Environmental Engineering and Management Journal

March 2018, Vol.17, No. 3, 661-674
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu

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ESTIMATION OF REAL-SKY GLOBAL AND DIFFUSE RADIATION FOR BRAŞOV URBAN AREA, ROMANIA

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Abstract

This paper proposes a study on the estimation of daily solar irradiation (global and diffuse irradiation) under real-sky conditions and the validation of proposed estimation models by analyzing the most important statistical indicators. Two types of regressions are proposed for the estimation of solar daily global irradiation; the first type is based on the second order degree Ångström-Prescott correlations; the second type uses the second order Ångström-Prescott correlations only for days with sunshine fraction values higher than 0.1; for days with sunshine fraction values less than 0.1, there are developed regressions depending on sunshine fraction, air temperature and amount of precipitable water. Based on the two types of models for estimating daily global irradiation, regressions to estimate the daily diffuse irradiation will also be determined. The particularization of regression coefficients is performed for basin urban area of Braşov (Romania). The proposal of some correlations having as input data, the air temperature and the amount of precipitable water was based on the following reasons: solar radiation is the main climatic factor that causes changes in other climatic parameters and the multitude of radiative factors, dynamic factors, physical-geographical factors and even those economical-geographical contribute to the individualization of Braşov urban area, giving this, its own characteristics. Finally, the statistical analysis is developed and the performances comparison of estimation models is achieved.

Key words: air temperature, daily solar irradiation, precipitable water amount, statistical analysis, sunshine fraction

Received: January, 2014; Revised final: July, 2014; Accepted July, 2014; Published in final edited form: March 2018

1. Introduction

The most important climatic parameters, with a significant influence in the design of solar energy conversion systems are solar radiation, wind speed, air temperature and humidity. From these parameters, solar radiation represents the main input, both in building energy simulation and in the systems design of solar energy conversion into thermal energy or electricity. In this context, this paper proposes the development of accurate models for estimating daily solar irradiation under real-sky conditions; the estimations of global and diffuse daily irradiation will be achieved for geographic and climatic conditions specific to Braşov (Romania) located in a depression urban area. The solar radiation is dependent on a number of factors such as: the latitude and the altitude of location, season, date, time, dust content, water vapor and aerosols from air. In addition, the current trend of assembling the solar energy conversion systems in urban areas requires the assessment of solar radiation in specific conditions of such an area. It is envisaged that an urban area represents an important climatic factor with a great influence on the climate and in urban areas, the atmospheric urban pollution can lead to an attenuation of solar radiation (Capsa et al., 2016; De Jong and Stewart, 1993; Meza and Varas, 2000).

Over the world, due to the small number of weather stations equipped with accurate sensors for solar radiation measuring, for many sites, the input data regarding the solar radiation are performed from estimations using mathematical models. In addition, a weather station that performs measurements and records data, because of its location, it can provide input data (in view of the design of solar energy conversion systems) only for relatively close geographical locations. Thus, it is necessary to develop accurate mathematical models to estimate the solar radiation in the premises of real-sky.

The study achieved by this paper proposes the modeling of the global and diffuse daily irradiations under real-sky conditions; of all solar radiation components, the greatest difficulties have been encountered to the estimation of diffuse radiation, given the fact that we refer to a depression urban area. As this paper will highlight, the estimation of diffuse radiation leads – at statistical testing – to the lowest values of Pearson's coefficient although the t-distribution indicator values have validated these models and the level of MBE (Mean Bias Error) indicator is relatively low. Considering this aspect, it is needed to develop urban climatology and to establish the city's role as a driving factor of its own climate. It is noted that, the values of diffuse fraction (the ratio between the diffuse radiation and global radiation) are specific to the analyzed area and this exerts an important influence on the amount of radiation on a capturing surface.

The most studies use for global solar radiation estimation, under real-sky conditions, the linear regression given by Ångström (1924); this model correlates the global solar radiation (on a horizontal surface) depending on the sunshine fraction and global radiation calculated considering clear-sky assumption.

The most generally used correlation is the modified version of Prescott (1940), where global radiation under clear-sky conditions was replaced by the extraterrestrial global radiation on a horizontal surface.

Also, for estimating global radiation, the literature provides models based on the second order or third order forms of the Ångström-Prescott correlation (Bakirci, 2009; Fagbenle, 1990; Ogolo, 2010; Udo, 2002). The determination of some estimation models depending on the sunshine fraction makes necessary the existence of recorded data regarding the sunshine duration; unfortunately, not all-weather stations have the possibility to measure sunshine duration.

Under these conditions a solution – to develop models for estimating global radiation – is to get correlations based on climatic available parameters offered by the meteorological equipment. Given the fact that most weather stations provide data on air temperature, relative humidity and rainfall, the literature offers a series of solar radiation estimation models that have as input data these meteorological parameters. In this respect, some methods for estimating global solar radiation are mentioned:

- the most estimation models have as input data the air temperature (maximum, minimum and/or average temperature); there are models such as those proposed by Abraha and Savage (2008), Annandale et al. (2002), Bristow and Campbell (1984), Donatelli and Campbell (1998), Goodin et al. (1999), Hargreaves and Samani (1982), Mahmood and Hubbard (2002), Meza and Varas (2000);
- estimations based on air temperatures and precipitation (Bindi and Miglietta, 1991; De Jong and Stewart, 1993; Winslow et al., 2001);
- correlations based on air temperature, precipitation and relative humidity (Thornton and Running, 1999);
- models based on air temperature and relative humidity (Rehman and Mohandes, 2008);
- models based on air temperature, relative humidity, sea level pressure, vapor pressure and sunshine duration (Trabea and Shaltout, 2000);
- models that use cloudiness as input data (Bădescu, 2002; Gul et al., 1998; Lam and Li, 1998);
- models that take into consideration the extinction processes in the atmosphere; we mention the model presented in Yang et al. (2006), model based on sunshine duration, surface pressure, precipitable water, ozone thickness and Ångström turbidity coefficient;
- models based on sunshine hour and air pollution index (Zhao et al., 2013).

Among the papers with the objective to estimate the diffuse solar radiation, there are mentioned researches of Li et al. (2011), Pandey and Katiyar (2009) and Ulgen and Hepbasli (2009). The most estimations of diffuse radiation are regressions based mainly on sunshine duration.

Regarding the researches for Romania area, we mention the models for estimation solar radiation under clear-sky conditions presented by Coste and Eftimie (2011), Nemeş and Istrate (2013), Paulescu (2005) and estimations under real-sky conditions presented by Paulescu (2005). However, there must be mentioned a series of studies regarding the aerosols monitoring from Aerosol Robotic Network (AERONET), studies that can be directly related to the estimation of solar radiation in Romania (Ajtai et al., 2013; Unga et. al., 2013).

This paper aims to estimate solar radiation for an urban basin area, where the sunshine duration is diminished due to the geographical conditions and the number of cloudy days during a year is relatively high; in these circumstances the estimation of global radiation using Ångström-Prescott relationship (correlations of second order) may lead to a good estimation only for sunny days characterized by high values of sunshine fraction.

Therefore, the use of second order Ångström-Prescott correlations to estimate global radiation, for days with any value of sunshine fraction can lead to an increase of statistical indicators values at performance estimation of these models (the Mean Bias Error – MBE, the Mean Percentage Error – MPE, the Root Mean Square Error – RMSE and t-distribution), although these models accurately estimate the global solar radiation for days whose sunshine fraction values are high.

