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An improved surface solar radiation estimation model using integrated meteorological-air quality data

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ABSTRACT

This paper proposes an improved high-precision surface solar radiation estimation model using the integration of the local meteorological data and air quality index based linear regression analysis. The proposed model was evaluated and compared to 8 conventional models and one generated by the commonly used PVsyst simulation software. The actual solar radiation, meteorological data and air quality index collected over 10 years (during 2011-2021) from standard measuring stations located at the northern zone of Thailand were used for developing the models while the collected data year 2022 were used for validating the developed models compared to the conventional models. The statistical error estimations in terms of mean absolute error (MAE), mean square error (MSE), root mean square error (RMSE), and mean absolute percentage error (MAPE) were used for the precision evaluation. The study found that the proposed models achieved better prediction results and the highest precision for monthly estimating of solar radiation than the other models by having the highest estimation precision of 94.70-97.19% compared to 87.53-96.74% of the conventional models and 90.38-95.96% of the PVsyst program.

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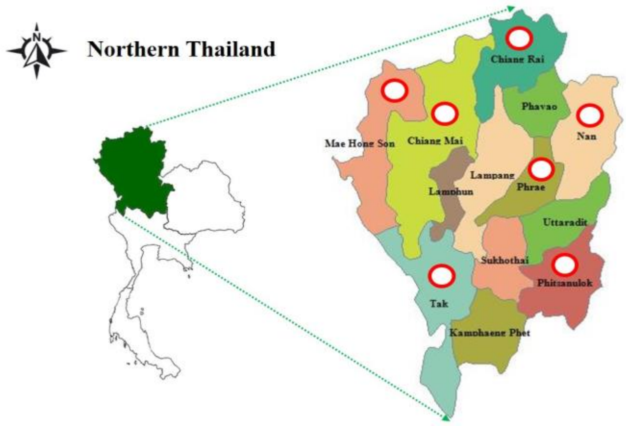
1. INTRODUCTION

Solar energy will be one of the most important energy for supporting world's future energy demand [1]. However, variation of solar radiation on the earth surface could lead to less cost-efficience solar energy harvesting [2], [3]. To overcome this problem, many solar radiation measurement stations or devices should be fully installed to achieve high-precision real-time maximum energy information but this would lead to extremely high cost, especially for large investment areas. Using mathematical models for surface solar radiation estimation could be therefore a more cost-effective way [4]-[9]. The mathematical model proposed in [4] could be used for yearly global solar radiation, or else as the physical, empirical, or semi-empirical models proposed in [5]. To achieve higher precision in the estimation, many researchers would utilize the artificial neural network (ANN) or regression analysis (RA) [6], or meteorology and topographic based empirical models [7], such as a simple Ångström-Prescott models [8], [9] and extended models with various factors (i.e. temperature, relative humidity, rainfall, cloud cover, and other factors) proposed in [10], [11]. Alternatively, the research studies by [12], [13] pointed out that quality of the air associated with various size of particle matters (PMs) significantly affected solar radiation. However, this effect of air quality casued by PMs has not been considered using for surface solar radiation estimation modeling before and thus lead this research interest. Luckily, the informaiton of $PM_{2.5}$ and PM_{10} (μm) is available precisely as a standard local open-data source [14]; therefore, an improved high-precision local surface solar radiation estimation model with the minimum investment cost was achieved in this research study. To validate the proposed model, the actual solar radiation data, meteorological data and air quality index ($PM_{2.5}$ and PM_{10}) for the year 2011-2021 of 7 provinces from the northern Thailand (Chiang Mai, Chiang Rai, Mae Hong Son, Nan, Phrae, Tak, and Phitsanulok) as shown in Figure 1, which currently have highest average levels of PM (100-550 μg/m^3) along the year in Thailand [15]-[19], were used for the model. The data for the year 2022 were used for validating the proposed model in comparison to other 8 conventional models.



