Total Global Solar Radiation Estimation with Relative Humidity and Air Temperature Extremes in Ireland and Holland

Can Ekici,[a, b], Ismail Teke [a]
[a]Yildiz Technical University, Department of Mechanical Engineering, Istanbul, Turkiye.
[b]Turkish Standard Institution, Gebze Calibration Laboratory, Kocaeli, Turkiye.
canekici@gmail.com

Abstract. Solar radiation is the earth's primary energy source for all biochemical and physical activities. Accurate knowledge of the solar radiation is important in engineering applications. This study aimed to calibrate some of the existing models in the literature for estimating daily total global solar radiation parameter using available measuring records (maximum and minimum air temperatures) and new models were developed based on maximum and minimum air temperatures, relative humidity and relative humidity extremes. Applicability of the Hargreaves model, Allen model, Bristow-Campbell model and Chen model were evaluated for computing the daily total solar global radiation, the geographical and meteorological data of Irish and Dutch cities were used. Meteorological data were taken from Royal Netherlands Meteorological Institute and Irish Meteorological Service. The models were compared on the basis of error tests which were mean percentage error (MPE), mean bias error (MBE), root mean square error (RMSE) and Nash-Sutcliffe equation (NSE). And, monthly MPE errors were given for each model. This study proposed new estimation models which were based on daily average relative humidity, relative humidity extremes and temperature extremes. Error analyses were applied to these models and results were given in the study.

Keywords: solar radiation; temperature; relative humidity; daily total global solar radiation; model comparison; Ireland; Holland; meteorological models; model validation

1 Introduction

Solar energy is the principal energy source for the processes such as biological, chemical and physical activities. Accurate knowledge of the solar radiation is important for many applications; simulations and modellings, architectural design, solar energy systems. There are many meteorological stations those measure basic meteorological parameters; but not all of them measure the global radiation in the worldwide. Sometimes, measurement of the solar radiation cannot be available due to the equipment's cost, maintenance and calibration requirements in developing countries. There are several empirical models in the literature to estimate the global radiation using various parameters (Chen *et. al.,* 2004; Menges *et. al,* 2006).

Solar energy is an energy source, which is clean, renewable and domestic and solar energy has high importance (Menges *et. al,* 2006). Without knowledge of solar radiation, it is impossible to design solar energy systems. Estimation models are widely used when solar radiation is not measured and available, these models help to obtain solar radiation value.

Amount of the solar radiation that received to the globe can change due to variables such as the time of day and the season, and the prevailing atmospheric conditions... In the northern hemisphere, the greatest amount of radiation is received in the location that is situated between 15 ºN and 35 ºN latitudes, for example Egypt. The next place which receive greatest amount of radiation is between 15 ºN and the equator which includes Central America. Countries located between the latitudes 35 ºN and 45 ºN, such as Spain and Turkey, show significant seasonal variations resulting in less radiation received. The least favorable locations are situated beyond 45 ºN receive the least amount of direct radiation; such as Ireland, England, Norway, Holland and Sweden. Approximately half of the radiation arrives at the surface as diffuse radiation, because there may be frequent heavy cloud cover in the atmosphere (Armstorng *et. al,* 2010).

Different types of models have been developed to estimate solar radiation when it is not measured (Gueymard *et. al,* 2008). There are several models in the literature, but a perfect model does not exist. A perfect model would be impossible due to measurement uncertainty and "true" solar irradiance cannot be determined theoretically (Gueymard *et. al,* 2008, Menges *et. al,* 2006). Ground-based statistical models show high performance. These models use one or more ground-based measurements as input parameters. However, there can be several errors in the estimations when using these models due to inaccurate data measured using un-calibrated and/or inaccurate instruments (Aksoy *et. al,* 2010). On the other hand, there are models in the literature that estimates ground level solar radiation using satellite data. Meteorological satellites provide observations of the atmospheric system. These satellite-based models can be divided in two categories: statistical approach based on relationship between satellite and ground data and a physical approach using radiative transfer models to express the relationship between satellite and ground measurements (Cano *et. al,* 2010). Validation of models based on satellite input data is much more complicated (Aksoy *et. al,* 2010). Temporary and spatial consistency questions are particularly annoying, as satellite data, while uniform, are usually sparse in time compared to surface observations. Spatial concerns are an even bigger problem, as surface observations are 'point' observations and satellite observations are spatially extended, even if at very high spatial resolution (Gueymard *et. al,* 2008). One of the main purposes of this study is the validation of the several ground-based models in the literature; those use the difference between maximum, minimum air temperatures, to estimate daily total global radiation in the cities of Ireland and Netherlands. These cities are Dublin, Eindhoven, Groningen, Maastricht, Rotterdam and Twente. The study suggests new estimation models for the prediction of the solar radiation. In this study, meteorological data for the cities were taken from Royal Netherlands Meteorological Institute and Irish Meteorological Service database and used for validation of the models. In the last years, calibration and metrology knowledge were developed; new methodologies were submitted by commissions like Euramet. So, it is thought the new data of meteorology institutes are more accurate and traceable. It has been thought that; the measurement’s reliability is higher in the data which have been recorded in recent past. Meteorological parameters were taken between 2008 and first half of 2016.

2 Some of the Main Mathematical Formulas about the Solar Radiation

Mathematical formulas about solar radiation, which were used in this study, are given in this part of the paper.

The plane of rotation of the earth around the sun is called the ecliptic plane. The rotation axis of the earth is called polar axis. The earth's rotation and the position of the earth axis causes diurnal and seasonal changes in solar radiation. The angle between the sun and the equatorial plane of the earth is different in every day of the year. This angle is called the solar declination angle; δ (Iqbal, 1983).

