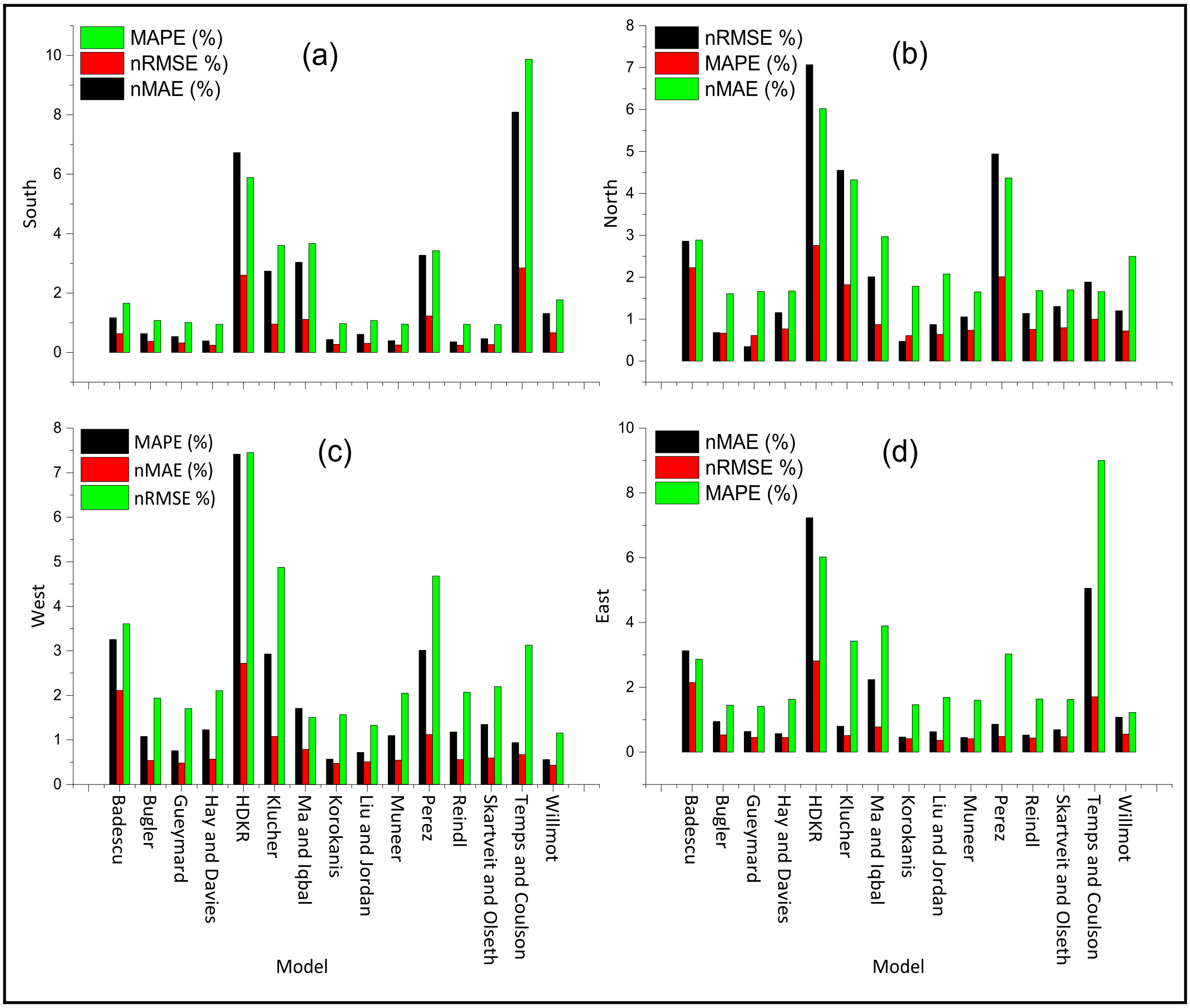

Fig. 7. Statistical analysis results to evaluate the accuracy of models for estimating global tilted solar radiation in the direction of (a) south, (b) north, (c) west, and (e) east.

