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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

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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).

One of the main purposes of this study is the validation of the several 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.

Met Éireann, the Irish National Meteorological Service, is a line division of the Department of the Environment, Community and Local Government. It is the leading provider of weather information and related services for Ireland.

The Royal Netherlands Meteorological Institute (KNMI) is the Dutch national weather service. Primary tasks of KNMI are weather forecasting, and monitoring of weather, climate, air quality and seismic activity. KNMI is also the national research and information centre for meteorology, climate, air quality, and seismology. KNMI focuses on monitoring and warning for risks with an atmospheric or seismic origin. In addition, KNMI offers advice and strategy prospects for both acute and future dangers. In order to improve future advice and therefore reach risk reduction, we actively seek to learn from past events.

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).

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

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.

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

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).

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

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.

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

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3.4 Chen Model

Chen et al. (2004) presented the model in equation 9.

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

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.

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

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

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.

$$\frac{H}{H_0} = a \cdot [1 - \exp(\{e_s \cdot (T_{max} - T_{min})^{0.5}\}^b)] + c \cdot \frac{RH_{min}}{RH_{max}} \quad (12)$$

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

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

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	Longtitude	Altitude
Dublin	53.423°	-6,238°	71 m
Eindhoven	51.451°	5.377°	22.6 m
Groningen	53.125°	6.585°	5.2 m
Rotterdam	51.962°	4.447°	-4.3 m
Maastricht	50.906°	5.762°	114.3 m

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Twente	52.274°	6.891°	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. $H_{i,m}$ 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).

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

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

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

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. $\bar{H}_m$ is the mean measured global radiation (Menges *et. al*, 2006).

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

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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

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 2. The coefficients were derived by using MATLAB R2015a and Minitab Statistical Software.

Table 2 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

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

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.

Table 3 Error analyses of the Hargreaves model

Location		Monthly MPE	Whole of the model	
Dublin	January	-38.061	MBE	0.02
	February	-20.832	RMSE	3.22
	March	-14.052	MPE	-22.18
	April	-11.314	NSE	0.80
	May	-8.364		
	June	-14.341		
	July	-17.631		
	August	-15.353		
	September	-12.452		
	October	-41.353		
	November	-31.560		
	December	-41.494		
Eindhoven	January	-23.704	MBE	0.21
	February	-21.700	RMSE	2.89
	March	-12.285	MPE	-17.06
	April	-8.681	NSE	0.86
	May	-14.863		
	June	-13.962		
	July	-12.756		
	August	-12.048		
	September	-15.123		
	October	-14.361		
	November	-27.165		
	December	-25.968		
Groningen	January	-34.742	MBE	0.35
	February	-18.449	RMSE	3.07
	March	-13.620	MPE	-18.89
	April	-8.559	NSE	0.844
	May	-14.581		
	June	-15.865		
	July	-11.197		
	August	-13.164		
	September	-17.897		
	October	-25.430		
	November	-28.266		
	December	-25.459		
Maastricht	January	-26.767	MBE	0.22
	February	-22.254	RMSE	2.94
	March	-15.592	MPE	-20.46
	April	-11.914	NSE	0.86
	May	-16.599		
	June	-17.894		

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	July	-15.036		
	August	-13.171		
	September	-14.800		
	October	-20.179		
	November	-27.354		
	December	-45.167		
Rotterdam	January	-32.303	MBE	-0.01
	February	-29.201	RMSE	3.19
	March	-13.401	MPE	-19.78
	April	-7.483	NSE	0.84
	May	-13.943		
	June	-11.204		
	July	-10.658		
	August	-10.848		
	September	-15.424		
	October	-25.473		
	November	-34.461		
	December	-34.136		
Twente	January	-25.681	MBE	0.22
	February	-22.185	RMSE	3.06
	March	-12.945	MPE	-18.32
	April	-10.124	NSE	0.84
	May	-18.467		
	June	-15.587		
	July	-14.841		
	August	-15.441		
	September	-16.108		
	October	-18.629		
	November	-24.909		
	December	-25.613		

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 5. 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

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210 **Table 5** Error analyses of Allen model

Location		Monthly MPE	Whole of the model	
Dublin	January	-38.507	MBE	-0,02
	February	-21.173	RMSE	3,24
	March	-13.993	MPE	-22,19
	April	-11.070	NSE	0,80
	May	-8.075		
	June	-13.786		
	July	-17.252		
	August	-15.013		
	September	-12.390		
	October	-41.641		
	November	-32.044		
	December	-41.987		
Eindhoven	January	-36.444	MBE	-0.24
	February	-30.261	RMSE	3.11
	March	-13.986	MPE	-19.20
	April	-3.287	NSE	0.84
	May	-12.722		
	June	-8.941		
	July	-10.254		
	August	-8.647		
	September	-11.853		
	October	-16.067		
	November	-38.415		
	December	-40.400		
Groningen	January	-45.674	MBE	-0.23
	February	-25.194	RMSE	3.21
	March	-14.749	MPE	-20.46
	April	-4.751	NSE	0.83
	May	-11.963		
	June	-11.910		
	July	-8.204		
	August	-9.629		
	September	-15.218		
	October	-27.360		
	November	-37.143		
	December	-34.041		
Maastricht	January	-45.347	MBE	-0.38
	February	-36.250	RMSE	3.29
	March	-17.914	MPE	-24.22
	April	-6.889	NSE	0.82
	May	-13.008		
	June	-11.612		
	July	-10.268		
	August	-7.599		