The solar declination angle's mathematical formula can be seen in equation 1. *J* is the calendar day in this equation with *J* = 1 on January 1 and *J* = 365 (or 366 during leap years) on December 31 (Campbell *et. al.,* 1998).

$$\sin\delta = 0.39785 * \sin[278.97 + 0{,}9856J + 1.9165 * \sin(356.6 + 0{,}9856J)] \quad (1)$$

Sunrise hour angle can be seen in equation 2. Here, ω_s is the sunrise angle; *ø* is the latitude of the site (Iqbal, 1983).

$$\omega_s = \cos^{-1}[-\tan ø * \tan\delta] \quad (2)$$

Reciprocal of the square of the radius vector of the earth is called the eccentricity correction factor of the earth's orbit, E_o. In many engineering applications, this factor can be expressed very simple. The simple expression of the eccentricity factor can be seen in equation 3 (Iqbal, 1983).

$$E_0 = 1 + 0.033 * \cos[(\frac{2\pi * J}{365})] \quad (3)$$

Mathematical equations are developed to determine the irradiation at various surface orientations and for different time periods. Daily extraterrestrial radiation is shown in equation 4 (Iqbal, 1983). I_{sc} is the solar constant and it is equal to 4.921 MJ/day.m^2 (Menges *et. al*, 2006).

$$H_0 = \frac{24}{\pi} * I_{sc} * E_0 * \sin\o * \sin\delta * [(\frac{\pi}{180}) * \omega_s - \tan\omega_s] \quad (4)$$

The purpose of this study is modelling and reaching to the daily total global solar radiation. Its notation is *H*. It refers to total energy accumulated over the day on horizontal plane of the ground. It can be said that, this value is the total daily dose. Daily total global solar radiation and extraterrestrial solar radiation expresses in energy per square meter. Daily total solar global radiation is in MJ/(day.m^2).

3 Model Description

3.1 Hargreaves Model

Hargreaves et al. (1985) suggested a simple method to estimate global solar radiation; the expression can be seen in equation 5. “a” and “b” are the empirical coefficients. In this study, Hargreaves model was used to predict daily total global solar radiation in Irish and Dutch cities. T_{max} can be taken as the daily maximum air temperature and T_{min} is the daily minimum air temperature. *H* is the daily total global solar radiation. T_{max} and T_{min} given in the models can be used in the units of Celcius.

$$\frac{H}{H_0} = a * (T_{max} - T_{min})^{0.5} + b \quad (5)$$

3.2 Allen Model

Allen (1997) reported a self-calibrating model to estimate mean monthly global solar radiation, which is the function of the mean monthly maximum and minimum temperatures. The model can be seen in equation 6. In this study, this model was processed to estimate daily total global solar radiation in the cities of Ireland and Netherlands.

$$\frac{H}{H_0} = a * (T_{max} - T_{min})^{0.5} \quad (6)$$

Also, “a” is an empirical coefficient, and it has been suggested as a mathematical expression, which is the function ratio of the atmospheric pressure at site (P, kPa) and at sea level (P_0, 101.3 kPa) in literature. The mathematical expression can be seen in equation 7. K_{ra} value can be taken 0.17 for interior regions, and 0.20 for coastal regions (Meza, 2000). The derivation of the coefficient a by the Equation 7 for regional stations allows that the model is self-calibrated (Allen, 1997).

$$a = K_{\mathrm{ra}} * \left(\frac{P}{P_0}\right)^{0.5} \quad (7)$$

3.3 Bristow-Campbell Model

Bristow and Campbell (1984) suggested a relationship between daily solar radiation as a function of daily extraterrestrial radiation and the difference between maximum and minimum air temperatures. The relationship can be seen in equation 8 and “a”, “b” and “c” are the empirical coefficients.

$$\frac{H}{H_0} = a * [1 - \exp(-b\Delta T^{c})] \quad (8)$$

3.4 Chen Model

Chen et al. (2004) presented the model in equation 9. “a” and “b” are empirical coefficients for the meteorological stations. T_{max} is the maximum daily air temperature. T_{min} is minimum daily air temperature.

$$\frac{H}{H_0} = a * \ln(T_{\mathrm{max}} - T_{\mathrm{min}}) + b \quad (9)$$

3.5 New Models Suggested in This Study

Three models based on daily temperature extremes and daily average relative humidity are suggested in the study. The models are shown in Eq. 10 and Eq. 11. *RH* is the relative humidity, “a”, “b”, “c”, “d” and “e” are the empirical coefficients. The H_0 value is calculated using the daily parameters. The usage and explanations of these parameters are given in the previous sections. Models will be used to calculate total daily global solar radiation values. In this study, the reason why the period is selected on a daily basis is due to the importance of daily meteorological estimations. It is also thought that there may be instantaneous changes in shorter time periods.

$$\frac{H}{H_0} = a\left(\frac{RH}{100}\right) + b(T_{\max} - \mathrm{T}_{\min})^{0.5} + \mathrm{c}(T_{\max} - T_{\min}) + d\left(\frac{RH}{100}\right)(T_{\max} - T_{\min})^{0.5} + e \qquad (10)$$

$$\frac{H}{H_0} = a \cdot [1 - \exp(-\Delta T^{b})] + c \cdot RH \qquad (11)$$

Daily relative humidity extremes were used to estimate solar radiation in this study. Two models were proposed for estimation the daily solar radiation related to relative humidity extremes. One of the models use the saturation vapor pressure, the ratio between daily maximum relative humidity and daily minimum relative humidity and the daily temperature extremes. Other model is based on temperature extremes, relative humidity ratio and the relative humidity. $RH_{\max}$ is the daily measured maximum relative humidity, $RH_{\min}$ is minimum relative humidity, e_s is the saturation vapor pressure at daily average temperature. The models are given in Eq. 12 and Eq. 13. Calculation of e_s is shown in Eq. 14. T_{avg} is daily average air temperature in Celcius.

$$\frac{\mathrm{H}}{\mathrm{H}_0} = a \cdot [1 - \exp(\{e_s \cdot (T_{\max} - T_{\min})^{0.5}\}^{b})] + c \cdot \frac{RH_{\min}}{RH_{\max}} \qquad (12)$$

$$\frac{H}{H_0} = a \cdot \left[1 - \exp\left(\{T_{\max} - T_{\min}\}^{0.5b}\right)\right] + c \cdot (T_{\max} - T_{\min})^{0.5} \cdot \frac{RH_{\min}}{RH_{\max}} + d \cdot (T_{\max} - T_{\min})^{0.5} \qquad (13)$$

$$e_s = 0.6108 \cdot \left[\exp\left(\frac{17.27 \cdot T_{avg}}{T_{avg} + 237.3}\right)\right] \qquad (14)$$

Empirical coefficients of the models for the cities and performance of the models can be seen in the next sections of the study.