a function of the mean clearness index of Malaysia, an empirical-theoretical model was obtained for estimating global tilted solar radiation in the Malaysia tropical climate as in Eq. (52):

$$S_T = \left(0.183\frac{COS(\theta_i)}{COS(\theta_z)} + 0.817((1 - N_G)R_{d0} + N_G R_{d1}) + \rho_g\left(\frac{1 - COS(\beta_c)}{2}\right)\right) \times S_H \tag{52}$$

where N_G is Gueymard's weighting factor for cloud opacity. It is estimated, when hourly cloud observations are not available, as [7,8]:

$$N_G = f_1\left(\frac{I_{dh}}{I_{gh}}\right) = \max[\min(Y, 1), 0] \tag{53}$$

where Y is given by Ref. [8]:

$$Y = \begin{cases} 6.6667\frac{G_{dH}}{G_H} - 1.4167 & \text{If } \left(\frac{G_{dH}}{G_H}\right) < 0.227 \\ 1.2121\frac{G_{dH}}{G_H} - 0.1758 & \text{otherwise} \end{cases} \tag{54}$$

The clear sky radiation, R_{do}, is given by a polynomial regression as function of the solar altitude (or elevation angle), ϒ, and β_c and the overcast sky radiation, R_{d1}, is a function of β_c in radians [7].

$$R_{do} = f_2(\theta_i, \beta_c, \alpha) \tag{55}$$

$$R_{d1} = f_3(\beta_c) \tag{56}$$

3.2. Evaluation of superior combined model precision under various weather conditions

Malaysia has a tropical climate with uniform temperature, randomly variable sunny-to-cloudy skies, frequent precipitation, and high relative humidity, which is characterized by northeast and southwest monsoon regimes [34,35]. Superior combined model accuracy (Eq. (52)) was evaluated to estimate global tilted solar radiation in arbitrary directions and under sunny, cloudy, and rainy weather conditions. The meteorological data used to determine the specific sky conditions related to the tropical climate were obtained from the meteorological research station at the Solar Energy Research Institute (SERI)-National University of Malaysia in 2017 confirmed by the Malaysian Meteorological Department. Four random days have been selected to monitor the global solar radiation received on the surface at various tilt and azimuth angles, which were November 22nd and December 12th for cloudy and rainy conditions and November 21st and December 17th for the partly sunny condition [19].

The statistical analysis results demonstrate that the combined model can assess the impact of weather conditions on incoming solar radiation on a tilted surface (Table 4). Statistical analysis indicators showed that the accuracy of the estimates for partly sunny skies exceeds that of cloudy and rainy skies due to an even distribution of errors with low variance, while the direction of errors rarely changes. Moreover, the estimate's precision in the south orientation is higher than in all other orientations, with the north orientation being the worst.

3.3. Assessment of superior combined model accuracy in Peninsular Malaysia

3.3.1. Estimation of global tilted solar irradiation

Data on sun irradiation was compared with theoretical results from the best-integrated model for calculating global solar radiation on a south-facing surface at a tilt angle of latitude and 15° latitude of the location. In terms of statistical analysis, five regions were chosen, including Johor, Kelantan, Penang, Kuantan, and Kuala Lumpur, to represent the Sothern, Northern, Western, Eastern, and central regions of Peninsular Malaysia. Fig. 8 exhibits the acceptable accuracy of the computational approach regarding the excellent agreement between the measured and the simulation results in evaluating solar radiation received for a tilt at latitude 15°.

Table 4
Statistical analysis of estimation of the global solar radiation in the tropical climate.

Orientation	Sky Conditions	nMAE (%)	nRMSE (%)	MAPE (%)
All direction	Cloudy and rainy	1.80	4.05	3.44
	Partly Sunny	0.57	1.60	1.33
South	Cloudy and rainy	0.63	0.74	0.48
	Partly Sunny	0.45	0.58	0.46
North	Cloudy and rainy	3.95	5.01	4.31
	Partly Sunny	0.96	2.09	1.95
East	Cloudy and rainy	2.48	2.94	3.00
	Partly Sunny	0.42	1.56	1.33
West	Cloudy and rainy	4.77	5.84	5.95
	Partly Sunny	1.26	1.79	1.58