Taking into consideration those above, this paper proposes two methods to estimate daily solar irradiation, namely:

- the determination of regression coefficients for daily global irradiation by means of second order Ångström-Prescott correlations (regardless of sunshine fraction value);

- the determination of regression coefficients for daily global irradiation by means of second order Ångström-Prescott correlations, for days with values of sunshine fraction higher than 0.1, and for cloudy days characterized by sunshine fraction values less than 0.1, the determination of some regressions depending on sunshine fraction, air temperature and the amount precipitable water.

Observation

The choice of the sunshine fraction value of 0.1 – as criterion for developing different estimation regressions – represents a result of preliminary researches; this is the value for what the monthly values of Pearson coefficient have the highest values.

Considering the two proposed methods of global daily irradiation estimation, adequately, two models for diffuse daily irradiation estimation will result.

In order to determine the correlations for estimating radiation on cloudy days, the major impact of the amount of water vapor in the atmosphere on solar radiation was considered (this is directly influenced by temperature and relative humidity). Also, to the choice of input data for the second method, it was taken into account (besides the need of available weather data) the fact that the models are destined to estimate solar radiation for a basin area characterized by: annual average humidity values of 75%, temperature inversion phenomenon, spring and autumn mornings characterized by fog and periods with high nebulosity.

The set of radiative, dynamic and physical-geographical factors and even those economic-geographical contribute to the climatic individualization of Braşov urban area, giving to this its own characteristics.

Taking into consideration the above mentioned, this study proposes to estimate solar daily irradiation using two approaches:

- the determination of the coefficients for Ångström-Prescott regression (these are characteristic for each month) using regressions of the type, (Eq. 1).

$$H/H_0 = function\left((n/N)^2, n/N\right) \tag{1}$$

to estimate global daily irradiation; the determination of regression coefficients (characteristic for each month) for the estimation equations of diffuse daily irradiation, using regressions of the type, (Eq. 2)

$$H_{dif}/H = function\left((H/H_0)^2, H/H_0\right) \tag{2}$$

- the determination of regressions for estimating global and diffuse daily irradiation using the same types of regressions as above mentioned, but these are applied only for the days when sunshine fraction values are higher than 0.1; for the days characterized by sunshine fraction values less than 0.1, there will be determined the regression coefficients of some regressions of the type, (Eq. 3)

$$H/H_0 = function\left(n/N, (T_{max} - T_{min})^{0.5}, w\right) \tag{3}$$

where: T_{max} and T_{min} are the maximum and minimum daily temperatures, w is the amount of precipitable water, and (Eq. 4)

$$H_{dif} = function\left((H/H_0)^2, H/H_0\right) \tag{4}$$

The proposed estimation models offer one or two – depending on the approach method – equations for each month, for estimating global and diffuse daily irradiation, the geographical particularization being achieved for Braşov urban area.

The performances determination and the validation of models for estimating daily solar irradiation are performed by means of the following statistical indicators: Mean Bias Error – MBE [kWh/m^2], Mean Percentage Error – MPE [%], the Root Mean Square Error – RMSE [kWh/m^2], t-distribution test and Pearson's coefficient (r) (respectively, correlation coefficients (R^2)).

2. Material and methods

2.1. Geographical and climatic description of the site

Braşov is located in the central-eastern area of Romania (south-eastern of Transilvania), in Carpathian Mountains internal curvature. Located in Braşov Depression at 45°39' North latitude and 25°36' East longitude, Braşov has an altitude of 790m. In physical-geographical terms, Braşov is located at junction of three major natural units: the Oriental Carpathians, Meridional Carpathians and Transilvania Plateau, resulting a pronounced complexity and diversity of geological and geomorphologic features, reflected in climate, water, soils, vegetation and fauna.

On the outskirts of Braşov Depression, a series of low-rise mountains (with a maximum altitude of 1200 m) form a border; these along with the high mountains that frame the basin, act as a barrier, limiting the wind speed.

Juxtaposition of mountainous massifs and lowland plains of Braşov create altitudinal and clinometric contrasts; in this context, the general characteristics of the zone climate are influenced in a great extent by physical and geographical local conditions. Under the influence of mountainous terrain, it is provided a subdivision of the general climate and a natural setting of climatic phenomena (Coste and Eftimie, 2011; Marcu and Huber, 2003).

Braşov Depression, by its geographical position, presents clear natural boundaries due to the mountainous massifs that close the basin, these being those that amplify or diminish a number of processes and climatic events in the region (Huber, 2008; Marcu and Huber, 2003; Marcu, 2010).

Braşov Depression is characterized by a climate regime (with four seasons characterized) with excessive variations, namely: high thermal amplitudes and frequent early and late frosts; pluviometric regime is affected by the frame of surrounding mountainous; the aeolian regime is also dependent on local orographic features (Huber, 2008).

The climate of the entire area has a temperate-continental climate: more humid and colder in mountain areas, with relatively low rainfalls and slightly low temperatures in depression (Huber, 2008; Marcu and Huber, 2003).

The interaction between local characteristics and general climate creates favorable conditions for temperature inversion phenomenon. In terms of thermal aspect, "the depression-effect" consists of the intensification of nocturnal radiative cooling and of diurnal heating processes (Marcu and Huber, 2003).

The urban area of Braşov shows typical features regarding the climatology, the topology and the environment. For a basin area due to the surrounding heights, the possible sunshine duration is diminished and the amount of diffuse radiation is increased. Furthermore, in an urban environment due to the atmospheric urban pollution, a significant attenuation of the "visible" sky is ascertained.

The yearly average of air temperature is 9.44°C, the maximum recorded temperature is 35.85°C (July 2007) and minimum temperature is -20.3°C (January 2010) (values measured in the urban area during the period 2006 – 2012).

2.2. Methods used

2.2.1. Estimation of daily global irradiation using second-order Ångström-Prescott regression (M1)

One of the most used methods to estimate the solar radiation is given by Ångström (1924); this model consists in the use of linear regressions that correlates the global solar radiation with the monthly average of the daily sunshine fraction. It is mentioned, in this paper this relation will be applied for estimating the daily global irradiation, respectively (Eq. 5),

$$H/H_{clear\_sky} = a + b\, n/N \tag{5}$$

where: H represents the daily value of global solar irradiation measured on a horizontal surface; H_{clear_sky} represents the daily global irradiation on a horizontal surface [kWh/m^2/day], assuming clear-sky conditions; a and b represent the regression coefficients determined empirically; n/N – sunshine fraction (n represents the number of sunshine hours recorded during a day and N represents the maximum daily sunshine duration).

In view of simplifying the calculation to estimate the global radiation, in 1940 Prescott proposes to replace the global radiation values calculated assuming clear-sky conditions (H_{clear_sky}, (Eq. 5)) with values of extraterrestrial radiation on a horizontal surface (relationship known as Ångström–Prescott regression, (Eq. 6)) (Prescott, 1940),

$$H/H_0 = a + b\, n/N \tag{6}$$

where, H_0 represents the daily extraterrestrial global irradiation on a horizontal surface [kWh/m^2/day].