4 Climatic Data

Daily climatic data for the Irish and Dutch cities were taken from meteorological public authorities of Ireland and Netherlands; Royal Netherlands Meteorological Institute and Irish Meteorological Service. Dublin, Eindhoven, Rotterdam, Groningen, Maastricht and Twente's daily meteorological data were used in the study. Locations and altitudes of the meteorological stations are given in Table 1.

The meteorological dataset is selected on a daily basis. These meteorological data belong to the period between 2008 and July 2016. Maximum and minimum temperatures, daily total global solar radiation, average daily relative humidity, daily maximum and minimum relative humidity values, daily average temperature values were taken from meteorological stations. Extraterrestrial solar radiation values were obtained by calculation. With the help of this data obtained from meteorological stations, the models in the literature have been calibrated and new models have been developed.

Table 1 Location and altitude information of the meteorological stations

Station name	Latitude	Longitude	Altitude
Dublin	53.423º	-6,238º	71 m
Eindhoven	51.451º	5.377º	22.6 m
Groningen	53.125º	6.585º	5.2 m
Rotterdam	51.962º	4.447º	-4.3 m
Maastricht	50.906º	5.762º	114.3 m
Twente	52.274º	6.891º	34.8 m

5 Methods of Comparison and Model Evaluation

Performances of the models were evaluated on the basis of mean percentage error (MPE), mean bias error (MBE) and root mean square error (RMSE). MPE, MBE and RMSE are given in the equation 15, 16 and 17. $\mathrm{H}_{i,m}$ is the *i*th measured value, $H_{i,c}$ is the *i*th calculated value and N is the total number of observations (Menges *et. al*, 2006). RMSE gives information about the short term performance of the correlations by using a term-by-term comparison of the deviations between the observed and calculated values. MBE presents the systematic error or bias and provides information on the long-term performance, positive value of MBE shows an over-estimate and negative value gives an under-estimate by the model. Values of MPE are calculated from the actual differences between calculated and measured values, and give the percentage errors of the correlation (Almorox, 2011). When MBE converges to zero, it is the ideal performance for the model, while a low value of RMSE and low MPE are desirable (Iqbal, 1983).

$$\mathrm{MPE} = \frac{1}{\mathrm{N}}\sum_{i=1}^{n}\left[\frac{H_{\mathrm{i,c}}-H_{\mathrm{i,m}}}{H_{\mathrm{i,m}}}\right]\cdot 100 \qquad (15)$$

$$\mathrm{MBE} = \frac{\sum_{i=1}^{n} H_{\mathrm{i,c}}-H_{\mathrm{i,m}}}{\mathrm{N}} \qquad (16)$$

$$\mathrm{RMSE} = \sqrt{\left|\frac{\sum_{i=1}^{n}\left(H_{\mathrm{i,c}}-H_{\mathrm{i,m}}\right)^{2}}{\mathrm{N}}\right|} \qquad (17)$$

The Nash-Sutcliffe equation is also an evaluation method. A model is more efficient when NSE is closer to 1. The equation is shown in equation 18. $\bar{H}_{\mathrm{m}}$ is the mean measured global radiation (Menges *et. al*, 2006).

$$\mathrm{NSE} = 1-\frac{\sum_{i=1}^{n}(H_{\mathrm{i,m}}-H_{\mathrm{i,c}})^{2}}{\sum_{i=1}^{n}\left(H_{\mathrm{i,m}}-\bar{H}_{\mathrm{m}}\right)^{2}} \qquad (18)$$

MBE and RMSE values explain the systematic errors of the models. When MBE value converges to zero; the systematic error of the model decreases. It can be illustrated by bull’s eye example. A marksman wants to shot a bull from its eye. The bull’s eye on the target represents the measured solar radiation parameter we wish to estimate. If the marksman’s aim is accurate, he/she scores a bull’s eye; on the other hand, the marksman misses the bull’s eye by some distance. And the marksman shoots the bull’s eye repeatedly at the target, each time aiming at the bull’s eye. The distance between the point clusters that shot by the marksman and the center of the eye explains the mean bias error (Biemer *et. al.*, 2003).

NSE is a method that indicates how well the plot of observed versus simulated data fits the line. If NSE equals to 1, the model corresponds to a perfect match between modelled and observed data.

6 Results and Discussions

Solar radiation data can give useful information in the design and for studies about the solar energy systems, agricultural processes, etc. In the literature, there are empirical models to estimate global solar radiation. These models can be suitable tools if the parameters can be calibrated for the different locations. In this study, some of the models in the literature were calibrated for Irish and Dutch cities to estimate daily total global solar radiation. Also, five new models were presented in this study and these models were validated with the meteorological data of Ireland and Holland. Validation of the models were performed with MPE, MBE, RMSE and NSE methods and given in the rest of the study.

6.1 Hargreaves Model

MPE, MBE, RMSE error analyze methods have been applied on the models. And, NSE value has been calculated via Excel 2013. The values are shown in Table 2. Also, mean percentage errors for the every month are given in Table 3.

In equation 5, Hargreaves model can be seen. *a* and *b* are the empirical coefficients. In this study, these empirical coefficients to estimate daily total global solar radiation in Irish and Dutch cities are found and given in Table 3. The coefficients were derived by using MATLAB R2015a and Minitab Statistical Software.