Station	Solar/Meteorological/Air Quality data Latitude (E)	Longitude (N)
Chiang Mai	18.92/18.47/(18.83,18.79)	99.02/99.59/(98.97,98.98)
Chiang Rai	19.94/19.58/(19.91, 20.42)	99.84/99.53/(99.82, 99.88)
Mae Hong Son	18.17/18.17/19.30	97.93/97.93/97.97
Nan	18.12/18.12/(18.79, 19.57)	100.16/100.16/(100.77, 101.08)
Phrae	16.87/16.87/18.13	99.14/99.14/100.16
Tak	18.76/18.76/16.73	100.76/100.76/98.56
Phitsanulok	16.92/16.47/16.82	100.23/100.16/100.26

Figure 1. Studying location for this research [18], [19]

2. SURFACE SOLAR RADIATION ESTIMATION MODELS

2.1. Conventional models

Table 1 shows some alternative conventional empirical models used for surface solar radiation estimation in this research (model M1-M8) [20]-[26] with the estimated value of R_{est}. The monthly average extraterrestial daily global solar radiation (R_o) can be calculated from (9) to (11) [27], [28]; where I_{sc} is the solar constant (1,367 W/m^2), φ is the latitude of the site, δ is the solar declination, ω_s is the mean sunrise hour angle for the given month, and k is the number of days of the year starting from the first January. The maximum possible sunshine period (S_o) depends on the latitude of the area and the angle of the sun's inclination, which can be calculated from (12). The parameters C refers to the rate of existing clouds (0.0-1.0), T_{min}, and T_{max} refer to the minimum and maximum ambient temperature, P and P_o refer to the measured and maximum air pressure (101.325 kPa), Rh refers to the relative humidity, and parameters a, b, c, d, e, f, g, h, and i are the model coefficents, which will be determined when applying the measured data from the measurement stations.

Table 1. Conventional empirical models for surface solar radiation estimation [20]-[26]

Model	Abbreviation	Equations		Influencing factor (s)
Iziomon and Mayer [20]	M1	$R_{est} = R_o\left(a + b\left(\frac{S}{So}\right)\right)$	(1)	Sunshine duration (S)
Ögelman *et al.* [21]	M2	$R_{est} = R_o\left(a + b\left(\frac{S}{So}\right) + c\left(\frac{S}{So}\right)^2\right)$	(2)	
Badescu [22]	M3	$R_{est} = R_o(a + d(C))$	(3)	Clouds (C)
Badescu [22]	M4	$R_{est} = R_o(a + d(C)) + e(C)^2$	(4)	
Garba *et al.* [23]	M5	$R_{est} = R_o\left(a + f\left(\frac{T_{min}}{T_{max}}\right)\right)$	(5)	Temperature (T) and air pressure (P)
Allen [24]	M6	$R_{est} = R_o\left(a\left(\frac{P}{P_o}\right)^{1/2}(T_{max} - T_{min})^{1/2}\right)$	(6)	
Chen and Li [25]	M7	$R_{est} = R_o\left(a + b\left(\frac{S}{So}\right) + g(T_{max}) + h(T_{min})\right)$	(7)	Relative humidity (Rh)
El-Sebaii *et al.* [26]	M8	$R_{est} = R_o\left(a + b\left(\frac{S}{So}\right) + i(Rh)\right)$	(8)	

$$R_o = \frac{24}{\pi} I_{sc}\left(1 + 0.033cos\left(\frac{360k}{365}\right)\right)\left(\frac{\pi}{180} sin\varphi sin\delta \; + \; cos\varphi cos\delta sin\omega_s\right) \quad (9)$$

$$\omega_s = cos^{-1}(-\tan\varphi tan\delta) \quad (10)$$

$$\delta \; = 23.45 sin\left(\frac{360(k+284)}{365}\right) \quad (11)$$

$$S_o = \frac{2}{15} cos^{-1}(-tan\varphi tan\delta) \quad (12)$$

2.2. The proposed models

The proposed model (M9) shown in Table 2 was represented by regular extraterrestial solar radiation coefficient term (a) and the exponencial attenuation coefficient term ($je^{(\tau_{md}+\tau_{aq})}$) based on Lord Rayleigh's theory [29], [30]; where τ_{md} refers to the attenuation caused by air molecules (τ_r) [29], [30], water vapor (τ_w) [31], [32], ozone (τ_o) [31], [33], and gas molecules (τ_g) [30] while τ_{aq} refers to the attenuation caused by air quailty (clouds, $PM_{2.5}$, and PM_{10}) derived based on Lord Rayleigh's theory [29], [30]. The variables in (13) can be determined from the related (14) to (22).