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	September	-11.910		
	October	-22.050		
	November	-42.285		
	December	-66.486		
Rotterdam	January	-41.692	MBE	-0.34
	February	-35.084	RMSE	3.34
	March	-13.571	MPE	-21.32
	April	-3.626	NSE	0.82
	May	-12.121		
	June	-8.053		
	July	-8.785		
	August	-8.523		
	September	-13.645		
	October	-27.340		
	November	-41.934		
	December	-42.664		
Twente	January	-37.525	MBE	-0.17
	February	-29.122	RMSE	3.18
	March	-14.001	MPE	-19.99
	April	-5.542	NSE	0.83
	May	-14.504		
	June	-10.647		
	July	-11.175		
	August	-12.255		
	September	-13.571		
	October	-20.498		
	November	-34.708		
	December	-37.001		

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 6 for the estimation of the daily total global solar radiation in Ireland and Holland.

Table 6 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 7. NSE value can be assumed as acceptable. Some of

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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.

Table 7 Error analyses of Bristow-Campbell model

Location		Monthly MPE	Whole of the model	
Dublin	January	-37.256	MBE	0.03
	February	-20.188	RMSE	3.22
	March	-13.768	MPE	-21.81
	April	-11.149	NSE	0.80
	May	-8.306		
	June	-14.489		
	July	-17.660		
	August	-15.368		
	September	-12.175		
	October	-40.657		
	November	-30.748		
	December	-40.631		
Eindhoven	January	-17.552	MBE	0.12
	February	-16.621	RMSE	2.85
	March	-10.278	MPE	-13.86
	April	-7.904	NSE	0.86
	May	-13.163		
	June	-12.926		
	July	-12.312		
	August	-11.762		
	September	-13.168		
	October	-10.953		
	November	-21.150		
	December	-19.429		
Groningen	January	-32.0205	MBE	0.11
	February	-16.228	RMSE	3.05
	March	-12.427	MPE	-17.65
	April	-8.362	NSE	0.85
	May	-14.272		
	June	-15.520		
	July	-10.861		
	August	-12.845		
	September	-17.167		
	October	-23.721		
	November	-25.838		
	December	-23.074		
Maastricht	January	-20.244	MBE	0.24
	February	-17.202	RMSE	2.91
	March	-12.745	MPE	-17.65
	April	-12.227	NSE	0.86
	May	-16.204		
	June	-17.867		
	July	-14.500		
	August	-13.061		

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	September	-13.336		
	October	-17.095		
	November	-21.225		
	December	-37.184		
Rotterdam	January	-23.510	MBE	0.09
	February	23.125	RMSE	3.17
	March	-11.610	MPE	-17.02
	April	-8.831	NSE	0.84
	May	-13.676		
	June	-11.797		
	July	-10.555		
	August	-11.245		
	September	-15.239		
	October	-22.519		
	November	-27.176		
	December	-26.169		
Twente	January	-37.525	MBE	-0.17
	February	-29.122	RMSE	3.18
	March	-14.001	MPE	-19.99
	April	-5.543	NSE	0.83
	May	-14.505		
	June	-10.647		
	July	-11.175		
	August	-12.255		
	September	-13.571		
	October	-20.498		
	November	-34.708		
	December	-37.000		

6.4 Chen Model

Chen model's empirical coefficients are seen in Table 8.

Table 8 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 9. Also, the monthly MPE analysis is shown in table.

Table 9 Error analyses of Chen model

Location		Monthly MPE	Whole of the model	

Dublin	January	-36.680	MBE	0.01
	February	-20.583	RMSE	3.25
	March	-12.998	MPE	-21.59
	April	-9.803	NSE	0.80
	May	-8.268		
	June	-14.297		
	July	-18.558		
	August	-16.293		
	September	-11.417		
	October	-39.952		
	November	-30.568		
	December	-40.496		
Eindhoven	January	-21.837	MBE	0.17
	February	-20.914	RMSE	2.98
	March	-14.049	MPE	-16.83
	April	-8.623	NSE	0.85
	May	-14.085		
	June	-14.082		
	July	-13.721		
	August	-13.726		
	September	-16.830		
	October	-15.798		
	November	-26.121		
	December	-23.303		
Groningen	January	-32.959	MBE	0.09
	February	-18.642	RMSE	3.15
	March	-13.912	MPE	-18.87
	April	-8.518	NSE	0.84
	May	-13.705		
	June	-16.450		
	July	-11.113		
	August	-13.522		
	September	-19.326		
	October	-27.241		
	November	-27.246		
	December	-24.593		
Maastricht	January	-20.563	MBE	0.37
	February	-17.567	RMSE	3.05
	March	-16.768	MPE	-20.01
	April	-12.301	NSE	0.85
	May	-17.037		
	June	-20.378		
	July	-17.256		
	August	-15.340		
	September	-18.403		
	October	-23.050		
	November	-23.829		
	December	-39.248		
Rotterdam	January	-30.659	MBE	-0.03
	February	-29.140	RMSE	3.22
	March	-14.228	MPE	-19.65
	April	-7.401	NSE	0.83
	May	-13.046		
	June	-11.287		
	July	-10.569		

