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ESTIMATION OF DAILY GLOBAL AND DIFFUSE RADIATION FOR BRAŞOV URBAN AREA, ROMANIA

Elena EFTIMIE
Transilvania University of Braşov, Romania

Abstract. In order to calculate the performance of an existing solar energy conversion system or to estimate the energy generated by this, from the design stage, appropriate weather data are required. Unfortunately, there are not always recorded meteorological data, for all areas, what makes necessary the use of some solar radiation estimation methods. In this way, the conceiving of some mathematical models is required, if it is possible simple models, easy to implement in renewable systems design software or in building energy simulation software; thus, the determination of solar radiation data is important for studies.

The proposed study is carried out in order to develop the monthly Ångström –Prescott equation coefficients from measured daily data for Braşov urban area and also to develop a monthly model for the diffuse radiation from daily clearness index. The models performance was evaluated by calculating three important statistical indicators: Mean Bias Error (MBE), Root Mean Square Error (RMSE) and t-statistic.

The RMSE, MBE (and Mean Percentage Error, MPE) and t-statistic are the most used statistical indicators for the comparison and performance estimation of the solar irradiation models. These calculated statistical indicators concerning the total and diffuse radiations are very good for the proposed estimation models and all the conclusions are very useful in the solar energy conversion systems design.

Keywords: Ångström –Prescott equation, total and diffuse radiation, MBE, RMSE, t-statistic

1. Problem description

The determination of solar radiation data is important because this represents the main input for many solar energy applications such as photovoltaic systems for electricity generation, solar collectors for heating, solar air conditioning climate control in buildings and passive solar devices. The proposed study is carried out in order to develop an accurate estimation model of the solar radiation (total and diffuse components).

Information on solar irradiance on the earth's surface is necessary for application of solar energy, for the determination of the amount of spectral global irradiance for the photovoltaic cells designing and for the selective absorbers for spectral thermal collectors.

The renewable systems design software and building energy simulation software for energy efficient buildings, use as a main input the solar radiation. The implementation of such systems in the urban environment requires accurate meteorological data for the interest area. The existence of a small number of weather stations that to offer data with regard to solar radiation as well as the limited access to these, make necessary the conceiving of some accurate estimation mathematical models for all solar radiation components [1, 2].

The branch literature offers a series of simple models for the radiation description: Hottel model for the direct component of the radiation; Bugler model for the diffuse component; Haurwitz, Adnot-Bourges-Campana-Gicquel and Kasten-Czeplak models for the global radiation [3].

The main advantage of these models is their simplicity (these models have as input parameters only the location and time marks), that makes them easy to use in practice.

However, these models are the most of time specific to a single location due to their derived method (these are empirical models obtained on the basis of local measurements).

The main input parameter of this kind of models, is the solar altitude angle, and this leads to a symmetrical radiation function.

Thus, using the empirical models the maximum radiation value is always obtained for the solar hour equal to 12; this is in fact the value corresponding to the maximum value of the solar altitude angle obtained during a day.

Moreover, a symmetrical variation means equal values of the radiation at the sunrise and sunset, which is not really true; the radiation values at the sunrise start from 0 but at the sunset is almost always higher (always for a clear sky day) [1, 2].

Braşov city (latitude 45.39°, longitude 25.35°) is a medium size town with a relative high pollution level. Braşov is a basin area characterized by a continental temperate climate, more precisely, a transition type between oceanic and temperate climate. The physical and geographical conditions extend the temperature inversion phenomena [4]; because of this, the temperature no longer decreases with altitude but increases.

Considering the period 2006-2011, January was the coldest month in Braşov with average temperature between –5.25°C and –2.11°C. The highest temperature was recorded in July 2006 and it was of 35.85 °C; the lowest temperature was –20.03 °C and it was recorded in January 2010.

In this context, the radiation modelling must take into consideration the geographical and climatic features of every site as well the influence of the urban conditions (if it is the case).

