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Estimation of real-sky daily solar irradiation Case study: Braşov, Romania

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Abstract

The study presented by this paper is intended to estimate the daily solar irradiation under real-sky condition for Braşov (Romania) area. To this end, it is presented the methodology that was led to determine the estimation regressions of daily solar irradiation and the results of meteorological data sets processing. It is also performed an analysis of the variation of some climatic parameters specific to the analyzed area as, the sunshine fraction, the sky ratio and the Perez's clearness index, in order to identify the possible sources of error and to assess their impact on accuracy of estimation models for daily solar irradiation. Special attention has been given to the analysis of statistical indicators that were the basis for performance analysis of the obtained models; focusing on optimizing the Pearson's coefficient, this paper presents the monthly regressions for two estimation models of daily global irradiance and corresponding to these, four estimation models of daily diffuse irradiation.

Keywords: Air temperature; Daily solar irradiation; Precipitable water amount; Statistical analysis; sunshine fraction.

1. Introduction

The concern for the cleaner production, regardless of what branch of the economy belongs, is not new. But new are the concerns for implementing of an integrated strategy of preventing on the processes, products and services in order to increase eco-efficiency and to reduce the risk on people and the environment, respectively the changing trends of development techniques of eco-industries and of environmental management.

On the direction of environmental protection and saving resources, there are enrolled the efforts made to replace fossil fuels (gas, oil) with renewable and clean resources (biomass, solar energy, wind energy, tidal energy, etc.); in this way, there are obtained both the saving of non-renewable resources as well the reduction of pollutant emissions per unit of product.

The climatic resources belong to the category of inexhaustible natural resources, these representing the totality of climatic elements and phenomena that can be capitalized. Of these, solar energy represents a major source of renewable energy, the theoretical potential of solar energy being very high. However, it should be mentioned that the exploitable potential of solar energy can be significantly reduced by the climatic conditions of the implementation area and by the performances of solar energy conversion systems. Among the factors that significantly influence the solar radiation at Earth's surface, there are mentioned: latitude and altitude (there are areas with limited sunshine duration), season, day, hour, the amount of dust and water vapor in the atmosphere. One of the most important parameters used in the design of solar energy conversion systems, is the integral flow of radiant energy that comes continuously from the Sun to Earth. Therefore within the solar applications, the solar radiation defined as the energy flow per unit area is the input date that we are interested to known. This input date is analyzed through the three components that define it: the direct component, the diffuse component and the global component.

An important aspect is represented by the fact that solar radiation (with all three components) at ground level contains both a deterministic factor generated by the solar geometry as well as a random one generated by the various changes that occur at the level of atmosphere.

The knowledge of statistical distribution of solar radiation at the solar equipments surface gives the possibility to assess the long term performances of these systems. However, for this it is necessary – for the areas of implementation of solar equipments – a meteorological database over a long period of time, the statistics on long-term of radiation being obtained by usual processing, but with an increased effort due to the large volume of processed data. Considering this aspect, the development of generalized estimation models became a major objective for designers of solar energy conversion systems.

At present, the specialty literature offers a wide range of models for estimation the solar radiation; these can be classified in relation to the component of modeled radiation (global radiation, direct radiation, diffuse radiation), the analysis method (analytical, statistical, combined) and the integration period of the modeled component (hourly, daily, seasonal).

As a general remark, the developed models are based on average values (corresponding to different integration periods) of global solar radiation on a horizontal surface or from the derived data from this.

It is noted the fact that date-sets of measured solar radiation are only available to a relatively small number of areas, that have weather stations equipped with sensors for measuring the solar radiation. In this context, the development of some estimation models of the solar radiation components represents an important and economical objective. For locations that do not have solar radiation measurements there are used statistical techniques of estimating the hourly values [1]; also based on data available on short term, there are used synthesis techniques for obtaining long term data (the aim is to obtain the estimations on long-term, on the basis of modeling achieved for a small number of days considered as representative) [2-4].

The most estimation models of the solar radiation use the empirical relationships dependent on different available meteorological observations, respectively the measured sunshine duration (linear regressions [5, 6], or regressions of second or third order, of the Ångström-Prescott correlation [7-10]), air temperature [11-18], air temperature and relative humidity [19], sunshine hour and air pollution index [20].

It is remarked that the most models for estimating the solar radiation refer to its global component, this paper mentioning only a small part of them [7, 12, 13, 15-18, 21, 22].