	August	-11.742		
	September	-16.618		
	October	-26.414		
	November	-33.475		
	December	-32.638		
Twente	January	-23.901	MBE	0.18
	February	-23.060	RMSE	3.17
	March	-13.966	MPE	-18.31
	April	-10.164	NSE	0.83
	May	-18.233		
	June	-15.642		
	July	-14.539		
	August	-16.079		
	September	-17.899		
	October	-20.544		
	November	-22.554		
	December	-23.844		

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 10. 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 10 Empirical coefficients for Ekici models

#	Location	"a" coefficient	"b" coefficient	"c" coefficient	"d" coefficient	"e" coefficient
Model 1 (Eq. 10)	Dublin	-1.092	-0.0333	0.009703	0.1331	1.007
	Eindhoven	-1.224	-0.1198	0.01446	0.2098	1.091
	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
Model 2 (Eq. 11)	Dublin	-0.4202	0.09728	-0.007322	-	-
	Eindhoven	-0.3242	0.1198	-0.00599		
	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		
Model 3 (Eq. 12)	Dublin	-0.6164	-0.02444	-0.920	-	-
	Eindhoven	-0.5782	-0.01691	-0.9104		
	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		
Model 4 (Eq. 13)	Dublin	-0.1046	0.3166	-0.21034	0.166	-
	Eindhoven	$4.47 \cdot 10^{-6}$	-2.000	0.130	0.202	
	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 11. 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 11 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					
Gr	January	-15.920	-17.355	-19.812	-11.472	MBE	0.19	0.22	0.15	-0.18

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	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. This graphic is given in Figure 1; it may be give idea about the models' daily trends. If you look at the daily trends of the models in the literature, it is seen that these models have more scattered errors. But in developed

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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 same tendency in general.

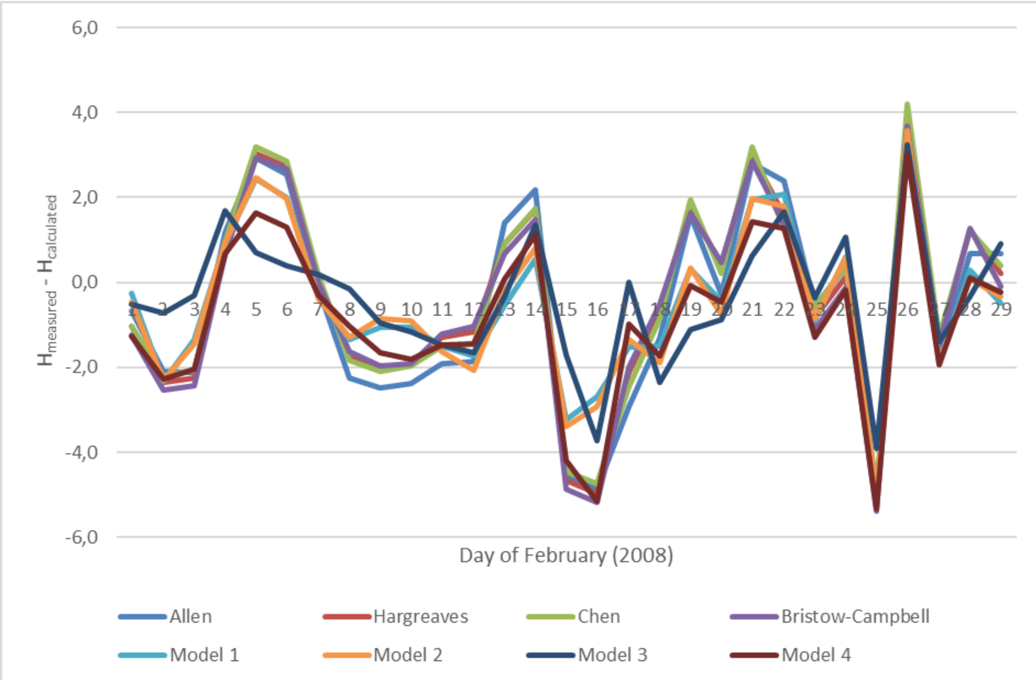

Figure 1 Differences between measured and calculated daily total global solar radiation values in February 2008

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.

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). 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.

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. 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.

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Whole of the model mean percentage errors of models will be discussed. 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 MPE analyses of this study, all of Ekici models show better performances than other models those exist in the literature. 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. Monthly performances of Ekici models are better than the models in literature. Best monthly MPE results are seen in Model 4.

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.

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Conflict of interest

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

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