For the determination of an estimation model and for its validation, a meteorological database of five years measurements was used (2006-2010). The local weather station Delta-T, is positioned on the roof of the Transilvania University of Braşov (Romania). A series of data have been collected since October 2005 up to the present; they comprise:

- global solar radiation [W/m^2],
- diffuse solar radiation [W/m^2],
- air temperature [°C], wind speed [m/s],
- wind direction [degrees],
- relative humidity [%],
- rainfall [pluviometric mm],
- sunshine.

From this study point of view, we are interested in horizontal global radiation and diffuse radiation measurements; all recorded data are related to 10 minutes range, in a continuous way.

2. Method used

The most solar radiation estimation studies are based on the Ångström correlation (1924) of global solar radiation, expressed as a fraction of solar radiation and daily maximum possible sunshine fraction (n/N) [3, 5, 6]:

$$H / H_{clear\_sky} = a + b \cdot n / N \, , \qquad (1)$$

where, H_{clear_sky} represents the monthly average of the daily global radiation on a horizontal surface [kWh/m^2/day], assuming clear sky; a and b represent the regression constants determined empirically.

Commonly used correlation is due to Prescott (1940):

$$H / H_0 = a + b \cdot n / N \, , \qquad (2)$$

where, H_0 represents the monthly average of the extraterrestrial global radiation on a horizontal surface [kWh/m^2 / day].

For the determination of daily Ångström – Prescott equation coefficients, algorithm stages are the following:

- in the first stage the daily global radiation on a horizontal surface (measured data – H_g), daily extraterrestrial radiation on a horizontal surface (H_0), daily diffuse radiation on a horizontal surface (measured data – H_{dif}), daily sunshine number of hours (n) and maximum daily sunshine duration (N) must be calculated;
- the coefficients of the Ångström–Prescott equation are calculated from regression analysis between H_g/H_0 and n/N; the regression coefficients are determined for each month;
- from regression analysis between H_{dif}/H_g and H_g/H_0, the regression coefficients of the daily diffuse radiation equations, for each month, is obtained.

Thus, the regression coefficients are determined and are specific to every month only for Braşov urban area. Twelve monthly-specific equations for H/H_0 and H_d/H are resulted (H and H_d represent the daily estimated global and diffuse radiation); for a certain day from a month the daily global and diffuse radiation can be determine using the monthly-specific equation (knowing the ratio of daily possible sunshine).

There are needed twelve monthly-specific equations so that to taken into consideration the specific climatological and geographical conditions of the site. Braşov is an urban depression located in a temperate zone with four seasons and important meteorological differences between them.

3. Results and discussions

3.1. Estimating solar radiation

In Table 1, there are presented the monthly-specific Ångström-Prescott correlations; these equations are obtained from the daily data during 2006-2010. The monthly-specific equations for the daily diffuse radiation estimation are presented in Table 2. Using the estimation equations proposed for the global and diffuse radiation (daily values), the graphical comparison between the measured and estimated values is achieved (Figure 1).

Table 1. Regression coefficients of the Ångström-Prescott equation for Braşov urban area

Month	Equation
January	$H/H_0 = 1.283(n/N)^3 - 1.876(n/N)^2 + 1.243(n/N) + 0.161$
February	$H/H_0 = 0.931(n/N)^3 - 1.511(n/N)^2 + 1.138(n/N) + 0.178$
March	$H/H_0 = 0.595(n/N)^3 - 1.051(n/N)^2 + 0.987(n/N) + 0.168$
April	$H/H_0 = 0.710(n/N)^3 - 1.173(n/N)^2 + 1.038(n/N) + 0.159$
May	$H/H_0 = 0.333(n/N)^3 - 0.690(n/N)^2 + 0.894(n/N) + 0.165$
June	$H/H_0 = 0.275(n/N)^3 - 0.492(n/N)^2 + 0.771(n/N) + 0.177$
July	$H/H_0 = 0.475(n/N)^3 - 1.01(n/N)^2 + 1.092(n/N) + 0.135$
August	$H/H_0 = 0.750(n/N)^3 - 1.207(n/N)^2 + 1.037(n/N) + 0.154$
September	$H/H_0 = 0.893(n/N)^3 - 1.544(n/N)^2 + 1.216(n/N) + 0.149$
October	$H/H_0 = - 0.372(n/N)^2 + 0.83(n/N) + 0.162$
November	$H/H_0 = - 0.473(n/N)^2 + 0.901(n/N) + 0.153$
December	$H/H_0 = - 0.449(n/N)^2 + 0.868(n/N) + 0.139$