Table 2. The proposed empirical models for surface solar radiation estimation

Model	Abbriviation	Equations		Influencing factors
Proposed model	M9	$R_{est} = R_o\left(a + je^{(\tau_{md}+\tau_{aq})}\right)$ $; \tau_{md} = \tau_r + \tau_w + \tau_o + \tau_g$ $\tau_r = exp\left(-0.0903 m_a^{0.84}(1 + m_a - m_a^{1.01})\right)$ $\tau_w = 1 - \left(\frac{2.4959 \cdot U}{(1 + 0.79034 \cdot U)^{0.638} + 6.385 \cdot U}\right)$ $\tau_o = 1 - \left(\frac{0.02118 U_o}{1 + 0.042 U_o + 0.000323 U_o^2} + \frac{1.082 U_o}{(1 + 0.042 U_o)^{0.805}} + \frac{0.0658 U_o}{1+(103.6 U_o)^3}\right)$ $\tau_g = e^{\left(-0.0127 m_a^{0.26}\right)}$ $\tau_{aq} = \; e^{\left(-\left(1-\frac{N_C}{10}\right)\right)} \cdot e^{\left(-\frac{N_{PM2.5}}{\sum PM2.5}\right)} \cdot e^{\left(-\frac{N_{PM10}}{\sum PM10}\right)}$	(13)	Meteorological data (*md*) and air quality (*aq*)

$$m_a = m_r\left(\frac{P_o e^{(-0.0001184\theta_z)}}{101.325}\right) = \left(\frac{1}{(cos\theta_z + 0.15(93.885-\theta_z))^{1.253}}\right)\left(\frac{P_o e^{(-0.0001184\theta_z)}}{101.325}\right) \quad (14)$$

$$\theta_z = cos^{-1}(sin\delta sin\varphi + cos\delta cos\varphi cos\omega) \quad (15)$$

$$\omega = 15(12 - ST) \quad (16)$$

$$ST = Local\ time - 4(L_{st} - L_{loc}) + E \quad (17)$$

$$E = 9.87 sin2B - 7.53 cosB - 1.50 sinB \qquad ; B = \left(\frac{360(k-81)}{364}\right) \quad (18)$$

$$U = m_r W_{var} \quad (19)$$

$$W_{var} = 0.8933 e^{\left(0.1715 \cdot Rh \cdot \frac{P_{vs}}{T_k}\right)} \quad (20)$$

$$P_{vs} = e^{\left(26.23 - \frac{5416}{T_k}\right)} \quad (21)$$

$$U_o = m_r \cdot l \quad (22)$$

Where m_a is the air masses from different air pressures at the sea level, m_r is the arbitrary air mass, θ_z is the zenith angle (the angle between the sun and the vertical axist referred from the earth's surface), ω is the hour angle of the sun (degrees), P_o=101.325 kPa, z is the attitude at the local studied (m), ST is the solar time which is the calculation of elapsed time based on the position of the sun in the sky, L_{st}, and L_{loc} are the standard longitude angle (e.g. Thailand 105°E) and the longitude of the location to be calculated, E is the difference between sunshine time and average sunshine time, W_{var} is the equation for determining water vapor content from surface meteorological data in terms of Rh, T_k is the ambient temperature (°K), P_{vs} is the saturated water vapor pressure (mbar), l is the ozone amount (cm), N_C is the cloud levels measured by the meteorological device having values between 1-10, $N_{PM2.5}$ and N_{PM10} are the particulate $PM_{2.5}$ and PM_{10} (µm) while $\Sigma PM_{2.5}$ and ΣPM_{10} are the total of the particulate matters $PM_{2.5}$ and PM_{10}, and j is the model coefficient.