Regarding the estimation of the diffuse component of solar radiation it is mentioned that due to the dependence of this component on weather conditions, the development of high-performance estimation models is difficult. Among the models proposed by specialty literature there are mentioned: [23-26], models that have as main input parameter, the sunshine duration.

2. Objectives

Among the studies regarding the development of some estimation models of the solar radiation for Romania, it is mentioned that the most have been aimed the estimations for clear sky conditions, namely [27-29]; among the estimation models of solar radiation for real-sky conditions, there are mentioned those of Paulescu [28] and of the author [30].

Although the specialty literature suggests a series of estimation models of the solar radiation for Romania, for these models it was not also achieved a complete analysis of their performances. In addition, the estimation problem of diffuse radiation is approached very little.

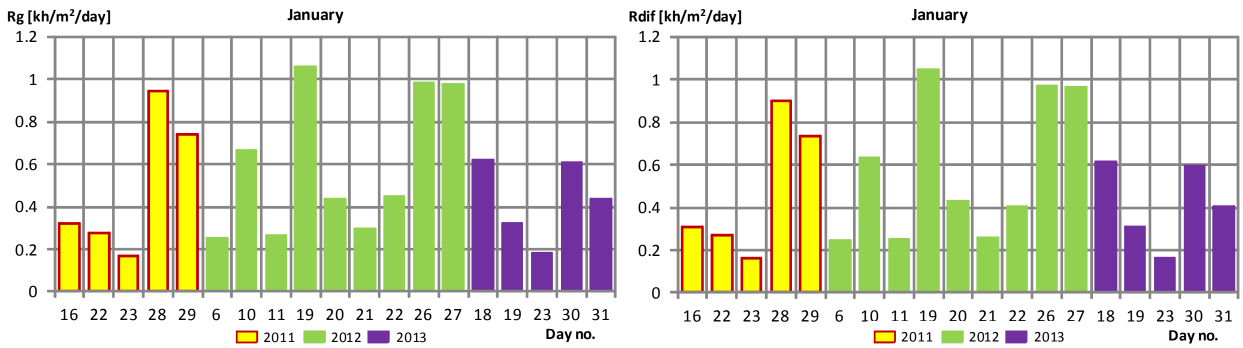
In this regard, this paper proposes the development of some estimation models both for the daily global irradiation as well as the daily diffuse irradiation, but also a complete statistical analysis for validation and testing of their performances; the area for which the study was achieved is the urban area of Braşov, Romania.

In estimating the solar radiation, the greatest difficulties were encountered in the case of estimations for cloudy days, respectively for those days in which the sunshine duration has very low values. For these days, there are recorded relatively large variations of daily solar radiation although the sunshine duration varies very little.