In Figures 2, there are presented: daily measured global radiations versus daily simulated global radiations; daily measured diffuse radiations versus daily simulated diffuse radiations.

From the study of these diagrams, it can be noticed that the proposed models work correctly for global radiation; the graphs reveal a greater spreading of the real recorded values, especially for lower values (less than 2 kW/m^2).

Regarding the diffuse radiation, its modelling is very difficult because this represents an area of discontinuity between the Oriental and Meridional Carpathians and the occurrence of radiative-orographic fogs and cloudiness causes the temperature inversion. Thus, from the daily diffuse radiation point of view the graphs reveal a greater spreading of all real recorded diffuse radiation values.

Table 2. Regression coefficients of the diffuse radiation equation for Braşov urban area

Month	Equation
January	$H_d/H = -1.515(H/H_0)^2 + 0.013(H/H_0) + 0.908$
February	$H_d/H = -2.35(H/H_0)^2 + 0.512(H/H_0) + 0.860$
March	$H_d/H = -1.594(H/H_0)^2 - 0.028(H/H_0) + 0.907$
April	$H_d/H = -0.940(H/H_0)^2 - 0.518(H/H_0) + 0.969$
May	$H_d/H = -0.389(H/H_0)^2 - 0.96(H/H_0) + 1.036$
June	$H_d/H = -0.331(H/H_0)^2 - 0.953(H/H_0) + 1.007$
July	$H_d/H = -0.418(H/H_0)^2 - 0.880(H/H_0) + 0.997$
August	$H_d/H = -1.092(H/H_0)^2 - 0.395(H/H_0) + 0.934$
September	$H_d/H = -1.625(H/H_0)^2 - 0.039(H/H_0) + 0.919$
October	$H_d/H = -1.921(H/H_0)^2 + 0.152(H/H_0) + 0.897$
November	$H_d/H = -1.370(H/H_0)^2 - 0.228(H/H_0) + 0.937$
December	$H_d/H = 9.078(H/H_0)^3 - 10.21(H/H_0)^2 + 2.344(H/H_0) + 0.719$

However, high values of the coefficients of determination across the variables are recorded; thus for the global radiation, it was obtained R^2 = 0.975 and for the diffuse radiation modelling R^2 = 0.8493. The high values of the correlation coefficients (r = 0.987 for global radiation modelling and r = 0.922 for the diffuse radiation) reveals the fact that these two models are applicable with great accuracy.