Table 2 Error analyses of the Hargreaves, Allen, Bristow-Campbell and Chen models

Location		Monthly MPE				Whole of the model				
		Hargreaves	**Allen**	**Bristow-Campbell**	**Chen**		**Hargreaves**	**Allen**	**Bristow-Campbel**	**Chen**
Dublin	January	-38.061	-38.507	-37.256	-36.680	MBE	0.02	-0,02	0.03	0.01
	February	-20.832	-21.173	-20.188	-20.583	RMSE	3.22	3,24	3.22	3.25
	March	-14.052	-13.993	-13.768	-12.998	MPE	-22.18	-22,19	-21.81	-21.59
	April	-11.314	-11.070	-11.149	-9.803	NSE	0.80	0,80	0.80	0.80
	May	-8.364	-8.075	-8.306	-8.268					
	June	-14.341	-13.786	-14.489	-14.297					
	July	-17.631	-17.252	-17.660	-18.558					
	August	-15.353	-15.013	-15.368	-16.293					
	September	-12.452	-12.390	-12.175	-11.417					
	October	-41.353	-41.641	-40.657	-39.952					
	November	-31.560	-32.044	-30.748	-30.568					
	December	-41.494	-41.987	-40.631	-40.496					
Eindhoven	January	-23.704	-36.444	-17.552	-21.837	MBE	0.21	-0.24	0.12	0.17
	February	-21.700	-30.261	-16.621	-20.914	RMSE	2.89	3.11	2.85	2.98
	March	-12.285	-13.986	-10.278	-14.049	MPE	-17.06	-19.20	-13.86	-16.83
	April	-8.681	-3.287	-7.904	-8.623	NSE	0.86	0.84	0.86	0.85
	May	-14.863	-12.722	-13.163	-14.085					
	June	-13.962	-8.941	-12.926	-14.082					
	July	-12.756	-10.254	-12.312	-13.721					
	August	-12.048	-8.647	-11.762	-13.726					
	September	-15.123	-11.853	-13.168	-16.830					
	October	-14.361	-16.067	-10.953	-15.798					
	November	-27.165	-38.415	-21.150	-26.121					
	December	-25.968	-40.400	-19.429	-23.303					
Groningen	January	-34.742	-45.674	-32.0205	-32.959	MBE	0.35	-0.23	0.11	0.09
	February	-18.449	-25.194	-16.228	-18.642	RMSE	3.07	3.21	3.05	3.15
	March	-13.620	-14.749	-12.427	-13.912	MPE	-18.89	-20.46	-17.65	-18.87
	April	-8.559	-4.751	-8.362	-8.518	NSE	0.844	0.83	0.85	0.84
	May	-14.581	-11.963	-14.272	-13.705					
	June	-15.865	-11.910	-15.520	-16.450					
	July	-11.197	-8.204	-10.861	-11.113					
	August	-13.164	-9.629	-12.845	-13.522					
	September	-17.897	-15.218	-17.167	-19.326					
	October	-25.430	-27.360	-23.721	-27.241					
	November	-28.266	-37.143	-25.838	-27.246					
	December	-25.459	-34.041	-23.074	-24.593					
Maastricht	January	-26.767	-45.347	-20.244	-20.563	MBE	0.22	-0.38	0.24	0.37
	February	-22.254	-36.250	-17.202	-17.567	RMSE	2.94	3.29	2.91	3.05
	March	-15.592	-17.914	-12.745	-16.768	MPE	-20.46	-24.22	-17.65	-20.01
	April	-11.914	-6.889	-12.227	-12.301	NSE	0.86	0.82	0.86	0.85
	May	-16.599	-13.008	-16.204	-17.037					
	June	-17.894	-11.612	-17.867	-20.378					
	July	-15.036	-10.268	-14.500	-17.256					
	August	-13.171	-7.599	-13.061	-15.340					
	September	-14.800	-11.910	-13.336	-18.403					
	October	-20.179	-22.050	-17.095	-23.050					
	November	-27.354	-42.285	-21.225	-23.829					
	December	-45.167	-66.486	-37.184	-39.248					
Rotterdam	January	-32.303	-41.692	-23.510	-30.659	MBE	-0.01	-0.34	0.09	-0.03
	February	-29.201	-35.084	23.125	-29.140	RMSE	3.19	3.34	3.17	3.22
	March	-13.401	-13.571	-11.610	-14.228	MPE	-19.78	-21.32	-17.02	-19.65
	April	-7.483	-3.626	-8.831	-7.401	NSE	0.84	0.82	0.84	0.83
	May	-13.943	-12.121	-13.676	-13.046					
	June	-11.204	-8.053	-11.797	-11.287					
	July	-10.658	-8.785	-10.555	-10.569					
	August	-10.848	-8.523	-11.245	-11.742					
	September	-15.424	-13.645	-15.239	-16.618					

	October	-25.473	-27.340	-22.519	-26.414					
	November	-34.461	-41.934	-27.176	-33.475					
	December	-34.136	-42.664	-26.169	-32.638					
Twente	January	-25.681	-37.525	-37.525	-23.901	MBE	0.22	-0.17	-0.17	0.18
	February	-22.185	-29.122	-29.122	-23.060	RMSE	3.06	3.18	3.18	3.17
	March	-12.945	-14.001	-14.001	-13.966	MPE	-18.32	-19.99	-19.99	-18.31
	April	-10.124	-5.542	-5.543	-10.164	NSE	0.84	0.83	0.83	0.83
	May	-18.467	-14.504	-14.505	-18.233					
	June	-15.587	-10.647	-10.647	-15.642					
	July	-14.841	-11.175	-11.175	-14.539					
	August	-15.441	-12.255	-12.255	-16.079					
	September	-16.108	-13.571	-13.571	-17.899					
	October	-18.629	-20.498	-20.498	-20.544					
	November	-24.909	-34.708	-34.708	-22.554					
	December	-25.613	-37.001	-37.000	-23.844					

Table 3 Empirical coefficients for Hargreaves model

Location	"a" coefficient	"b" coefficient
Dublin	0.1472	-0.01362
Eindhoven	0.1777	-0.1336
Groningen	0.1716	-0.1004
Maastricht	0.1983	-0.1739
Rotterdam	0.1814	-0.1045
Twente	0.1609	-0.09308

NSE values show good fit between calculated and measured values for Dutch cities, but for Dublin it is worse. Maximum average MPE values of Hargreaves model is around 20 percent. It may be acceptable, but in some months MPE values are higher than others; for instance winter months. In Dutch cities the errors in April, in Dublin the error in May are more satisfactory.