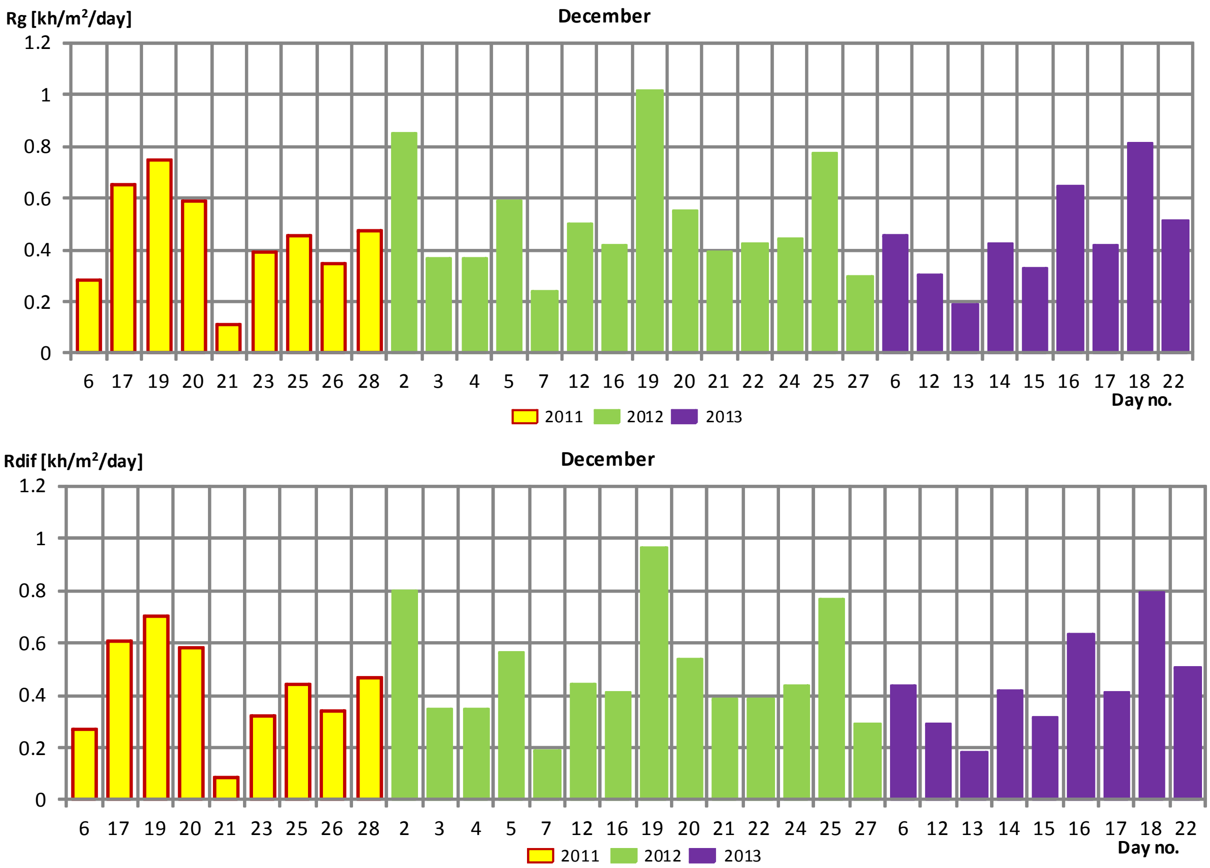
To illustrate this, Figure 1 shows the variation of daily solar irradiation – global and diffuse irradiations – for the days from January and December (2011-2013) with sunshine fraction equal to 0 (the sunshine fraction n/N is defined as the ratio between the number of sunshine hours recorded during a day, n, and the maximum daily sunshine duration, N).

It is also noted that if an estimation model of solar radiation approximates to a large extent the observed values for sunny days (high values of sunshine duration), the same model does not approximate satisfactorily the observed values of solar radiation for small values of the sunshine duration [29].

In addition, the location for which it is intended to estimate the solar radiation it is characterized annually by a large number of days for which the sunshine duration is less than 0.2 (Figure 2); during the winter months, the monthly percentage of days with a sunshine duration less than 0.2 is greater than 50%, and during periods of spring and autumn this percentage varies between 25% and 35%.



(a)



(b)

Figure 1. Variation of daily global irradiation and daily diffuse irradiation for cloudy days with sunshine fraction equal to 0: (a) January 2011-2013; (b) December 2011-2013.

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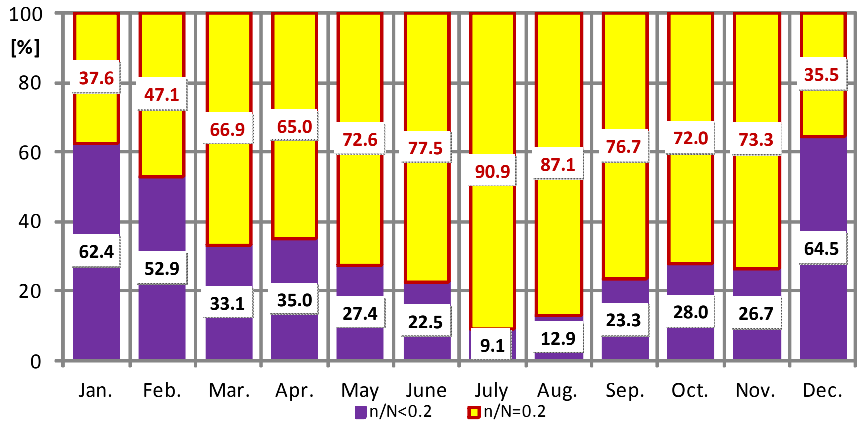


Figure 2. Monthly distribution of days with sunshine fraction n/N<0.2, respectively n/N≥0.2.