To estimate daily global irradiation for Braşov urban area this paper proposes the use of second-order Ångström-Prescott regressions, (Eq. 7):

$$H/H_0 = a + b n / N + c\left(n/N\right)^2 \tag{7}$$

This conclusion resulted from the comparative analysis of Pearson's coefficient values (r) determined for linear regressions, second and third order regressions. Pearson's coefficient has the lowest values for linear regressions, this indicating a weak relationship between the two variables.

In the case of using third order regressions, the Pearson's coefficient has the highest values, but the insignificant differences between its values and those of Pearson's coefficient calculated for second order regressions does not justify the complexity of the third order regressions.

2.2.2. Estimating the daily global irradiation by means of regressions dependent on sunshine fraction, the air temperature and the amount of precipitable water (M2)

The use of second order Ångström-Prescott regressions to estimate daily global irradiation for any sunshine fraction values may lead to a decrease of the models performance. It is envisaged that the use of some regressions depending only on sunshine fraction for estimating solar radiation on cloudy days (sunshine fraction values less than 0.1 can lead to estimation errors.

Observation

For Braşov urban area, during a year, there are days characterized by a sunshine fraction value even of 0 (days characteristic to all four seasons); for these days, the global solar radiation values can vary within relatively large limits, making improper the use of estimations that use regressions only dependent on sunshine fraction. Therefore, the proposal to use different regressions for cloudy days (regressions having as input data the sunshine fraction, air temperature and the amount of precipitable water) is based on the following considerations:

- Braşov urban depression area is characterized by a climate regime with excessive variations, frequent temperature inversions, high values of humidity, a diminution of sunshine duration, a relatively large number of cloudy days and significant values of diffuse radiation;
- using regressions of the type, (Eqs. 8-9):

$$H/H_0 = a_1 + b_1\, n/N + c_1\left(T_{max} - T_{min}\right)^{0.5} + d_1\, w \quad \text{for} \quad n/N \le 0.1 \tag{8}$$

$$H/H_0 = a_2 + b_2\left(n/N\right)^2 + c_2\, n/N \quad \text{for} \quad n/N > 0.1 \tag{9}$$

the Pearson's coefficient values were higher compared with those obtained for other types of regressions (have been tried and tested different combinations of input data regarding air temperature, relative humidity, the amount of precipitable water, sunshine duration). In (Eq. 8), T_{max} and T_{min} represent the maximum and minimum daily values of air temperature, and w – the water vapor total amount in a vertical column (so called the amount of precipitable water); w is calculated using the relation proposed by Gueymard (Gueymard, 1994; L´opez and Batlles, 2004), (Eq. 10):

$$w = 21.67\left(0.4976 + 1.5265\frac{T}{273.15} + \cdot\right.$$
$$\left. + exp\left(13.6897\frac{T}{273.15} - 14.9188\left(\frac{T}{273.15}\right)^3\right)\right)\cdot\frac{humid_{rel}}{100}\cdot\frac{p_s}{T} \qquad (10)$$

were $humid_{rel}$ represents the relative humidity, T – air temperature [K], p_s – saturation pressure calculated with relation [mbar], (Eq. 11)

$$p_s = exp\left(22.33 - \frac{4914}{T} - \frac{109220}{T^2} - 0.3902\frac{T}{100}\right) \qquad (11)$$

2.2.3. Estimation of daily diffuse solar irradiation

Similarly to the (Eq. 6), the daily diffuse irradiation can be determined by means of linear regressions or using second or third order regressions. For Braşov urban area, the determination of daily diffuse irradiation was performed using second order regressions, as follows:

- for estimation of daily global irradiation using second order Ångström-Prescott regressions (model M1, (Eq. 12) and model M2 for $n/N > 0.1$, (Eq. 13)),

$$H_{dif}/H = a_{dif} + b_{dif}\, H/H_0 + c_{dif}\,(H/H_0)^2, \text{ for M1} \qquad (12)$$

$$H_{dif}/H = a_{dif\_1} + b_{dif\_1}\, H/H_0 + c_{dif\_1}\,(H/H_0)^2, \text{ for M2, } n/N > 0.1 \qquad (13)$$

- for estimation of daily global irradiation using regressions depending on the sunshine fraction, the air temperature and the amount of precipitable water (M2 model for $n/N \leq 0.1$), (Eq. 14)

$$H_{dif} = a_{dif\_2} + b_{dif\_2}\, H/H_0 + c_{dif\_2}\,(H/H_0)^2 \text{ for M2, } n/N \leq 0.1 \qquad (14)$$

The types of regressions used to estimate daily diffuse irradiation have resulted from the analysis of Pearson's coefficient values. The use of linear regression to estimate the daily diffuse irradiation leads to low values of Pearson's coefficient; this means that changes in estimated variable are not correlated with changes in the measured variable. The insignificant differences between the Pearson's coefficient values calculated for daily diffuse irradiation estimations made with second and third order regressions does not justify the use of the third order regressions.

It is also noted the different type of daily diffuse irradiation regressions when the estimation of daily global irradiation is performed with regressions depending on the sunshine fraction, the air temperature and the amount of precipitable water (model M2 for $n/N \leq 0.1$). It is mentioned that regressions as $H_{dif}=H_{dif}(H/H_0, (H/H_0)^2)$ led to higher values of Pearson's coefficient (this means that changes in one variable are strongly correlated with changes in the second variable) than in the case of using regressions by type $H_{dif}/H=H_{dif}/H(H/H_0, (H/H_0)^2)$.

3. Experimental

3.1. Meteorological data

For meteorological data collection and processing, Department of Renewable Energy Systems and Recycling of Transilvania University of Braşov, uses its own weather station. The meteorological data have been measured and recorded since October 2005 and they comprise the following meteorological parameters:

1. *solar radiation* – the sensor assembled on the weather station is a modern sensor, type SPN1 pyranometer (Wood, 2007), that measures simultaneously global solar radiation [W/m^2], diffuse solar radiation [W/m^2] and sunshine (overall accuracy for total and diffuse radiation: ±5% for daily measurements; resolution: 0.6 W/m^2; range: 0 to 2000 W/m^2);
2. *air temperature* [°C] and *relative humidity* [%] are measured by specialized sensors (types RHT2 and AT2) assembled inside of a "pagoda" protector, away from direct sunlight (RH2 accuracy at 23°C: ± 2%; AT2 accuracy: ± 0.2°C at -10 to +50°C);
3. *the amount of precipitations* [pluviometric mm] is measured by a sensor dump bucket (type RG1); number of discharges cup is counted and sent through a digital channel to data logger, which records the quantities of rainfall in 10 minute intervals;
4. *wind speed* [m/s] and *wind direction* [degrees] are recorded by an electromagnetic induction anemometer (type AN4, accuracy: ± 0.5 m/s for measurements from 0.5 to 10 m/s) and an automatic wind vane (type WD1, accuracy: ±2 degrees obtainable in steady winds over 5 m/s); wind direction, recorded by automatic vane, is expressed by the azimuthal angle (formed by the wind direction and north direction, clockwise). The weather station measures data at 10 minutes' range, automatically, in a continuous way. The data are recorded by means of an environmental data logger and these can be collected without interrupting logging. The weather station was installed in conditions similar to those under which solar and wind energy small installations operate (meteorological station was installed in accordance with the meteorological requirements of the urban area of Braşov). The national network of meteorological

stations gives measurements made under the standard conditions imposed by the World Meteorological Organization (grass platform, height 2m etc.). The daily irradiation estimations were performed on databases consisting on measurements recorded from January 2006 through October 2013. Only those days for which all hourly values were recorded are included in the study. To make possible a complete and reliable estimation analysis, the Romanian National Meteorological Administration has installed in the same location a weather station (that works in parallel with Delta-T weather station) for data comparing and validation.