6.2 Allen Model

Allen model was applied for the estimation of the daily solar global radiation in Irish and Dutch cities. Empirical coefficient "a" was found by MS Office Excel 2013, coefficients can be seen in Table 4. Error analyses of the Allen method's application is seen in Table 2. NSE value is seen usable in the table. But some of the monthly MPE values are higher than Hargreaves Model. In November and December, there are higher deviations between the predicted and observed values.

Table 4 Empirical coefficients for Allen model

Location	"a" coefficient
Dublin	0.1418

Eindhoven	0.1291
Groningen	0.1335
Maastricht	0.1317
Rotterdam	0.1403
Twente	0.1266

6.3 Bristow-Campbell Model

Bristow-Campbell model's equation can be seen in equation 8. "a", "b" and "c" are the empirical coefficients. They are shown in Table 5 for the estimation of the daily total global solar radiation in Ireland and Holland.

Table 5 Empirical coefficients for Bristow-Campbell model

Location	"a" coefficient	"b" coefficient	"c" coefficient
Dublin	1.991	0.5956	0.066
Eindhoven	1.260	0.9157	0.050
Groningen	1.644	0.7726	0.053
Maastricht	0.975	1.0940	0.051
Rotterdam	0.833	1.0690	0.075
Twente	2.523	0.7001	0.036

MBE, MPE, RMSE and NSE error analyses were applied to the model. These analyses and monthly MPE analyses can be seen in Table 2. NSE value can be assumed as acceptable. Some of the monthly MPE values do not give satisfaction for example in winter months. But for other months; it can be said, the deviations are not too high.

6.4 Chen Model

Chen model's empirical coefficients are seen in Table 6.

Table 6 Empirical coefficients for Chen model

Location	"a" coefficient	"b" coefficient
Dublin	0.1841	0.0269
Eindhoven	0.2337	-0.1014
Groningen	0.2168	-0.0521
Maastricht	0.2695	-0.1525
Rotterdam	0.2244	-0.0464
Twente	0.2083	-0.0539

MBE, MPE, RMSE and NSE error analyses can be seen in Table 2. Also, the monthly MPE analysis is shown in table.

6.5 Ekici Models

Three daily solar radiation estimation models are suggested in this study. They were shown in Equation 10, 11, 12 and 13. There are empirical coefficients in the models. The empirical coefficients of the models can be seen in Table 7. These coefficients are calculated by regression analyses of Minitab 17 Statistical Software and MATLAB fitting toolboxes. In the table, Equation 10 is called as Ekici's Model 1, Equation 11 is Model 2 and Equation 12 and Equation 13 are named as Model 3 and Model 4.

Table 7 Empirical coefficients for Ekici models

#	Location	"a" coefficient	"b" coefficient	"c" coefficient	"d" coefficient	"e" coefficient
	Dublin	-1.092	-0.0333	0.009703	0.1331	1.007
	Eindhoven	-1.224	-0.1198	0.01446	0.2098	1.091
Model 1 (Eq. 10)	Groningen	-1.435	-0.156	0.01554	0.2321	1.343
	Maastricht	-1.433	-0.2583	0.03107	0.2874	1.348
	Rotterdam	-1.472	-0.2572	0.03116	0.2803	1.413
	Twente	-1.256	-0.1483	0.02002	0.1801	1.216
	Dublin	-0.4202	0.09728	-0.007322		
	Eindhoven	-0.3242	0.1198	-0.00599		
Model 2 (Eq. 11)	Groningen	-0.4326	0.0931	-0.007682	-	-
	Maastricht	-0.350	0.1138	-0.00647		
	Rotterdam	-0.4068	0.1047	-0.007442		
	Twente	-0.3921	0.09542	-0.007086		
	Dublin	-0.6164	-0.02444	-0.920		
	Eindhoven	-0.5782	-0.01691	-0.9104		
Model 3 (Eq. 12)	Groningen	-0.6233	-0.01365	-0.9556	-	-
	Maastricht	-0.5752	0.003312	-0.9478		
	Rotterdam	-0.6457	-0.009491	-1.026		
	Twente	-0.5729	-0.01314	-0.9082		
	Dublin	-0.1046	0.3166	-0.21034	0.166	
	Eindhoven	$4.47 \cdot 10^{-6}$	-2.000	0.130	0.202	
Model 4 (Eq. 13)	Groningen	0.001094	1.210	-0.2093	0.2899	-
	Maastricht	0.210	0.520	-0.1923	0.5897	
	Rotterdam	0.00081	1.256	-0.2441	0.319	
	Twente	0.006525	0.9105	-0.2017	0.2839	

RMSE, MBE, MPE and NSE error analyses were executed to the application of the models that are suggested in the study to estimate solar radiation of Irish and Dutch cities. The error values can be seen in the Table 8. Error values can be seen as acceptable, monthly MPE values are also seen as acceptable. For Dublin, in January, December and October, the monthly MPE values are higher than the others. For Dutch cities, in May, the monthly values are seen higher than other months. The correlation between the observed and the measured values (NSE) for all cities are seen acceptable.