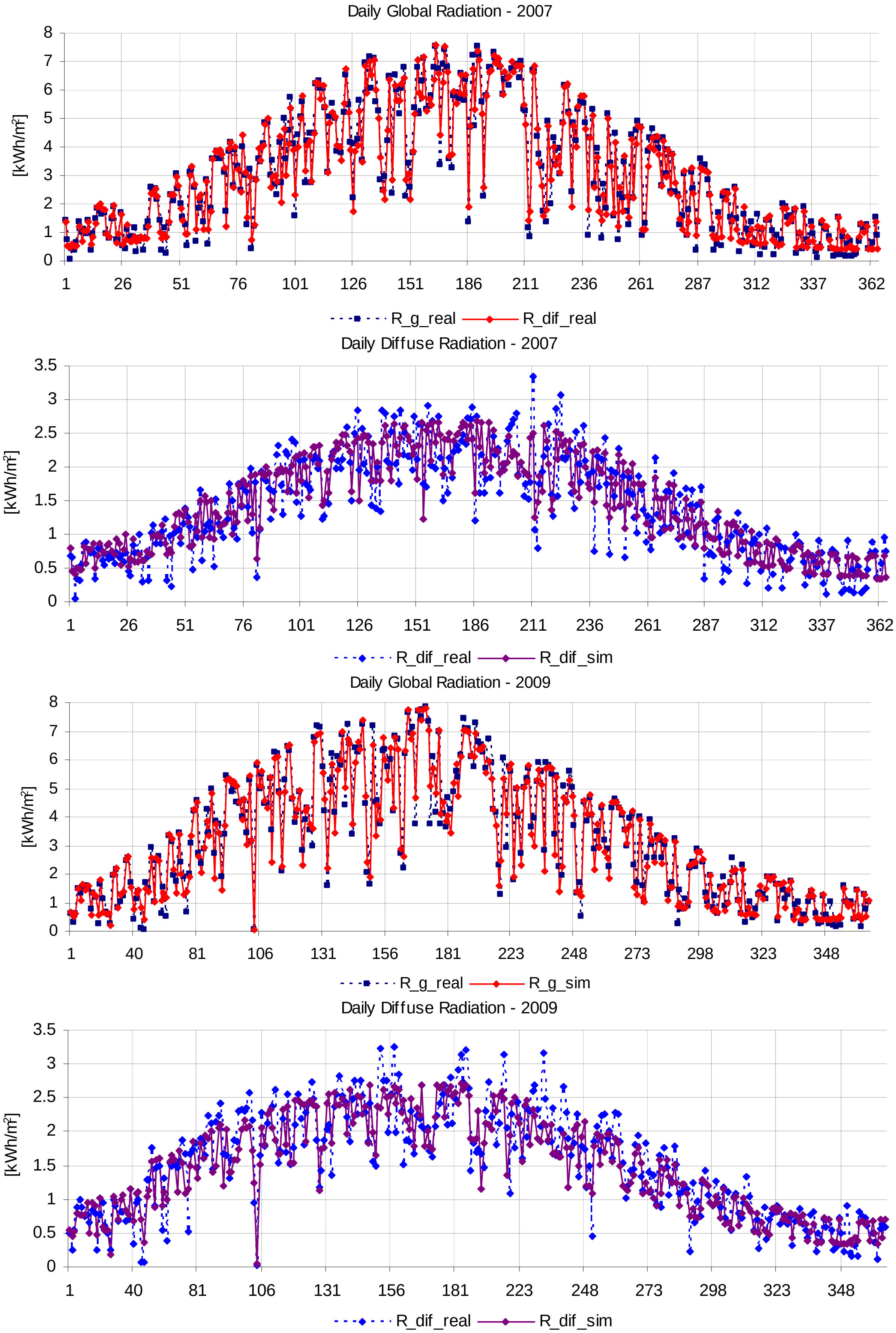

Figure 1. Estimated and real daily solar radiation (R_g – global radiation; R_dif – diffuse radiation)