3.2. Computational methods

Meteorological data management was performed using the Visual FoxPro programming environment. To the choice of software environment for meteorological data processing, the following issue was considered: the large amount of data to be stored and processed makes necessary the use of a specialized database management system, that to make possible the obtaining of specialized results.

In this way, there were possible: data management, defining the rules for databases, creating queries using visual design tools, and finally building applications.

For the determination of daily equation coefficients (for the two estimation models, M1 and M2), the algorithm stages are the following:

- in the first stage the daily global irradiation on a horizontal surface (measured data – $H_{g\_measured}$), daily extraterrestrial irradiation on a horizontal surface (H_0), daily diffuse irradiation on a horizontal surface (measured data – $H_{dif\_measured}$), number of daily sunshine hours (n) and maximum daily sunshine duration (N) must be calculated;
- for model M2 it was necessary to extract the maximum and minimum daily air temperature values and to calculate the daily amount of precipitable water;
- for model M1 the coefficients of the Ångström–Prescott regressions are calculated from regression analysis between $H_{g\_measured}/H_0$ and n/N (according to (Eq. 7)); from regression analysis between $H_{dif\_measured}/H$ and H/H_0, the regression coefficients of the daily diffuse irradiation estimations, for each month, were obtained (according to (Eq. 12));
- for the model M2, the days with sunshine fraction values higher than 0.1 have been selected and regression coefficients were determined in a similar manner to the previous stage (according to the (Eq. 9) and (Eq. 13));
- for model M2 and the days with sunshine fraction values less than 0.1, the regression coefficients are calculated from correlations of the type $H_{g\_measured}/H_0$ depending on n/N, $(T_{max}\text{-}Tmin)^{0.5}$, w (according to (Eq. 8)); from the analysis of correlation between $H_{dif\_measured}$ and H/H_0, the regression coefficients of the daily diffuse irradiation equations, for each month, are obtained (according to (Eq. 14)).

The algorithm above mentioned will be applied for every month. Under these circumstances, for each month, one or two regressions will be determined, depending on the model adopted, both for daily global irradiation and daily diffuse irradiation. Twelve monthly-specific equations are resulted for model M1 and twenty-four monthly-specific equations for model M2 (for H/H_0 and H_{dif}/H, were H and H_{dif} represent the global and diffuse estimated daily irradiations).

Table 1. Estimation regressions of the daily global irradiation for Braşov urban area (Model M1)

Month	***Regression***	***r***	***R²***
January	$H/H_0 = -0.309\,(n/N)^2 + 0.948\,(n/N) + 0.181$	0.93	0.88
February	$H/H_0 = -0.402\,(n/N)^2 + 0.997\,(n/N) + 0.212$	**0.92**	0.85
March	$H/H_0 = -0.369(n/N)^2 + 0.923(n/N) + 0.196$	0.94	0.89
April	$H/H_0 = -0.333(n/N)^2 + 0.958(n/N) + 0.146$	0.97	0.94
May	$H/H_0 = -0.153(n/N)^2 + 0.747(n/N) + 0.188$	0.97	0.94
June	$H/H_0 = -0.2428(n/N)^2 + 0.8426(n/N) + 0.1626$	0.97	0.94
July	$H/H_0 = 0.0531\,(n/N)^2 + 0.4548\,(n/N) + 0.2643$	0.97	0.94
August	$H/H_0 = -0.1268(n/N)^2 + 0.6876\,(n/N) + 0.1995$	0.97	0.94
September	$H/H_0 = -0.2961(n/N)^2 + 0.8662(n/N) + 0.1772$	**0.97**	0.95
October	$H/H_0 = -0.347(n/N)^2 + 0.942(n/N) + 0.168$	0.97	0.94
November	$H/H_0 = -0.4053(n/N)^2 + 0.945(n/N) + 0.1824$	**0.97**	0.95
December	$H/H_0 = -0.3836(n/N)^2 + 0.9408(n/N) + 0.188$	0.93	0.87

4. Results and discussions

4.1. Estimating daily solar irradiation

The Ångström-Prescott regressions (model M1) obtained for Braşov urban area are presented in Table 1; these equations are obtained from the daily data during January 2006 – October 2013. The regressions for the estimation of daily diffuse irradiation are presented in Table 2.

Regressions for estimating daily global irradiation according to correlations that take into account the values of sunshine fraction (model M2 uses two different regressions for every month) and the regressions for estimating daily diffuse irradiation are presented in Tables 3- 4.

Table 2. Regressions of the daily diffuse irradiation for Braşov urban area (daily global irradiation determined with equations from Table 1)

Month	***Regression***	***r***	***R²***
January	$H_{dif}/H = -1.4256\left(H/H_0\right)^2 + 0.3031\left(H/H_0\right) + 0.9062$	**0.56**	0.31
February	$H_{dif}/H = -2.8551\left(H/H_0\right)^2 + 1.6358\left(H/H_0\right) + 0.6577$	**0.54**	0.23
March	$H_{dif}/H = -2.3396\left(H/H_0\right)^2 + 0.8946\left(H/H_0\right) + 0.7924$	**0.63**	0.39
April	$H_{dif}/H = -1.2522\left(H/H_0\right)^2 - 0.0546\left(H/H_0\right) + 0.9043$	**0.69**	0.46
May	$H_{dif}/H = -0.4391\left(H/H_0\right)^2 - 0.8596\left(H/H_0\right) + 1.0674a$	**0.69**	0.47
June	$H_{dif}/H = -0.5214\left(H/H_0\right)^2 - 0.7737\left(H/H_0\right) + 1.0098$	0.73	0.54
July	$H_{dif}/H = 0.2634\left(H/H_0\right)^2 - 1.7094\left(H/H_0\right) + 1.2846$	**0.83**	0.69
August	$H_{dif}/H = -0.1917\left(H/H_0\right)^2 - 1.1255\left(H/H_0\right) + 1.1048$	0.76	0.58
September	$H_{dif}/H = -1.175\left(H/H_0\right)^2 - 0.1703\left(H/H_0\right) + 0.942$	0.74	0.54
October	$H_{dif}/H = -1.8402\left(H/H_0\right)^2 + 0.4224\left(H/H_0\right) + 0.8733$	0.76	0.58
November	$H_{dif}/H = -1.8213\left(H/H_0\right)^2 + 0.3445\left(H/H_0\right) + 0.9014$	**0.57**	0.25
December	$H_{dif}/H = -2.211\left(H/H_0\right)^2 + 0.8063\left(H/H_0\right) + 0.8475$	**0.49**	0.23

Table 3. Estimation regressions for daily global irradiation depending on sunshine fraction value for Braşov urban area (Model M2)