Table 8 Error analyses of Ekici models

Location		**Monthly MPE**				**Whole of the model**				
		Model 1	**Model 2**	**Model 3**	**Model 4**		**Model 1**	**Model 2**	**Model 3**	**Model 4**
Dublin	January	-25.235	-24.388	-18.213	-13.394	MBE	0.12	0.14	-0.26	-0.20
	February	-10.202	-10.384	-11.488	-4.729	RMSE	2.87	2.88	3.04	2.85
	March	-11.597	-11.098	-10.927	-6.530	MPE	-15.61	-15.60	-12.17	-10.57
	April	-11.708	-11.104	-11.396	-9.094	NSE	0.84	0.84	0.82	0.84
	May	-10.182	-10.663	-10.092	-7.244					
	June	-15.929	-16.458	-10.480	-13.134					
	July	-15.513	-16.528	-8.728	-12.087					
	August	-13.247	-13.997	-8.500	-10.298					
	September	-5.481	-5.320	-2.284	-3.650					
	October	-26.453	-26.050	-19.642	-21.148					
	November	-17.868	-17.478	-14.118	-10.018					
	December	-23.569	-23.641	-19.324	-15.885					
Eindhoven	January	-8.835	-9.163	-6.242	-0.433	MBE	0.21	0.23	0.12	-0.27
	February	-13.657	-12.540	-15.225	-3.400	RMSE	2.50	2.52	2.67	2.56
	March	-12.550	-11.735	-19.983	-5.134	MPE	-9.94	-10.20	-9.74	-4.23
	April	-11.340	-11.690	-14.066	-6.359	NSE	0.89	0.89	0.88	0.89
	May	-15.829	-16.826	-17.411	-9.980					
	June	-14.657	-15.341	-12.688	-8.924					
	July	-11.137	-12.053	-10.107	-7.627					
	August	-7.655	-7.965	-5.326	-4.727					
	September	-4.628	-4.582	0.683	-1.414					
	October	-1.345	-1.563	2.193	3.127					
	November	-9.766	-10.257	-10.474	-4.589					
	December	-6.660	-7.570	-5.699	-0.796					
Groningen	January	-15.920	-17.355	-19.812	-11.472	MBE	0.19	0.22	0.15	-0.18
	February	-8.471	-9.072	-14.571	-3.804	RMSE	2.69	2.72	2.83	2.74
	March	-12.085	-11.751	-19.692	-8.338	MPE	-11.41	-12.06	-12.69	-7.95
	April	-10.680	-11.224	-13.434	-7.985	NSE	0.88	0.88	0.87	0.88
	May	-18.449	-19.006	-18.554	-12.480					
	June	-19.135	-19.683	-16.147	-13.248					
	July	-10.085	-10.637	-8.251	-7.276					
	August	-7.770	-8.009	-4.920	-6.443					
	September	-8.914	-8.849	-4.650	-6.274					

	October	-9.194	-10.796	-9.728	-8.948					
	November	-6.440	-8.270	-11.528	-6.733					
	December	-8.368	-8.743	-8.266	-1.505					
Maastricht	January	-11.981	-13.557	-6.351	-3.049	MBE	0.20	0.26	0.17	-0.38
	February	-12.894	-13.262	-13.523	-5.014	RMSE	2.56	2.60	2.89	2.65
	March	-15.778	-16.126	-22.315	-9.260	MPE	-12.49	-13.71	-12.37	-6.44
	April	-13.430	-14.107	-16.024	-8.168	NSE	0.89	0.89	0.86	0.88
	May	-15.524	-17.091	-18.371	-10.377					
	June	-15.283	-16.430	-15.796	-9.899					
	July	-11.854	-13.351	-13.047	-6.925					
	August	-9.867	-10.356	-12.796	-5.931					
	September	-5.210	-5.871	-4.380	-0.843					
	October	-6.255	-7.507	-2.746	-0.367					
	November	-11.456	-12.673	-8.681	-3.417					
	December	-19.431	-23.383	-12.587	-13.317					
Rotterdam	January	-12.753	-14.002	-19.495	-12.373	MBE	-0.10	0.14	0.15	0.12
	February	-13.132	-14.693	-16.008	-11.746	RMSE	2.80	2.83	3.03	2.87
	March	-9.348	-10.602	-11.886	-7.111	MPE	-10.45	-12.47	-13.89	-11.65
	April	-5.673	-7.933	-8.921	-8.512	NSE	0.87	0.87	0.85	0.87
	May	-12.697	-15.982	-18.672	-16.642					
	June	-11.266	-13.943	-13.896	-12.566					
	July	-10.053	-12.864	-15.893	-13.827					
	August	-7.876	-10.825	-10.229	-11.122					
	September	-6.429	-8.056	-6.183	-8.472					
	October	-8.100	-10.846	-9.107	-10.975					
	November	-11.574	-13.213	-15.741	-13.437					
	December	-16.452	-16.651	-19.986	-13.202					
Twente	January	-10.432	-8.949	-10.447	-2.942	MBE	0.21	0.20	0.12	0.10
	February	-10.972	-10.570	-13.437	-5.158	RMSE	2.55	2.56	2.62	2.56
	March	-11.132	-10.558	-17.593	-8.649	MPE	-9.99	-9.76	-10.21	-7.58
	April	-12.212	-12.455	-14.283	-12.194	NSE	0.89	0.89	0.89	0.89
	May	-19.080	-19.676	-18.206	-17.750					
	June	-15.377	-15.624	-12.137	-13.460					
	July	-11.850	-12.117	-9.708	-11.698					
	August	-7.437	-7.942	-5.319	-8.728					
	September	-2.294	-2.481	1.179	-2.307					
	October	0.475	-0.861	3.326	0.883					
	November	-7.174	-5.421	-12.309	-4.469					
	December	-10.611	-8.737	-11.010	-3.257					

A graphic showing the differences between the measured and calculated solar radiation values of the models on daily basis for the month of February 2008 was drawn for Eindhoven. This graphic is given in Figure 1; it may be give idea about the models' daily error tendencies. If you look at the daily tendencies of the models in the literature, it is seen that these models have more scattered errors. But in developed models, it can be said that the errors are a little bit more closer to each other on daily basis. Since it can be said that all models show the similar tendency in general.

In the figure, Equation 10 is called as Model 1, Equation 11 is Model 2 and Equation 12 and Equation 13 are named as Model 3 and Model 4 for Ekici models.