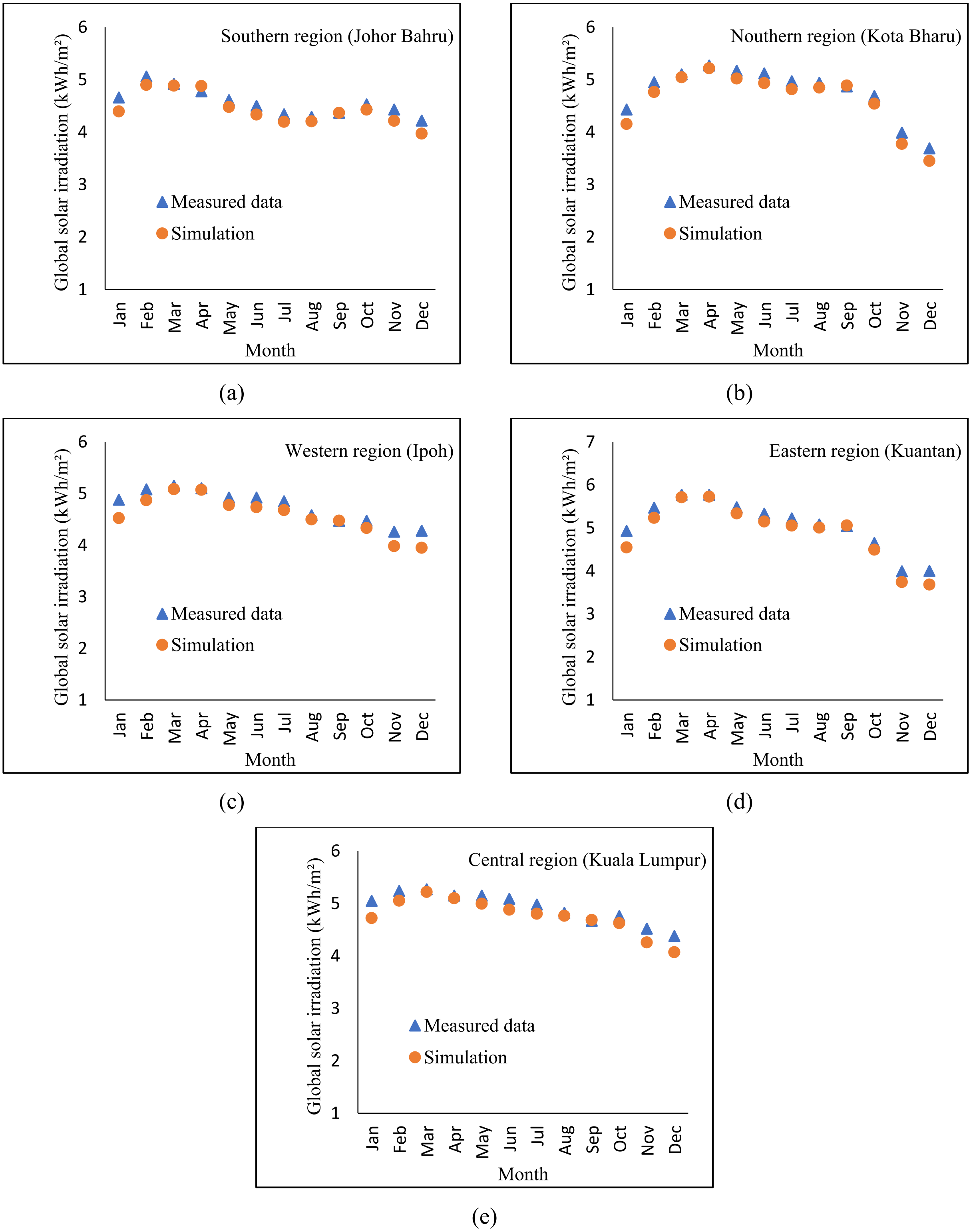

Fig. 8. Daily mean hourly global tilted solar irradiation at 15° latitude of the location in the southern region (Johor Bahru), (b) northern region (Kota Bharu), (c) western region (Penang), (d) eastern region (Kuantan), and (e) central region (Kuala Lumpur).

Table 5
Statistical analysis results to discover network calculation accuracy to forecast the diffuse solar radiation at the latitude tilt angle in Peninsular Malaysia.

Region	nMAE (%)	nRMSE (%)	MAPE (%)
Southern (Johor Bahru)	0.23	0.27	0.23
Northern (Kota Bharu)	0.60	0.67	0.66
Western (Penang)	0.83	0.95	0.86
Eastern (Kuantan)	0.94	1.11	1.02
Center (Kuala Lumpur)	0.22	0.26	0.23

In addition, statistical analysis summarized in Table 5 shows that the prediction errors in estimating global solar radiation on the surface at the tilt angle of latitude were distributed with small variance, and their direction has rarely changed.