Month		**Regression**	***r***	***R²***
January	$n/N \le 0.1$	$H/H_0 = 1.575\left(n/N\right) + 0.045\left(T_{max} - T_{min}\right)^{0.5} - 0.247w + 0.305$	0.96	0.93
	$n/N > 0.1$	$H/H_0 = 0.293\left(n/N\right)^2 + 0.262\left(n/N\right) + 0.333$		
February	$n/N \le 0.1$	$H/H_0 = 1.794\left(n/N\right) + 0.075\left(T_{max} - T_{min}\right)^{0.5} - 0.059w + 0.085$	**0.94**	0.89
	$n/N > 0.1$	$H/H_0 = 0.348\left(n/N\right)^2 + 0.156\left(n/N\right) + 0.397$		
March	$n/N \le 0.1$	$H/H_0 = 1.467\left(n/N\right) + 0.079\left(T_{max} - T_{min}\right)^{0.5} - 0.059w + 0.064$	0.96	0.92
	$n/N > 0.1$	$H/H_0 = -0.0326\left(n/N\right)^2 + 0.532\left(n/N\right) + 0.2861$		
April	$n/N \le 0.1$	$H/H_0 = 2.262\left(n/N\right) - 0.029\left(T_{max} - T_{min}\right)^{0.5} - 0.166w + 0.376$	0.97	0.95
	$n/N > 0.1$	$H/H_0 = -0.068\left(n/N\right)^2 + 0.64\left(n/N\right) + 0.223$		
May	$n/N \le 0.1$	$H/H_0 = 1.244\left(n/N\right) + 0.070\left(T_{max} - T_{min}\right)^{0.5} - 0.029w + 0.071$	0.98	0.96
	$n/N > 0.1$	$H/H_0 = 0.095\left(n/N\right)^2 + 0.452\left(n/N\right) + 0.260$		
June	$n/N \le 0.1$	$H/H_0 = 0.737\left(n/N\right) + 0.0779\left(T_{max} - T_{min}\right)^{0.5} + 0.09w - 0.217$	0.97	0.95
	$n/N > 0.1$	$H/H_0 = -0.0441\left(n/N\right)^2 + 0.5884\left(n/N\right) + 0.2333$		
July	$n/N \le 0.1$	$H/H_0 = 0.1843\left(T_{max} - T_{min}\right)^{0.5} - 0.1981$	0.97	0.95

	$n/N > 0.1$	$H/H_0 = 0.178(n/N)^2 + 0.294(n/N) + 0.310$		
August	$n/N \leq 0.1$	$H/H_0 = 2.1022(n/N) + 0.1391w - 0.2263$	0.97	0.95
	$n/N > 0.1$	$H/H_0 = -0.035(n/N)^2 + 0.567(n/N) + 0.234$		
September	$n/N \leq 0.1$	$H/H_0 = 1.09(n/N) + 0.0756(T_{max} - T_{min})^{0.5} - 0.0019w + 0.006$	0.98	0.96
	$n/N > 0.1$	$H/H_0 = -0.1768(n/N)^2 + 0.7159(n/N) + 0.2169$		
October	$n/N \leq 0.1$	$H/H_0 = 1.429(n/N) - 0.020(T_{max} - T_{min})^{0.5} - 0.058w + 0.259$	0.97	0.95
	$n/N > 0.1$	$H/H_0 = -0.051(n/N)^2 + 0.564(n/N) + 0.269$		
November	$n/N \leq 0.1$	$H/H_0 = 1.41(n/N) + 0.12(T_{max} - T_{min})^{0.5} - 0.006w - 0.024$	**0.98**	0.97
	$n/N > 0.1$	$H/H_0 = -0.1324(n/N)^2 + 0.612(n/N) + 0.2684$		
December	$n/N \leq 0.1$	$H/H_0 = 2.011(n/N) + 0.043(T_{max} - T_{min})^{0.5} - 0.033w + 0.139$	0.94	0.90
	$n/N > 0.1$	$H/H_0 = -0.0626(n/N)^2 + 0.6011(n/N) + 0.25$		

Table 4. Regression equations of the daily diffuse irradiation estimation for Braşov urban area (daily global irradiation determined with equations from Table 3)

Month		***Regression***	***r***	***R^2***
January	$n/N \leq 0.1$	$H_{dif} = -7.0269(H/H_0)^2 + 6.1558(H/H_0) - 0.2705$	0.76	0.57
	$n/N > 0.1$	$H_{dif}/H = 1.4911(H/H_0)^2 - 2.8458(H/H_0) + 1.6452$		
February	$n/N \leq 0.1$	$H_{dif} = -9.5129(H/H_0)^2 + 8.3442(H/H_0) - 0.3281$	**0.63**	0.40
	$n/N > 0.1$	$H_{dif}/H = 1.986(H/H_0)^2 - 3.9676(H/H_0) + 2.1576$		
March	$n/N \leq 0.1$	$H_{dif} = 8.2127(H/H_0)^2 + 2.9658(H/H_0) + 0.3556$	0.74	0.55
	$n/N > 0.1$	$H_{dif}/H = 1.2293(H/H_0)^2 - 2.9396(H/H_0) + 1.7306$		
April	$n/N \leq 0.1$	$H_{dif} = -12.291(H/H_0)^2 + 11.87(H/H_0) - 0.1916$	0.74	0.56
	$n/N > 0.1$	$H_{dif}/H = 0.852(H/H_0)^2 - 2.297(H/H_0) + 1.438$		
May	$n/N \leq 0.1$	$H_{dif} = -7.3114(H/H_0)^2 + 11.585(H/H_0) + 0.0481$	0.79	0.63
	$n/N > 0.1$	$H_{dif}/H = 0.474(H/H_0)^2 - 1.783(H/H_0) + 1.270$		
June	$n/N \leq 0.1$	$H_{dif} = 8.1608(H/H_0) + 0.369$	0.78	0.61
	$n/N > 0.1$	$H_{dif}/H = 0.655(H/H_0)^2 - 2.050(H/H_0) + 1.330$		
July	$n/N \leq 0.1$	$H_{dif} = 7.9786(H/H_0) + 0.4791$	**0.85**	0.73
	$n/N > 0.1$	$H_{dif}/H = 1.2062(H/H_0)^2 - 2.799(H/H_0) + 1.5869$		
August	$n/N \leq 0.1$	$H_{dif} = 8.2432(H/H_0) + 0.1453$	0.78	0.61
	$n/N > 0.1$	$H_{dif}/H = 0.301(H/H_0)^2 - 1.661(H/H_0) + 1.239$		
September	$n/N \leq 0.1$	$H_{dif} = 6.918(H/H_0) - 0.038$	0.77	0.59
	$n/N > 0.1$	$H_{dif}/H = -1.32(H/H_0)^2 + 0.0622(H/H_0) + 0.8517$		
October	$n/N \leq 0.1$	$H_{dif} = 5.232(H/H_0) - 0.012$	0.79	0.62
	$n/N > 0.1$	$H_{dif}/H = -0.650(H/H_0)^2 - 0.801(H/H_0) + 1.137$		
November	$n/N \leq 0.1$	$H_{dif} = 3.109(H/H_0) + 0.047$	**0.69**	0.47
	$n/N > 0.1$	$H_{dif}/H = 3.4151(H/H_0)^2 - 5.3461(H/H_0) + 2.3468$		
December	$n/N \leq 0.1$	$H_{dif} = 2.403(H/H_0) + 0.059$	**0.59**	0.35
	$n/N > 0.1$	$H_{dif}/H = 0.947(H/H_0)^2 - 2.3407(H/H_0) + 1.5196$		