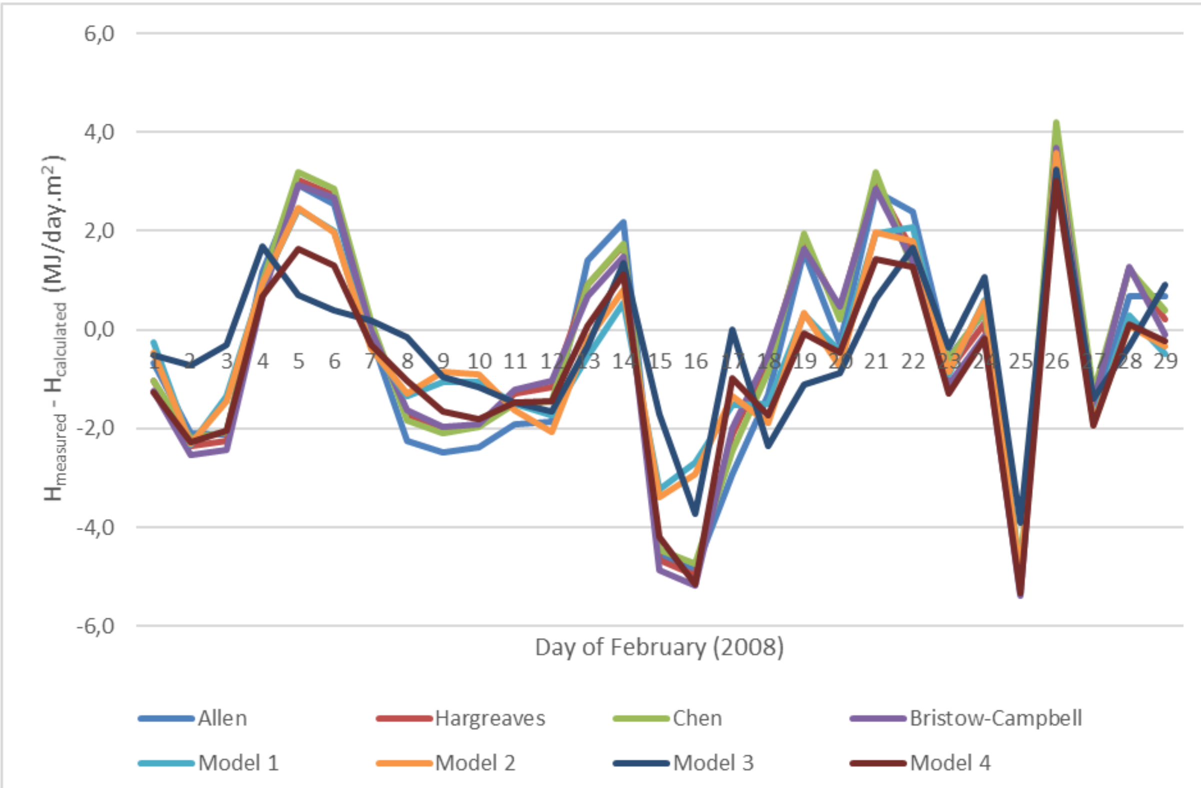

Figure 1 Differences between measured and calculated daily total global solar radiation values in February 2008 (Eindhoven)

Weather conditions for February 2008 in Eindhoven is given in Figure 2. Some comments can be given by looking at this figure. It can be said; in the days when the difference between ΔT and daily average air temperature is lower, the errors in the models are more than the other days. It can be said that for Model 3, while the differences between the maximum and minimum relative humidity values are higher, the results are better than the other models.

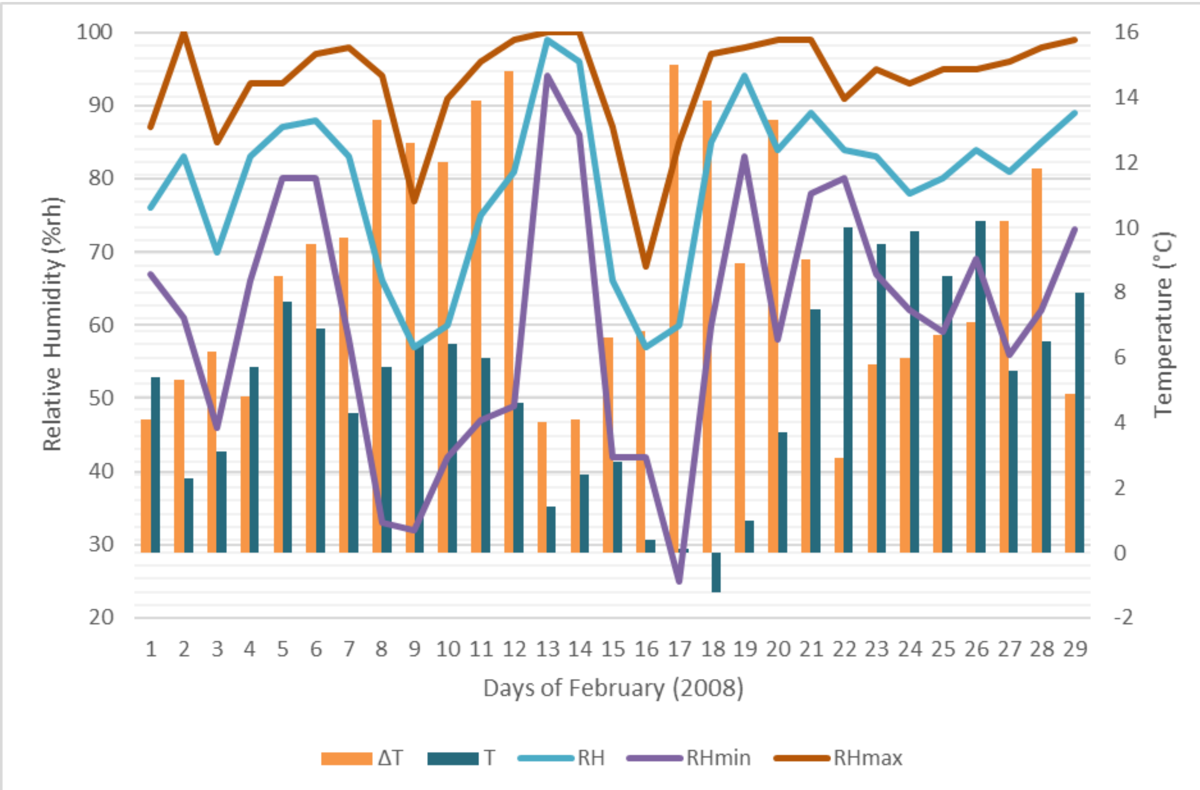

Figure 2 Measured weather data in February 2008 (Eindhoven)

MPE values of Allen model, Hargreaves model, Chen model and Bristow-Campbell model are seen closer to each other, lay between -15 % ~ -20 %. The best value (-13.86 %) is seen in Eindhoven's Bristow-Campbell model, the worst value (-24.22 %) is seen in Allen Model for Maastricht. Ekici models give better performance in MPE analyses. Model 4 performs best in MPE analyses. The best performance is seen in Eindhoven for Model 4. It is thought, the main reason of that situation is caused by using more parameters than other Ekici models. Saturation vapor pressure is an extra parameter in Model 4 to describe solar radiation, which related to average air temperature.