3. RESULTS AND DISCUSSIONS

3.1. Resultant test models

As aforementioned information, the actual data collected during 2011-2021 from 7 provinces of the northern Thailand (Chiang Mai, Chiang Rai, Mae Hong Son, Nan, Phrae, Tak, and Phitsanulok). These data were used to develop the test models under this research study. When applying all the data to the mathematical models in Tables 1 and 2, the parameters *a*, *b*, *c*, *d*, *e*, *f*, *g*, *h*, *i*, and *j* were obtained results shown in Table 3 (in APPENDIX).

3.2. Precision for the proposed models

The data collected from the investigated areas in the year 2022 was used to test the precision of the proposed models in comparision to the conventional models listed in Table 1, as well as, to the calculated results of the PVsyst software (copyright) [34], [35]. The statistical error estimation techniques in terms of mean absolute error (MAE), mean square error (MSE), root mean square error (RMSE), and mean absolute percentage error (MAPE) as shown in (23) to (26) [36], [37] were used.

$$MAE = \frac{\sum_{t=1}^{n}|A_t - F_t|}{n} \tag{23}$$

$$MSE = \frac{\sum_{t=1}^{n}(A_t - F_t)^2}{n} \tag{24}$$

$$RMSE = \sqrt{\frac{\sum_{t=1}^{n}(A_t - F_t)^2}{n}} \tag{25}$$

$$MAPE = \frac{\sum_{t=1}^{n}\left|\frac{A_t - F_t}{A_t}\right|}{n} \tag{26}$$

Figures 2 to 8 show the comparison test results between the actual and the estimated solar radiation obtained from the conventional and the proposed models for each investigated province: Chiang Mai, Chiang Rai, Mae Hong Son, Nan, Phrae, Tak, and Phitsanulok, respectively. The corresponding error estimations according to Figures 2 to 8 are summarized in Table 4.

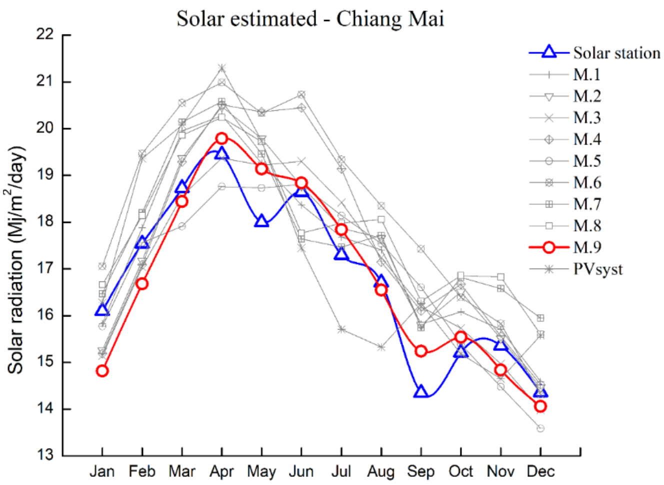


Figure 2. The estimated solar radiation obtained from the proposed model compared to the actual, conventional models and PVsyst for Chaing Mai

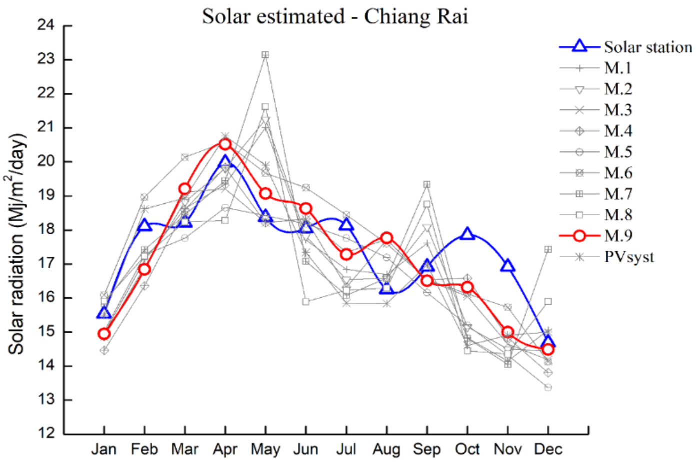


Figure 3. The estimated solar radiation obtained from the proposed model compared to the actual, conventional models and PVsyst for Chaing Rai