3.3.2. Determination of optimum tilt angle

The optimum tilt angle of the south-facing surface during a specific period was determined to increase the incident solar radiation. Accordingly, a method described in the methodology's particle swarm optimization (PSO) was used based on the results of the superior combined model and the measured horizontal solar radiation. Fig. 9 indicates the contours of the monthly solar radiation received on the surface with a tilt angle of up to 45° from January to December in five regions of Peninsular Malaysia obtained using a combined solar radiation model including Gueymard and Louche models and monthly horizontal solar radiation.

As described in Table 6, the statistical analysis indicators evaluated the accuracy of the combined model for estimating the monthly optimum tilt angle by comparison of the optimal angles achieved by NASA and determined by the combined model. Statistical analysis reveals the accuracy of the combined model to control the monthly optimum tilt angle lowest in the eastern region (Kuantan), mostly due to the lower accuracy of meteorological data derived from sophisticated interpolation models compared to the measurement data obtained from weather stations. The combined model is therefore suitable for determining the optimum monthly tilt angle in various regions of Peninsular Malaysia, considering the accuracy factor of meteorological data. Eventually, the annual optimum tilt angle supplied by NASA and the results obtained from the precise combined model were compared. Moreover, the global tilted solar irradiation reduction due to the difference between the measured and calculated annual optimum tilt angle was estimated for a year. As indicated in Table 7, the lowest precision and the highest reduction in tilted solar irradiation received were related to the eastern region (Kuantan) for the same reason as explained above concerning the impact of the precision of the meteorological data.

In summary, statistical analysis displayed that assuming the availability of horizontal solar radiation and taking into account the geometric factor and diffuse ground reflectance, the combined model consisting of the Gueymard and Louche models was the most precise model to obtain the global tilted solar radiation and determine optimum tilt angle in the tropical climate.

4. Conclusions

A computational network based on experimental and theoretical approaches was developed to identify the precious combined model for estimating global tilted solar radiation concerning the horizontal solar radiation, tilt angle, azimuth angle, and climate zone. The combined model integrated with horizontal global solar radiation included the geometric factor for approximation of the tilted beam solar radiation, horizontal and tilted diffuse fraction models for estimation of the tilted diffuse solar radiation, and the ground reflectance to obtain global reflected radiation. Theoretical results demonstrated a reduction in estimation accuracy for all models with an increasing tilt angle, while the estimate's precision is higher for the tilted surfaces toward the south, except for the combined model that includes the Temps and Coulson model. Detailed statistical analysis revealed that the combined model, including Gueymard and Louche models, is reliable for estimating the global tilted solar radiation by considering the tilt angle, azimuth angle, and the tropical climate of Malaysia. In addition, the combined model developed can be utilized to determine the optimum tilt angle of a surface as a significant factor influencing the performance of solar systems, i.e., thermal and photovoltaic systems. Ultimately, it is important to note that this research's methods can be used in many climates.

Author contribution statement

Mir Hamed Hakemzadeh: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.
Adnan Ibrahim: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.
Kamaruzzaman Sopian: Conceived and designed the experiments; Analyzed and interpreted the data.
Ag Sufiyan Abd Hamid: Performed the experiments; Contributed reagents, materials, analysis tools or data.
Hasila Jarimi: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