Considering those above mentioned, it appears necessary both the use of some estimation models of the solar radiation that use different regressions depending on the sunshine duration values as well as the use of some regressions that have as input parameters – in addition to sunshine duration – also other meteorological parameters; it was aimed the introduction of some meteorological parameters characteristic to the climatic conditions of the depression area of Braşov.
Therefore, the estimation models of daily global irradiation (H), proposed by this paper, are based on regressions dependent on three climate parameters, respectively, sunshine fraction (n/N), the difference between the maximum and minimum temperature (T_{max} and T_{min}) and the precipitable water amount (w – calculated according to [31, 32]).
Each month is characterized by its own estimation models, and there are two situations for which the determination of regression coefficients was achieved:

- a single regression was determined for any value of the daily sunshine fraction (a single regression on each month);
- two regressions were determined depending on the variation range of sunshine fraction values, respectively, a regression for values of sunshine fraction less than 0.2 (n/N<0.2) and a regression for n/N≥0.2 (two regressions for each month).

For the estimation of daily diffuse irradiation (for each month) are proposed two types of regressions, namely:

- regressions of second order, $H_{dif}/H(H/H_0)$, where H_0 represents the daily extraterrestrial global irradiation on a horizontal surface (H is the estimated global irradiation); they will result two sets of regressions depending on the adopted estimation model of the global irradiation;
- regressions of second order dependent on sunshine fraction, H_{dif}/H (n/N); they will result two sets of regressions depending on the estimation model of the global radiation.

As mentioned above one of the estimation models of global radiation proposes different regressions depending on the sunshine fraction values.
The limit value of 0.2 for sunshine fraction was chosen as a result of a large number of simulations that have aimed the obtaining of a high performance of the estimation models. Concretely, it was followed that Pearson's coefficient to be as close to 1.
The performances assessment of the proposed estimation models will be achieved based on the analysis of the most used statistical indicators: Mean Bias Error (MBE [kWh/m^2]), Mean Percentage Error (MPE [%]), the Root Mean Square Error (RMSE [kWh/m^2]) and t-distribution test, but it is also proposed an analysis of Pearson's coefficients.
It is mentioned that, there are situations where though the values of statistical indicators MBE, RMSE and t-distribution can take low absolute values (values that lead to the conclusion that models largely approximates the observed values) the analysis of graphs by the type: estimated values versus observed values, does not always lead to the same conclusion.
Considering this aspect, the paper also proposes the analysis of Pearson's coefficients, whose calculated values could lead to the wording of a conclusion regarding the degree to which the estimated values approximate the observed values (if Pearson's coefficient values are higher than 0.6 it can be said that the estimated values largely approximate the observed values [33]).

3. Geographical and climatic description

Obviously, solar radiation on the Earth's surface is unevenly distributed and the geographical position and the local weather conditions have a great influence for the impact of solar radiation on the terrestrial surface.

The city of Braşov (Romania) occupies an important place in the national economic system, both in size and also as activities performed by the economic agents, who are the main beneficiaries and competitors in exploitation of climate resources. Its geographical position (45°39' North latitude and 25°36' East longitude and an altitude of 790m) determines both resources of solar radiation and heat as well as the circulation specific of air masses, atmospheric processes and the climatic complex entirely.

A detailed geographical and climatic description of this city has been carried out in [29], this paper proposing a different approach, respectively a description of the variability of sky conditions; for this purpose there will be analyzed two parameters by means of which it can be made a classification of sky conditions for Braşov depression, namely: the sky ratio, SR and Perez's clearness index [4, 34].

The analysis of these parameters was performed using the weather data recorded during a period of three years, respectively 2011-2013, the diagrams of frequency occurrence being shown in Figure 3.

Classification of sky conditions for Braşov city is shown in Table 1, the limit values of the three sky conditions types being according to the values recommended by [34].

According to sky ratio values, the sky conditions for Braşov depression are mostly cloudy; according to classification after Perez clearness index, the percentage of 41.24% is represented by clear sky conditions.

Considering the two classifications, it can be said that the sky type is cloudy and partially cloudy in the proportion of about 60% - 65%.