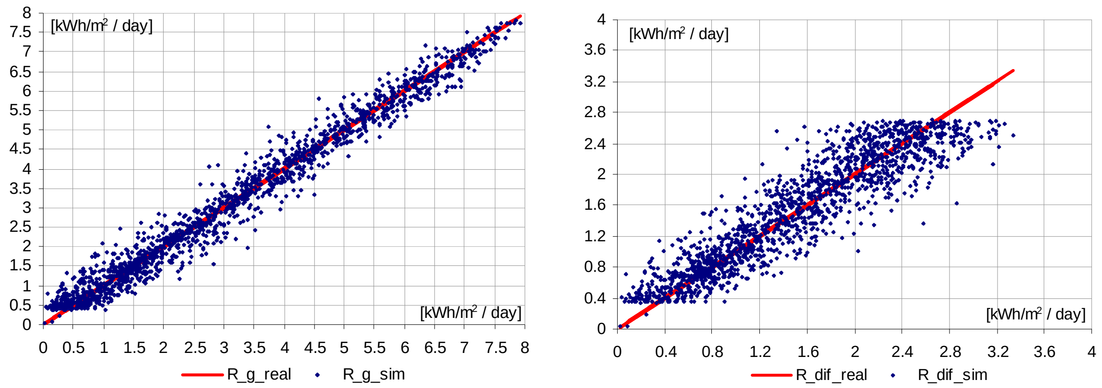

Figure 2. Estimated versus real daily values for the horizontal global and diffuse radiation

3.2. Models performance

For the models performance estimation, three of the most important statistical indicators (Root Mean Square Error (RMSE), Mean Bias Error (MBE), *the Mean Percentage Error (MPE)* and t-values) were calculated [3, 5, 6].

The MBE (MPE), RMSE and *t-values* were determined using measured data of global and diffuse solar radiations on horizontal surface recorded with the Delta-T weather station for the period between 2006 and August 2010.

The values of the statistical indicators (MBE, RMSE and *t-statistic*) applied to validate the models performances, for the entire database, are presented in Table 3 and Table 4.

Figure 3 presents the MBE monthly values, for diffuse and global radiations (daily values), calculated for every year between 2006 and August 2010; the MBE, RMSE and *t-statistic* (monthly values) for the entire five-year database are presented in Figure 4, Table 3 and Table 4.

The highest MBE values were recorded for the diffuse radiation (five years database). As it can be seen, the Mean Bias Errors for the diffuse component of the solar radiation are between 0 and 0.025 kWh/m^2/day, depending on the season month.

Regarding the global solar radiation, the MBE values are between -0.0025 and 0.006 kWh/m^2/day. These values indicated that the percentage error for a single month is between –0.13% and 0.2% (monthly values for the entire database).

The comparison between the modelled radiation components (global and diffuse) and the measured ones, leads to the conclusion that, the highest MBE values were obtained for the diffuse solar radiation during the period June-September (a different conclusion can be worded when the errors are expressed as percentages (MPE), the period being between December and February).

Table 3. Statistical parameter values (MBE, RMSE, t-statistic) - Global radiation estimation

Month	RMSE [kWh/m^2]	MBE [kWh/m^2]	t
January	0.20021	-0.00140	0.08298
February	0.28500	-0.00163	0.06402
March	0.33119	-0.00206	0.07698
April	0.35647	-0.00199	0.06825
May	0.38284	0.00050	**0.01627**
June	0.42704	-0.00165	0.04560
July	0.39448	-0.00163	0.04831
August	0.40043	-0.00080	**0.02458**
September	0.31364	0.00666	0.23151
October	0.23412	0.00357	0.16833
November	0.19438	-0.00052	**0.02916**
December	0.17567	-0.00096	0.06072

Table 4. Statistical parameter values (MBE, RMSE, t-statistic) – Diffuse radiation estimation

Month	RMSE [kWh/m^2]	MBE [kWh/m^2]	t
January	0.17483	0.01269	0.86119
February	0.24920	0.01957	0.88062
March	0.30140	0.02173	0.89395
April	0.32748	0.01823	0.68038
May	0.33308	0.01769	0.65993
June	0.35998	0.02376	0.77987
July	0.37882	0.02300	0.71205
August	0.38317	0.02418	0.77954
September	0.27200	0.02413	**0.97172**
October	0.22907	0.00830	0.40035
November	0.15835	0.00163	**0.11198**
December	0.16286	0.00931	0.63509

Regarding the level of scatter that the models produce, the maximum RMSE values are obtained for global radiation during the June, July and August, and for the diffuse radiation during the same period.