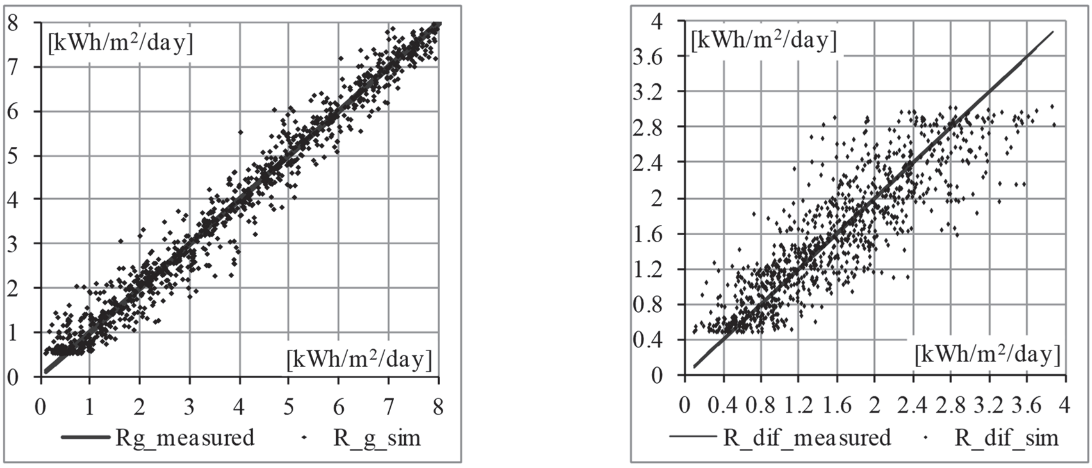
Considering the two estimation methods, the next stage consisted in the solar irradiation simulation (global and diffuse daily irradiations).

Therefore, in Figs. 1-2, there are presented daily measured global irradiations versus daily simulated global irradiations and daily measured diffuse irradiations versus daily simulated diffuse irradiations (for model M1 in Fig. 1 and for model M2 in Fig. 2). Based on the diagrams analysis, it can be ascertained that the proposed models approximate to a great extent the global irradiation.

For the estimation considering Ångström-Prescott regressions (model M1) the graph reveals a lack of simulated values of daily global irradiation for lower values (less than 0.5 kWh/m^2/day). In the case of using regressions having as input parameters: sunshine fraction, air temperature and the amount of precipitable water, for sunshine fraction values less than 0.1, it is ascertained a better estimation of daily global irradiation for low values. In addition, for Model M2, the values of the Pearson's coefficient are higher than in the case of using model M1.

Regarding the daily diffuse irradiation estimation, its modeling is very difficult because the diffuse fraction has a distribution specific to the analyzed area, showing a significant influence on the quantity of radiation on capturing surface. Estimating daily diffuse irradiation, the graph for model M1 reveals a greater spreading of all estimated daily diffuse irradiation values; for model M2, especially for lower values of the daily diffuse irradiation, it is ascertained a closeness of the estimated values to those measured (for the estimation with model M1, similar to the case of estimating daily global irradiation, a lack of estimated values is noticed, for lower values of daily diffuse irradiation).

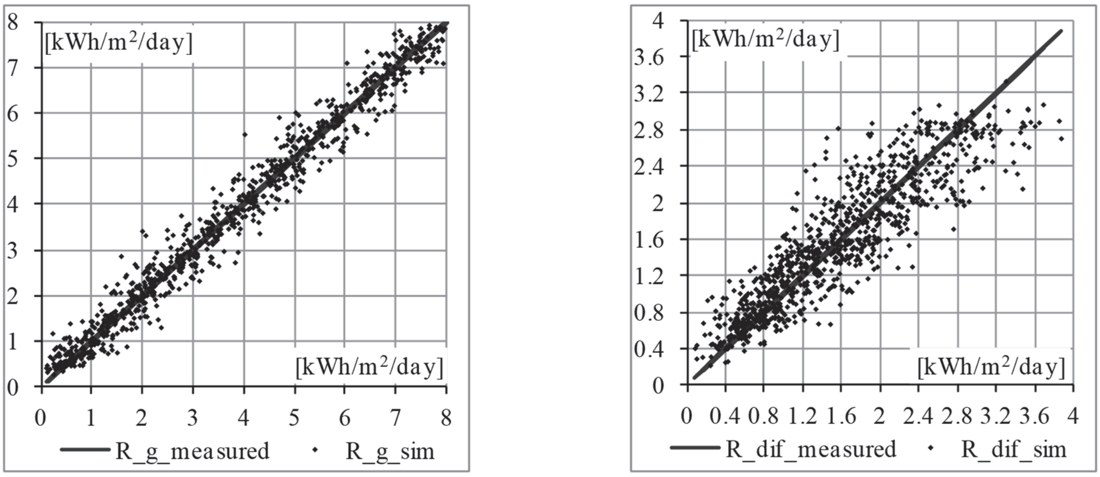
However considering the entire database (statistical indicators were also calculated at the entire database level), high values of the correlation coefficients are recorded; thus for the global irradiation estimations, for model M1 it was obtained R^2=0.973 and for model M2, R^2=0.980; regarding the diffuse irradiation modeling, for model M1 it was obtained R^2= 0.756 and for model M2, R^2= 0.804.



(a)

(b)

Fig. 1. Estimated versus measured daily values – model M1: (a) for the global irradiation, (b) for diffuse irradiation



(a)

(b)

Fig. 2. Estimated versus measured daily values – model M2: (a) for the global irradiation, (b) for diffuse irradiation

The high values of the correlation coefficients for daily global irradiation estimation (both models) reveal the fact that these two models are applicable with great accuracy. The nest stage consists of the graphical comparison between the measured data and estimated values (daily values of the global and diffuse irradiation). The comparative graphs are plotted for January 2013 (Fig. 3) and also for the all days with a sunshine fraction less than 0.1 during the period February-October 2013 (Fig. 4).