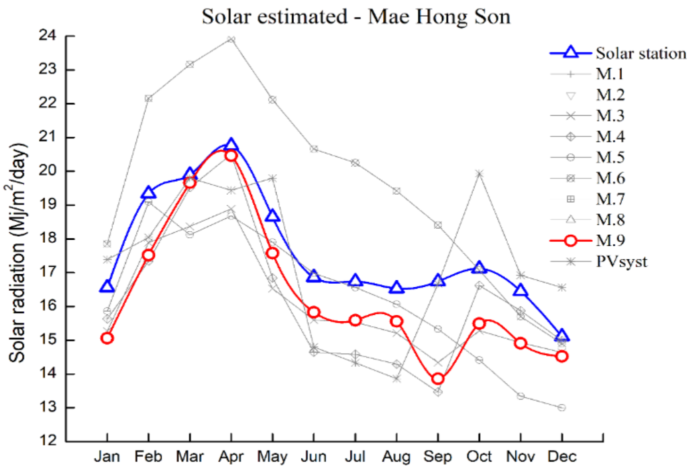


Figure 4. The estimated solar radiation obtained from the proposed model compared to the actual, conventional models and PVsyst for Mae Hong Son

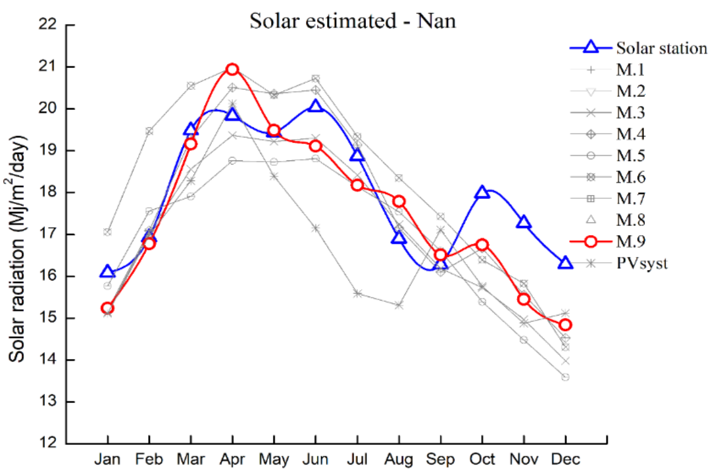


Figure 5. The estimated solar radiation obtained from the proposed model compared to the actual, conventional models and PVsyst for Nan

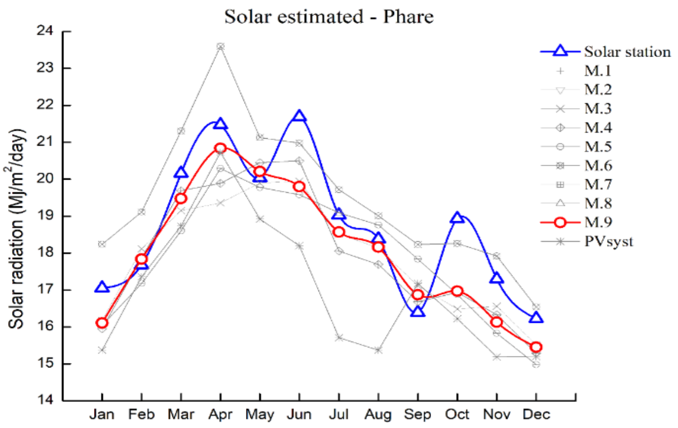


Figure 6. The estimated solar radiation obtained from the proposed model compared to the actual, conventional models and PVsyst for Phare