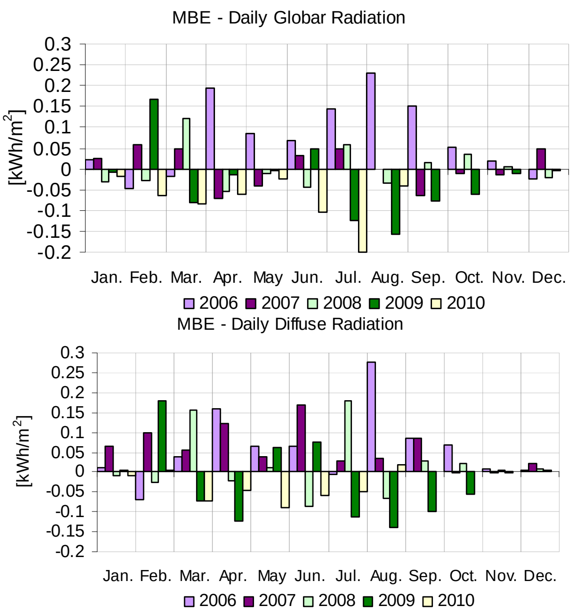

Figure 3. Monthly values of the MBE calculated for diffuse and total solar radiation

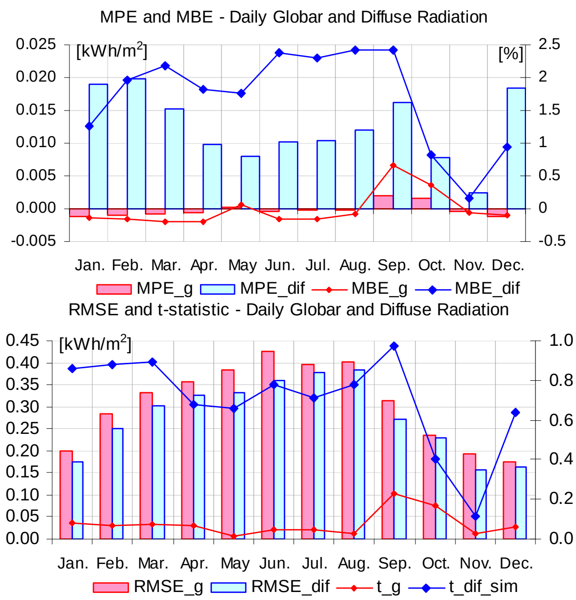

Figure 4. Monthly errors – average on 4 years

The t-values are calculated for both proposed models. The highest *t-values* were obtained when the estimation was achieved for the diffuse radiation. The highest value was 0.97, recorded for September and this is lower than the than the critical *t-value*, obtained from standard statistical tables (*t_critical* at 5% is 1.645).

Considering all the months, the calculated t-values are less than the critical *t-value*, showing that the equations have statistical significance for all months. The best performance can be found by selecting the lowest *t-values*. Period January-August and November-December are the months with the best performance considering the model for the global radiation; for the diffuse radiation model, the best performance was recorded for November.

According to the models performance study, the models fitted the data adequately and can be used to estimate the daily values of global and diffuse solar radiations. As a conclusion, it can be asserted that the proposed models application for Braşov urban area leads to very good results. The superimposed real and estimated diagrams proved that the proposed models are efficient models in daily solar radiation simulation (global and diffuse radiation) for Braşov urban area.

4. Conclusions

The main issues in the renewable systems design is the radiation modelling and finding of a more accurate relation of this. This paper proposed the daily estimation of the global and diffuse radiation; the equations are monthly-specific functions and have as input parameter the daily fractional sunshine.

The models performance was evaluated with the following statistical indicators: the root mean square error (RMSE), the mean bias error (MBE) (and also mean percentage error (MPE)) and *t-statistic*.

The calculated values of these statistical indicators, concerning the global and diffuse radiations (daily values) are very good for the proposed estimation models.

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