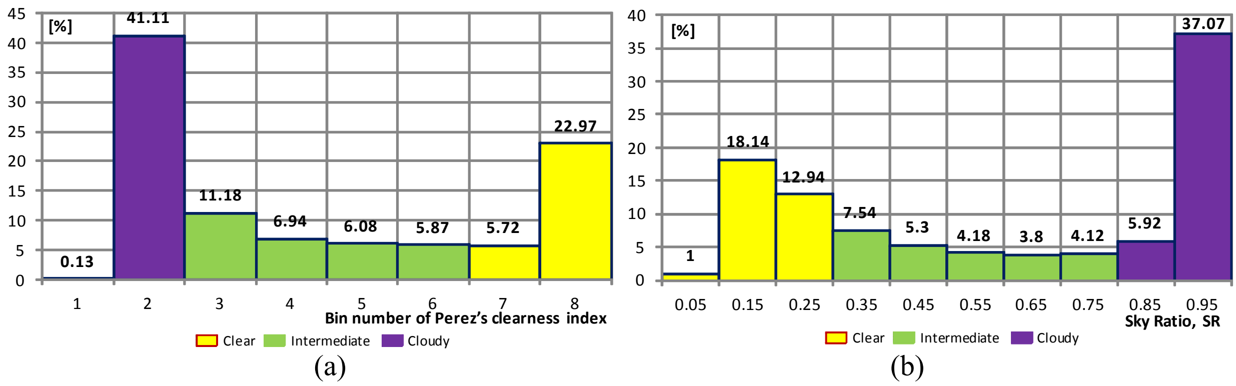


Figure 3. (a) Frequencies occurrence of sky ratio; (b) Perez's clearness index.

Table 1. Classification of sky conditions for Braşov area.

	Sky conditions		
	Clear	Partly cloudy or intermediate	Cloudy
Classification after sky ratio value, SR	SR ≤ 0.3	0.3 < SR < 0.8	SR ≥ 0.8
Frequency of SR	32.08%	24.94%	42.99%
Classification after Perez clearness index, ε	ε ≤ 1.23	1.23 < ε < 4.5	ε ≥ 4.5
Frequency of ε	41.24%	30.07%	28.69%

This analysis also comes in support of the decision to use different regressions to estimate the daily solar irradiation depending on the sky conditions (the estimation of daily solar irradiation will be achieved with different regressions for the days with clear sky and respectively for days with cloudy sky).

4. Methods

Estimation of the daily solar irradiation was achieved on the basis of the meteorological data resulted from the measurements with a weather station Delta-T for the period 2011-2013.

The solar radiation (both global radiation and diffuse radiation) was monitored at a 10 minutes range, using a SPN1 pyranometer with an uncertainty of 5% for daily measurements [35]). The weather station was described in [29].
For periodically comparing and validating the recorded data, the Delta-T weather station is working in parallel with a weather station, Vaisala equipped with a Kipp&Zonnen CM6B pyranomenter, installed by the Romanian National Institute for Meteorology and Hydrology.
The meteorological data processing has required the use of specialized software to allow the processing of large volume of data, respectively Visual FoxPro.

5. Models for estimation of the daily solar irradiation

5.1 Estimation of the daily solar irradiation using for the global component one regression specific to every month – the M1 model

The first estimation model of daily global irradiation proposes the use of regressions that have as input data: the sunshine fraction, air temperature and precipitable water amount.
Twelve regressions were developed to estimate the daily global irradiation, regressions specific to each month of the year (Table 2).
On the basis of estimation regressions of the daily global irradiation, for estimation of the daily diffuse irradiation, two types of regressions are proposed, namely:

- regressions of the type $H_{dif}/H(H/H_0)$ – this type of regression is proposed mostly by the literature (Table 3);
- regressions of the type $H_{dif}/H(n/N)$ (Table 4); the obtaining of an estimation model as precisely – that approximates the observed values largely – involves the assessment of its performances; as mentioned before, there are a series of statistical parameters based on which, the performances assessment of a model is made; however, there are situations when although a statistical indicator validates the proposed model, in terms of another statistic indicator, the model does not present satisfactory performance; in this study, the main objective (that was the basis for determination the estimation models) consisted in the obtaining of higher values of Pearson's coefficient; following the determination of Pearson's coefficients for the two type of tested regressions, the type $H_{dif}/H(n/N)$ led to high values of this coefficient, especially for the periods of cold months (this aspect will be developed in the next section).

Table 2. Regressions for estimation of the daily global irradiation – the M1 model.