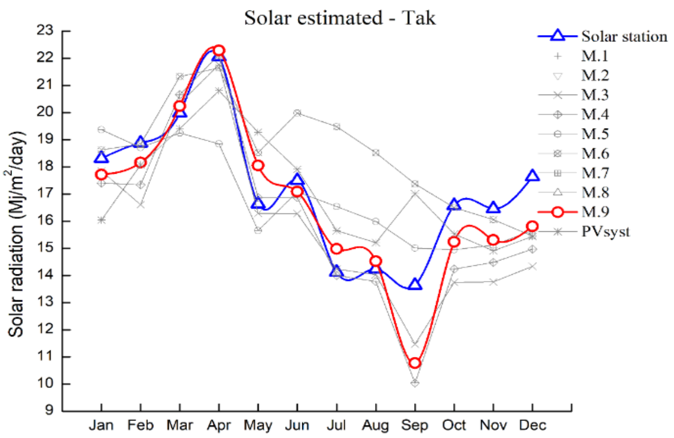


Figure 7. The estimated solar radiation obtained from the proposed model compared to the actual, conventional models and PVsyst for Tak

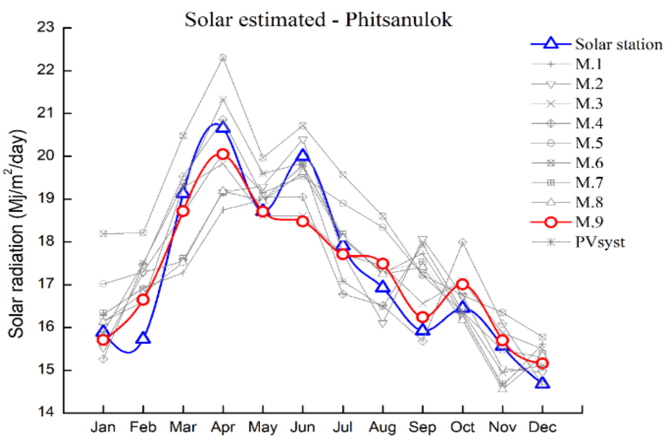


Figure 8. The estimated solar radiation obtained from the proposed model compared to the actual, conventional models and PVsyst for Phisanulok

It can be seen from the experimental test results that The estimated solar radiation results were varied dependent on the locations. However, the proposed model provided the best precision over all the conventional models and the PVsyst model. This is reflected by the minimal errors obtained from the proposed model as shown in Table 4; achieving lowest errors MAE, MSE, RMSE, and MAPE of 0.492-0.923%, 0.394-1.107%, 0.628-1.052%, and 2.806-5.298% compared to conventional models of 0.560-2.239%, 0.448-6.731%, 0.670-2.622%, and 3.257-12.470%, and also better than PVsyst model of 0.676-1.814%, 0.828-4.383%, and 4.036-9.623%. In other words, the proposed model achieved highest estimation precision of upto 94.70-97.19% compared to 87.53-96.74% of the conventional models and 90.38-95.96% of the PVsyst program.