In monthly MPE analyses, Allen model has got higher errors than other models. Bristow-Campbell model shows better monthly MPE performance than Chen model and Hargreaves model. In winter months, models do not fit the measured values as well. It is thought; cloudy days affect to the model performance in prediction of solar radiation with low accuracy. In winter months, the weather conditions may be more complicated, as clouds, precipitation etc. Expression of the solar radiation with mathematical model becomes more difficult in cloudy and complicated weather conditions. Monthly performances of Ekici models are better than the models in literature. Best monthly MPE results are seen in Model 4.

6 Conclusions

Empirical models are usable tools to estimate global solar radiation, if the radiation parameters are not available in the station. Main aim of this study is estimation of the daily total solar global radiation values by using maximum and minimum daily air temperatures and daily average and extreme relative humidity values. The daily data were taken from meteorological agencies of Ireland and Holland. These data are daily total global solar radiation, daily average relative humidity values, daily relative humidity extremes, daily minimum air temperatures and daily maximum air temperatures. Data were selected between 2008 and 2016's first half. It is thought; the recent measurements are more accurate and traceable.

Hargreaves, Allen, Bristow-Campbell and Chen models were applied to the cities for the prediction of the daily total global solar radiation.

In MPE analyses of this study, all of Ekici models show better performances than other models those exist in the literature.

Hargreaves and Allen models have got good agreement in mean bias errors for Dutch and Irish cities, but for Dublin the value of MBE is seen better than other cities' values. The situation of Dublin about MBE values for Bristow-Campbell and Chen models are seem similar as Hargreaves and Allen models. Allen Model's MBE values are greater than other three models' MBE values. Ekici models' MBE values are closer to the MBE values of other models. The greatest value of

MBE in Ekici models is seen in Maastricht for Model 4. RMSE values of all models are seen closer to each other, but in Ekici models RMSE values are a little bit better than others. It can be said; the systematic errors of the models are similar, Ekici models' values are a little bit lesser than others.

Nash-Sutcliffe error analyses were applied to the all models. All of the models' NSE values are greater than 0.80. Ekici models in Eindhoven, Maastricht and Twente show best fits in the study and have got the greatest NSE values.

In this study, four new models that are based on the relative humidity, relative humidity extremes and the difference between maximum and minimum air temperatures were suggested. Model 1 and 3 gives good score in mean bias error. But all of the Ekici models' MBE and RMSE values are closer to each other. NSE values are all of the Ekici models are similar. So it can be said; all of the Ekici models show good agreement between calculated and measured values. All of the four models give better scores in error analyses than the other models that exist in the literature for the estimation of the Irish and Dutch cities' daily total solar global radiation.

Conflict of interest

The author declares that there is no conflict of interest regarding the publication of this article.

References

- Aksoy, B., Rüşen, S. E., Akınoğlu, B. G. (2011). A simple correlation to estimate global solar irradiation on a horizontal surface using METEOSAT satellite images. Turkish Journal of Engineering and Environmental Sciences, 35(2), 125-137.
- Allen, R., (1997). "Self-calibrating method for estimating solar radiation from air temperature", Journal of Hydrologic Engineering, 2(2): 56-67.

- Almorox, J. (2011). Estimating global solar radiation from common meteorological data in Aranjuez, Spain. Turkish journal of physics, 35(1), 53-64.
- Armstrong, S., & Hurley, W. G. (2010). A new methodology to optimise solar energy extraction under cloudy conditions. Renewable Energy, 35(4), 780-787.
- Biemer, P. P., & Lyberg, L. E. (2003). Introduction to survey quality (Vol. 335). John Wiley & Sons.
- Bristow, K. L., & Campbell, G. S. (1984). On the relationship between incoming solar radiation and daily maximum and minimum temperature. Agricultural and forest meteorology, 31(2), 159-166.
- Campbell, G.S., Norman, J.M. (1998). “An introduction to environmental biophysics”, Springer Science & Business Media.
- Cano, D., Monget, J. M., Albuisson, M., Guillard, H., Regas, N., Wald, L. (1986). A method for the determination of the global solar radiation from meteorological satellites data. Solar energy, 37(1), 31-39.
- Chen, R., Ersi, K., Yang, J., Lu, S., & Zhao, W. (2004). Validation of five global radiation models with measured daily data in China. Energy Conversion and Management, 45(11), 1759-1769.
- Hargreaves, G. L., Hargreaves, G. H., & Riley, J. P. (1985). Irrigation water requirements for Senegal River basin. Journal of Irrigation and Drainage Engineering, 111(3), 265-275.
- Gueymard, C. A., Myers, D. R. (2008). Validation and ranking methodologies for solar radiation models. Modeling solar radiation at the earth’s surface, 479-510, Springer, Berlin, Heidelberg.
- Iqbal M. (1983). An Introduction to Solar Radiation. Academic Press, Toronto.
- Menges, H. O., Ertekin, C., & Sonmete, M. H. (2006). Evaluation of global solar radiation models for Konya, Turkey. Energy Conversion and Management, 47(18), 3149-3173.
- Meza, F., & Varas, E. (2000). Estimation of mean monthly solar global radiation as a function of temperature. Agricultural and Forest Meteorology, 100(2), 231-241.