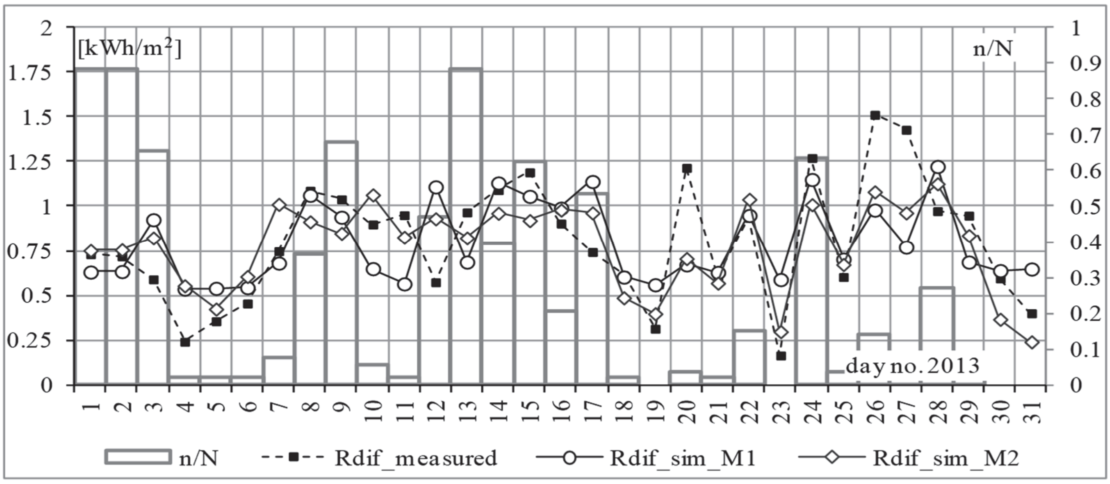
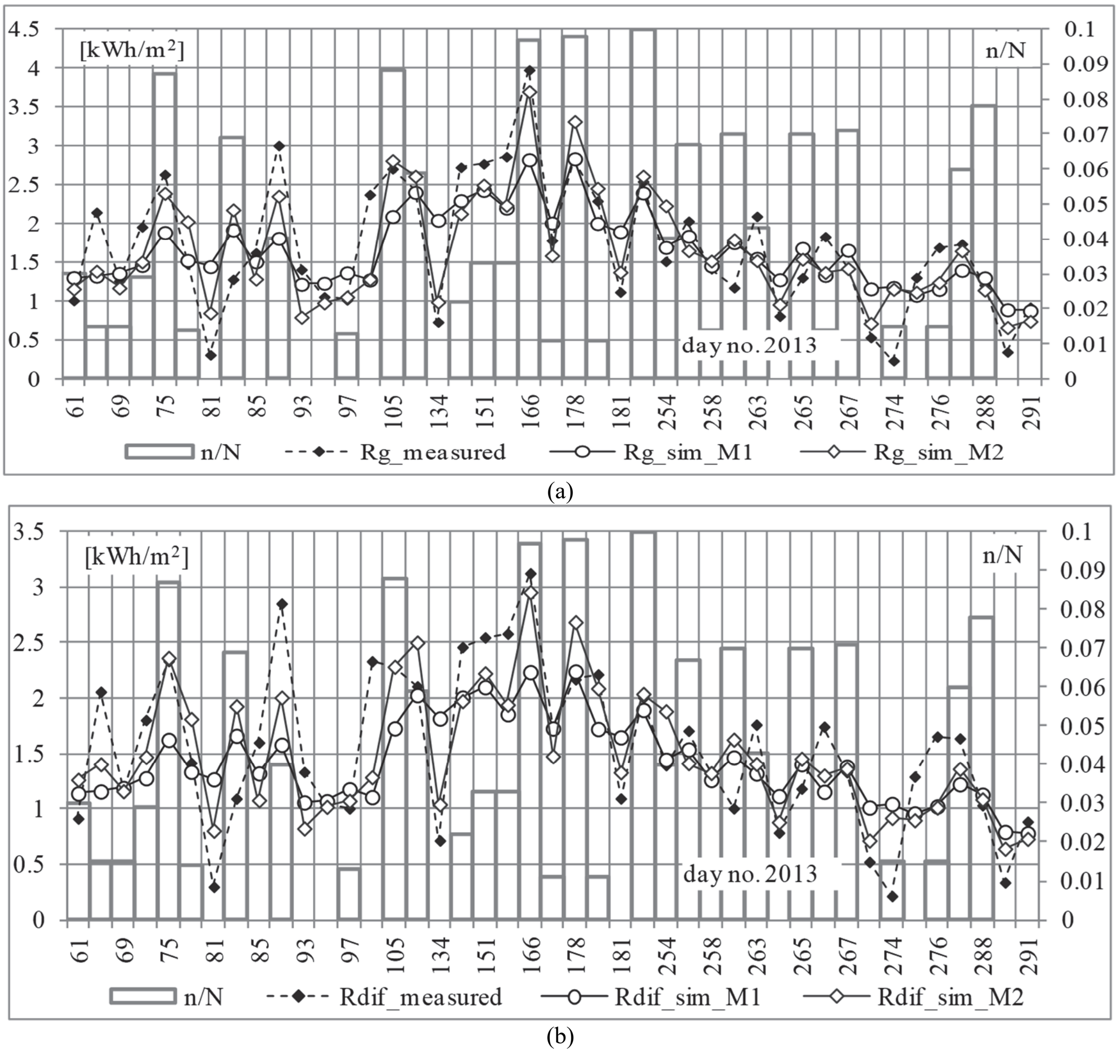


Fig. 3. Theoretical and measured values of daily global irradiation and daily diffuse irradiation for all days during January 2013



(a)

(b)

Fig. 4. Theoretical and measured values of daily irradiation for all days with sunshine fraction values less than 0.1, during February-October 2013: (a) global irradiation, (b) diffuse irradiation

The presented diagrams reveal a better estimation, both for the global and diffuse irradiation, if the model M2 is used.

The superimposed measured and estimated diagrams proved that the proposed models are efficient models in daily solar irradiation simulation (global and diffuse irradiation) for Braşov urban area, even for cloudy days (sunshine fraction values less than 0.1).

4.2. Models performance

For the assessment of models performances, the most important statistical indicators were calculated, namely: Mean Bias Error (MBE), Mean Percentage Error (MPE), Root Mean Square Error (RMSE), t-distribution and Pearson's coefficient. The MBE, MPE, RMSE and t-distribution are defined by Eqs. (15-18) (Montgomery and Runger; 2011; Zhao et al., 2013):

$$MBE = \left(\sum_{i=1}^{N} \left(Rc_i - Rm_i \right) \right) / N \ \text{[kWh/m}^2\text{]} \tag{15}$$

$$MPE = \left(\sum_{i=1}^{N} \left(\frac{Rc_i - Rm_i}{Rm_i} \right) 100 \right) / N \cdot 100 \ [\%] \tag{16}$$

$$RMSE = \sqrt{\left(\sum_{i=1}^{N} \left(Rc_i - Rm_i \right)^2 \right) / N} \ \text{[kWh/m}^2\text{]} \tag{17}$$

$$t = \sqrt{\left((N-1) MBE^2 \right) / \left(RMSE^2 - MBE^2 \right)} \tag{18}$$

where: Rm_i and Rc_i are the i^{th} measured and model-estimated daily values of the global or diffuse irradiation; N represents the number of observations.

Information on long-term regarding the performance of a model is offered by MBE indicator (Montgomery and Runger, 2011; Paulescu, 2005); this statistical indicator can test the model tendency to underestimate or overestimate the measured values of the analyzed parameter. As lower the values of analyzed indicators are (in absolute value as close to 0) the model performance is better.

The statistical indicator RMSE tests the scattering level of a model; values closer to 0 of RMSE indicator reflect a high performance of tested model. However, there are situations where, although the performances testing using the indicators: MBE, MPE and RMSE leads to low values of these parameters, the estimation model does not validate in a satisfactory manner the real variation of the analyzed parameter. So, sometimes the testing of an estimation model only with these statistical indicators (MBE, MPE and RMSE) is not enough. Given this, it is recommended to corroborate the results obtained with these statistical indicators, with those of t-distribution test.

The calculated values of t-distribution indicator, in view of the tested model validation, must be less than the t-critical (values provided by the statistical tables; the t-critic value is depending on the confidence level adopted for the proposed model and the number of measurements). The obtained values of the MBE, RMSE and t-distribution are presented in Table 5, for the daily global irradiation estimation models and in Table 6 for the daily diffuse irradiation estimation models. Considering daily global irradiation estimation, the Mean Bias Errors are between -0.0094 and 0.0075 kWh/m^2/day for estimation with model M1 and between -0.005 and 0.007 kWh/m^2/day for estimation with model M2. For the daily diffuse irradiation estimation, MBE values are between-0.0073 and 0.015 kWh/m^2/day for the estimation that uses model M1, between -0.0018 and 0.0079 kWh/m^2/day for the estimation with model M 2, depending on the season month.