Table 4. % Error estimation results for the models

Location	Std.	M1	M2	M3	M4	M5	M6	M7	M8	M9	PVsyst
Chiang Mai	MAE	0.683	0.774	0.696	1.082	0.709	1.595	1.086	1.171	0.570	1.249
	MSE	0.648	0.881	0.715	1.673	0.809	3.177	1.381	1.576	0.459	1.929
	RMSE	0.805	0.938	0.846	1.294	0.899	1.782	1.175	1.255	0.677	1.389
	MAPE	4.095	4.653	4.284	6.400	4.405	9.420	6.603	7.180	3.454	7.367
Chiang Rai	MAE	1.182	1.183	0.941	0.973	0.995	0.995	1.746	1.610	0.923	1.051
	MSE	2.350	2.317	1.267	1.397	1.672	1.250	4.981	3.798	1.107	2.020
	RMSE	1.533	1.522	1.126	1.182	1.293	1.118	2.232	1.949	1.052	1.421
	MAPE	6.720	6.731	5.440	5.710	5.794	5.692	10.11	9.120	5.298	5.905
Mae Hong Son	MAE	-	-	1.522	1.370	1.305	2.239	-	-	1.227	1.390
	MSE	-	-	2.545	2.847	2.692	6.731	-	-	1.987	2.750
	RMSE	-	-	1.595	1.687	1.641	2.594	-	-	1.410	1.658
	MAPE	-	-	8.617	7.920	7.518	12.47	-	-	7.141	8.086
Nan	MAE	-	-	0.831	0.818	1.021	1.346	-	-	0.764	1.495
	MSE	-	-	0.942	1.070	1.614	2.323	-	-	0.866	3.159
	RMSE	-	-	0.970	1.034	1.270	1.524	-	-	0.931	1.777
	MAPE	-	-	4.654	4.720	5.747	7.557	-	-	4.312	8.257
Phare	MAE	-	-	0.976	0.901	1.107	1.037	-	-	0.797	1.814
	MSE	-	-	1.451	1.073	1.652	1.345	-	-	0.975	4.383
	RMSE	-	-	1.204	1.036	1.285	1.160	-	-	0.987	2.093
	MAPE	-	-	5.105	4.780	5.943	5.551	-	-	4.237	9.623
Tak	MAE	-	-	1.356	1.267	1.424	1.878	-	-	0.995	1.552
	MSE	-	-	3.180	2.816	2.697	6.479	-	-	1.555	3.153
	RMSE	-	-	1.783	1.678	1.642	2.622	-	-	1.247	1.776
	MAPE	-	-	8.094	7.790	8.499	12.23	-	-	6.228	9.501
Phisa nulok	MAE	0.851	0.849	0.560	0.678	0.760	1.380	0.767	0.743	0.492	0.676
	MSE	1.166	1.128	0.448	0.733	0.811	2.263	0.865	0.835	0.394	0.828
	RMSE	1.080	1.062	0.670	0.856	0.901	1.504	0.930	0.914	0.628	0.910
	MAPE	4.948	4.915	3.257	3.980	4.519	8.099	4.480	4.320	2.806	4.036

4. CONCLUSION

This research proposed an improved surface solar radiation estimation model developed based on the integrated local meteorological-air quality data collected from standard meteorological stations and air quality measurement stations (in terms of clouds and commonly measured $PM_{2.5}$ and PM_{10}). The local meteorological data and air quality data of the nortern zone of Thailand during 2011-2021 were used to develop the model while the data during 2022 were used to test the developed models. The eperimental test results showed that the proposed model achieved the best surface solar radiation estimation with the highest precision upto 94.70-97.19% compared to the conventional models (87.53-96.74%) and the PVsyst model (90.38-95.96%).

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APPENDIX

Table 3. Resultant coefficients for each model under this research study

Province	Model	a	b	c	d	e	f	g	h	i	j
Chiang Mai	M1	0.330	0.306	-	-	-	-	-	-	-	-
	M2	0.203	0.830	-0.488	-	-	-	-	-	-	-
	M3	0.590	-	-	-0.020	-	-	-	-	-	-
	M4	0.523	-	-	0.024	-0.005	-	-	-	-	-
	M5	0.902	-	-	-	-	-0.593	-	-	-	-
	M6	0.170	-	-	-	-	-	-	-	-	-

Table 3. Resultant coefficients for each model under this research study *(Continued)*