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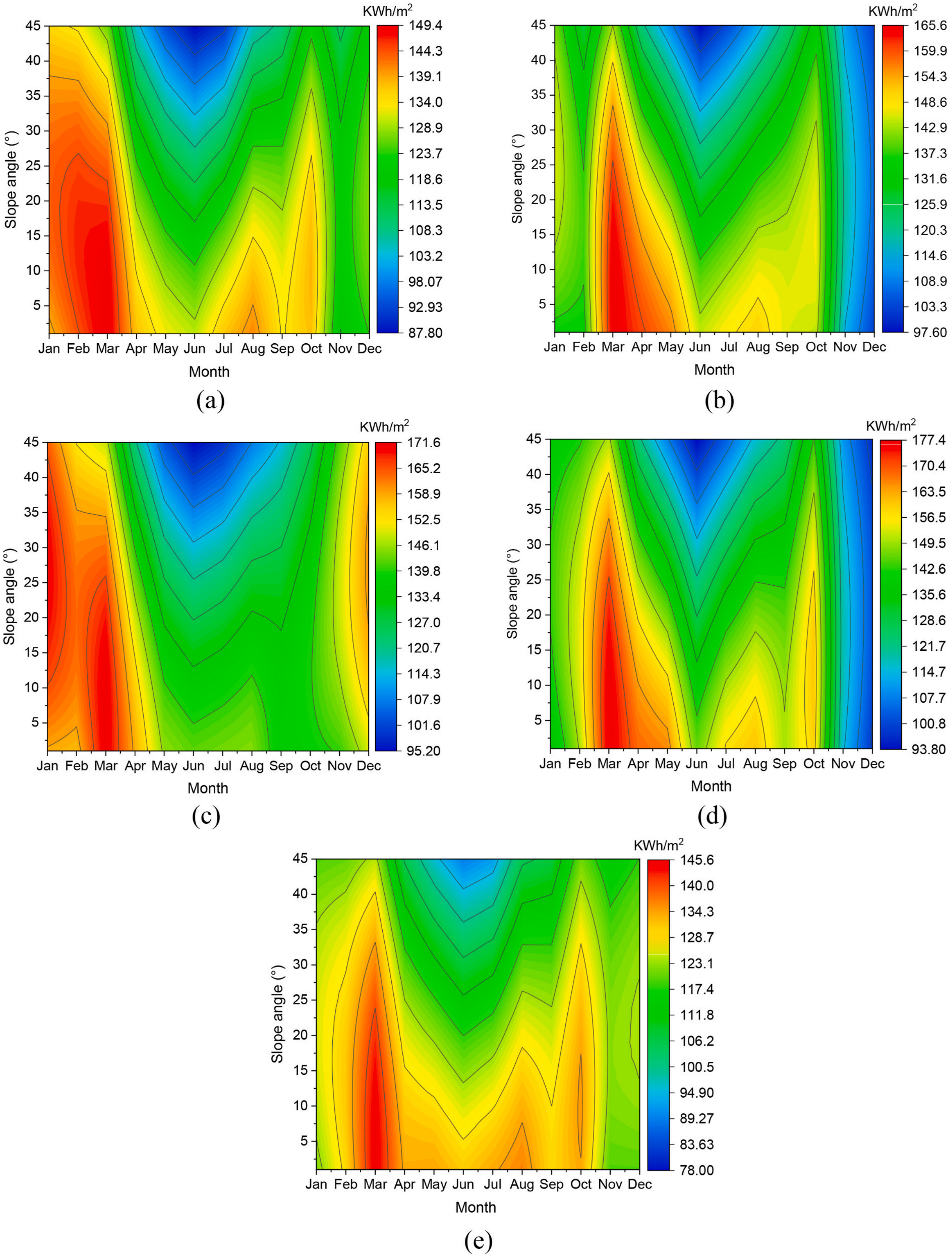

Fig. 9. Contours of monthly global tilted solar radiation up to 45° in the southern region (Johor Bahru), (b) northern region (Kota Bharu), (c) western region (Penang), (d) eastern region (Kuantan), and (e) central region (Kuala Lumpur).

Table 6
Statistical analysis results to discover the model's accuracy developed to estimate the monthly optimum tilt angle in Peninsular Malaysia.

Region	nMAE (%)	nRMES (%)	MAPE(%)
Southern (Johor Bahru)	10.4	16.1	6.0
Northern (Kota Bharu)	15.6	26.0	6.8
Western (Penang)	15.7	24.5	7.1
Eastern (Kuantan)	27.5	38.9	17.8
Center (Kuala Lumpur)	10.2	16.4	7.9

Table 7
Monthly optimum tilt angle in Peninsular Malaysia.

Region	Measured	Simulation	Difference (KWh/m^2)
Southern region (Johor Bahru)	6.3°	6.9°	1.3 (0.07%)
Northern region (Kota Bharu)	8°	9.3°	2.52 (0.15%)
Western region (Penang)	8.5°	9.8°	1.68 (0.09%)
Eastern region (Kuantan)	6.8°	8.7°	5.14 (0.29%)
Center region (Kuala Lumpur)	6.7°	7.3°	1.03 (0.07%)

Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no conflict of interest.

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