The MPE monthly values, for daily global and diffuse irradiations are presented in Fig. 5. It can be noticed, the MBE and MPE values calculated for model M2 are much lower compared to those calculated for estimations achieved using model M1 (both for global irradiation and diffuse irradiation estimations). The highest MBE and MPE values (Tables 5, 6 and Fig. 5) are recorded for winter months (November-December and January-February).

The MBE and MPE values calculated for the diffuse irradiation estimations are higher than those calculated for global irradiation (both models). Regarding the level of scattering that the models produce, the maximum RMSE values are obtained for global irradiation during the period February – June, and for the diffuse irradiation during the same period (Table 5 and Table 6). It must be mentioned, the level of scattering is lower if we take into consideration that the maximum RMSE value is 0.504 kWh/m^2 (estimation of daily global irradiation with model M1, for April).

The t-distribution values are calculated both for global and diffuse daily irradiation (the two proposed models). The highest t-distribution values were obtained when the estimation was achieved for the daily diffuse irradiation using model M1 (but this value of 0.56 recorded for November is much less than the t-critical at 5% obtained from standard statistical, namely 1.645). Considering the entire database, the calculated t-distribution values are less than the t-critical at 5% showing that the equations for both models have statistical significance for all months (for the estimation of daily global irradiation with model M1, t-distribution is 0.006 and using model M2, t-distribution is 0.0118; for the estimation of daily diffuse irradiation with model M1, t-distribution is 0.133 and using model M2, t-distribution is 0.0961). The best performance can be found by selecting the lowest t-distribution values. The statistical analysis also included the calculation of Pearson's coefficient (r) between the measured and estimated values.

Table 5. Statistical indicators values (MBE, RMSE, t-distribution – estimation of global irradiation

Month	***model M1***			***model M2***		
	RMSE [kWh/m²]	***MBE [kWh/m²]***	***t-distribution***	***RMSE [kWh/m²]***	***MBE [kWh/m²]***	***t- distribution***
January	0.26959	**-0.00936**	0.271	0.19217	**-0.00505**	0.205
February	0.40384	0.00502	0.093	0.33483	-0.00184	0.041
March	0.48148	-0.00516	0.103	0.41509	-0.00363	0.084
April	0.49373	0.00168	0.032	0.43856	0.00059	0.013
May	0.50832	-0.00048	0.009	0.40707	-0.00042	0.010
June	**0.53957**	0.00120	0.021	**0.47646**	-0.00027	0.005
July	0.36170	-0.00129	0.034	0.31705	-0.00122	0.037
August	0.37485	-0.00125	0.032	0.34966	-0.00128	0.035
September	0.32612	-0.00370	0.107	0.30438	-0.00003	0.001
October	0.29390	**0.00751**	0.245	0.26964	**0.00695**	0.247
November	0.15735	0.00679	**0.348**	0.12257	0.00379	**0.249**
December	0.21118	0.00098	0.036	0.19188	-0.00039	0.016

Table 6. Statistical indicators values (MBE, RMSE, t-distribution – estimation of diffuse irradiation

Month	model M1			model M2		
	RMSE [kWh/m²]	MBE [kWh/m²]	t- distribution	RMSE [kWh/m²]	MBE [kWh/m²]	t- distribution
January	0.27893	**-0.00731**	0.205	0.21914	**-0.00179**	0.064
February	0.42111	0.01067	0.190	0.37240	**0.00793**	0.159
March	0.47550	-0.00106	0.021	0.40939	-0.00138	0.032
April	**0.50434**	-0.00143	0.027	**0.45591**	-0.00113	0.023
May	0.46943	0.00138	0.028	0.39426	-0.00086	0.021
June	0.49061	0.00062	0.012	0.44819	-0.00089	0.019
July	0.34966	0.00007	0.002	0.32387	-0.00077	0.023
August	0.36023	-0.00104	0.028	0.34947	-0.00013	0.004
September	0.33868	0.00425	0.118	0.32133	0.00563	0.165
October	0.26268	0.00186	0.068	0.24854	0.00277	0.107
November	0.21509	**0.01491**	**0.560**	0.18049	0.00635	**0.284**
December	0.22180	0.00083	0.029	0.20436	-0.00006	0.002

The value of the Pearson coefficient ranges between -1 and +1 and if its value is closer to -1 or 1 this reflects the existence of a strong relationship between the two data sets (measured and estimated values).

Estimating daily global irradiation, the minimum values of Pearson's coefficient were obtained for February (0.922 for estimation with model M1 and 0.947 for estimation with model M2).

Estimation of daily diffuse irradiation with model M1 leads to values of Pearson's coefficient higher than 0.7 only for the period June – October.

Using model M2 for daily diffuse irradiation estimation, an increase of Pearson's coefficient was obtained, values less than 0.7 being obtained for February, November and December.

5. Conclusions

According to the statistical analysis (MBE, MPE, RMSE and t-distribution values), the proposed estimation models fitted the measured data in a great extent and these can be used to estimate the daily values of solar irradiations. The comparison between the estimated daily irradiation values (global and diffuse irradiation) and the measured ones, leads to the conclusion that, the highest values of the statistical indicators (MBE, MPE, RMSE and t-distribution) were obtained for the daily diffuse solar irradiation estimation during winter season (January-February and November-December).

However, for a complete statistical analysis of the performances of a model is not enough just to obtain low values of statistical indicators mentioned above, it is also necessary the Pearson's coefficient calculation. In this respect, it should be mentioned that an objective of this study was to develop accurate models for estimating daily solar irradiation for which the absolute value of the Pearson's coefficient to be as close to unity.

Thus, it must be noted that the models for estimating the daily global irradiation lead to high values of Pearson's coefficient (for model M1, values of this coefficient varies between 0.922 and 0.979 and for model M2, between 0.947 and 0.979). Thus, it can be asserted that the application of proposed models for estimating daily global irradiation leads to very good results.

Unfortunately for models of estimating the daily diffuse irradiation, although the values of statistical indicators MBE, MPE, RMSE and t-distribution validate these models, however, the maximum value of Pearson's coefficient is 0858 (value obtained for July, estimation with the model M2). The best estimation of daily diffuse irradiation if obtained if model M2 is used, but it must be mentioned, for three months (February, November and December) Pearson's coefficient values are less than 0.7. To our knowledge, this is the first research concerning the estimation of solar radiation under real-sky conditions, for Braşov urban area (estimation of global and diffuse daily irradiation).

We previously covered only a study for estimating monthly solar irradiations under real-sky conditions. Because it is important to accurately estimate solar irradiance in this region, the present paper was developed on the priority to determine more accurate estimation models of daily solar irradiation (both global and diffuse irradiation) and to validate these models by means of a complete statistical analysis.

The results obtained from the investigations in this paper, open new research perspectives in estimating solar radiation in order to design and optimize solar energy conversion systems for Braşov region.

Acknowledgements

The meteorological data used in this study were provided by Department of Renewable Energy Systems and Recycling, from Transilvania University of Braşov, Romania.

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