Province	Model	a	b	c	d	e	f	g	h	i	j
	M7	0.558	0.484	-	-	-	-	-0.018	0.012	-	-
	M8	-0.019	0.457	-	-	-	-	-	-	0.004	-
	M9	0.816	-	-	-	-	-	-	-	-	-0.007
Chiang Rai	M1	0.302	0.356	-	-	-	-	-	-	-	-
	M2	0.136	1.014	-0.604	-	-	-	-	-	-	-
	M3	0.594	-	-	-0.022	-	-	-	-	-	-
	M4	0.500	-	-	0.030	-0.006	-	-	-	-	-
	M5	0.832	-	-	-	-	-0.503	-	-	-	-
	M6	0.170	-	-	-	-	-	-	-	-	-
	M7	0.535	0.672	-	-	-	-	-0.027	0.018	-	-
	M8	-0.360	0.580	-	-	-	-	-	-	0.007	-
	M9	0.835	-	-	-	-	-	-	-	-	-0.007
Mae Hong Son	M1	N/A	N/A	-	-	-	-	-	-	-	-
	M2	N/A	N/A	N/A	-	-	-	-	-	-	-
	M3	0.597	-	-	-0.025	-	-	-	-	-	-
	M4	0.538	-	-	0.021	-0.005	-	-	-	-	-
	M5	0.939	-	-	-	-	-0.702	-	-	-	-
	M6	0.170	-	-	-	-	-	-	-	-	-
	M7	N/A	N/A	-	-	-	-	N/A	N/A	-	-
	M8	N/A	N/A	-	-	-	-	-	-	N/A	-
	M9	0.810	-	-	-	-	-	-	-	-	-0.007
Nan	M1	N/A	N/A	-	-	-	-	-	-	-	-
	M2	N/A	N/A	N/A	-	-	-	-	-	-	-
	M3	0.590	-	-	-0.019	-	-	-	-	-	-
	M4	0.516	-	-	0.030	-0.005	-	-	-	-	-
	M5	0.792	-	-	-	-	-0.432	-	-	-	-
	M6	0.170	-	-	-	-	-	-	-	-	-
	M7	N/A	N/A	-	-	-	-	N/A	N/A	-	-
	M8	N/A	N/A	-	-	-	-	-	-	N/A	-
	M9	0.764	-	-	-	-	-	-	-	-	-0.006
Phare	M1	N/A	N/A	-	-	-	-	-	-	-	-
	M2	N/A	N/A	N/A	-	-	-	-	-	-	-
	M3	0.751	-	-	-0.034	-	-	-	-	-	-
	M4	0.257	-	-	0.124	-0.012	-	-	-	-	-
	M5	0.794	-	-	-	-	-0.413	-	-	-	-
	M6	0.170	-	-	-	-	-	-	-	-	-
	M7	N/A	N/A	-	-	-	-	N/A	N/A	-	-
	M8	N/A	N/A	-	-	-	-	-	-	N/A	-
	M9	0.850	-	-	-	-	-	-	-	-	-0.007
Tak	M1	N/A	N/A	-	-	-	-	-	-	-	-
	M2	N/A	N/A	N/A	-	-	-	-	-	-	-
	M3	0.727	-	-	-0.051	-	-	-	-	-	-
	M4	0.626	-	-	0.003	-0.006	-	-	-	-	-
	M5	1.418	-	-	-	-	-1.331	-	-	-	-
	M6	0.170	-	-	-	-	-	-	-	-	-
	M7	0.535	0.672	-	-	-	-	-0.027	0.018	-	-
	M8	-0.360	0.580	-	-	-	-	-	-	0.007	-
	M9	1.118	-	-	-	-	-	-	-	-	-0.014
Phitsanulok	M1	0.375	0.239	-	-	-	-	-	-	-	-
	M2	0.141	1.101	-0.744	-	-	-	-	-	-	-
	M3	0.629	-	-	-0.021	-	-	-	-	-	-
	M4	0.373	-	-	0.081	-0.009	-	-	-	-	-
	M5	0.955	-	-	-	-	-0.633	-	-	-	-
	M6	0.170	-	-	-	-	-	-	-	-	-
	M7	0.318	0.210	-	-	-	-	0.004	-0.003	-	-
	M8	0.470	0.202	-	-	-	-	-	-	-0.001	-
	M9	0.747	-	-	-	-	-	-	-	-	-0.005

Note: N/A means the actual data from the measurement stations are not available.

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