Month	Regression
January	$H/H_0 = 0.2391 + 0.5331(n/N) + 0.06262(T_{max} - T_{min})^{0.5} - 0.1586\,w$
February	$H/H_0 = 0.1991 + 0.5383(n/N) + 0.052(T_{max} - T_{min})^{0.5} - 0.0673\,w$
March	$H/H_0 = 0.1883 + 0.4691\,(n/N) + 0.0651(T_{max} - T_{min})^{0.5} - 0.1065\,w$
April	$H/H_0 = 0.0771 + 0.4888(n/N) + 0.07161(T_{max} - T_{min})^{0.5} - 0.0272\,w$
May	$H/H_0 = 0.1141 + 0.4801(n/N) + 0.0705(T_{max} - T_{min})^{0.5} - 0.0394\,w$
June	$H/H_0 = 0.14607 + 0.47478(n/N) + 0.06989(T_{max} - T_{min})^{0.5} - 0.04061\,w$
July	$H/H_0 = 0.2107 + 0.45698(n/N) + 0.04123(T_{max} - T_{min})^{0.5} - 0.02371\,w$
August	$H/H_0 = 0.1522 + 0.48999(n/N) + 0.03417(T_{max} - T_{min})^{0.5} - 0.00278\,w$
September	$H/H_0 = 0.135793 + 0.469811(n/N) + 0.04577(T_{max} - T_{min})^{0.5} - 0.00741\,w$
October	$H/H_0 = 0.196326 + 0.550929(n/N) + 0.030483(T_{max} - T_{min})^{0.5} - 0.03611\,w$
November	$H/H_0 = 0.143933 + 0.519905(n/N) + 0.033916(T_{max} - T_{min})^{0.5} + 0.00972\,w$
December	$H/H_0 = 0.213506 + 0.548727(n/N) + 0.031329(T_{max} - T_{min})^{0.5} - 0.07047\,w$

Table 3. Regressions for estimation of the daily diffuse irradiation (estimation of the daily global irradiation with the M1 model).

Month	Regression
January	$H_{dif}/H = -1.7643(H/H_0)^2 + 0.707(H/H_0) + 0.7884$
February	$H_{dif}/H = -1.746(H/H_0)^2 + 0.6845(H/H_0) + 0.7834$
March	$H_{dif}/H = -1.7138(H/H_0)^2 + 0.4664(H/H_0) + 0.8137$
April	$H_{dif}/H = -0.9432(H/H_0)^2 - 0.2483(H/H_0) + 0.917$
May	$H_{dif}/H = -0.4788(H/H_0)^2 - 0.7659(H/H_0) + 1.0311$
June	$H_{dif}/H = -0.3851(H/H_0)^2 - 0.84(H/H_0) + 1.0084$
July	$H_{dif}/H = -0.4152(H/H_0)^2 - 0.8722(H/H_0) + 1.0338$
August	$H_{dif}/H = -0.3298(H/H_0)^2 - 0.914(H/H_0) + 1.0293$
September	$H_{dif}/H = -1.9071(H/H_0)^2 + 0.7417(H/H_0) + 0.6805$
October	$H_{dif}/H = -1.6653(H/H_0)^2 + 0.4317(H/H_0) + 0.7963$
November	$H_{dif}/H = -1.0474(H/H_0)^2 - 0.2187(H/H_0) + 0.9347$
December	$H_{dif}/H = -1.502(H/H_0)^2 + 0.2058(H/H_0) + 0.9237$

Table 4. Regressions for estimation of the daily diffuse irradiation (estimation of the daily global irradiation with the M1 model).

Month	Regression
January	$H_{dif}/H = -0.6031(n/N)^2 - 0.1883(n/N) + 0.8759$
February	$H_{dif}/H = -0.5301(n/N)^2 - 0.2802(n/N) + 0.8671$
March	$H_{dif}/H = -0.2829(n/N)^2 - 0.489(n/N) + 0.8662$
April	$H_{dif}/H = -0.2413(n/N)^2 - 0.5142(n/N) + 0.8497$
May	$H_{dif}/H = 0.021(n/N)^2 - 0.783(n/N) + 0.8839$
June	$H_{dif}/H = 0.0301(n/N)^2 - 0.7621(n/N) + 0.843$
July	$H_{dif}/H = -0.108(n/N)^2 - 0.5751(n/N) + 0.798$
August	$H_{dif}/H = -0.0261(n/N)^2 - 0.6583(n/N) + 0.8241$
September	$H_{dif}/H = -0.4541(n/N)^2 - 0.1882(n/N) + 0.7738$
October	$H_{dif}/H = -0.6857(n/N)^2 - 0.0972(n/N) + 0.817$
November	$H_{dif}/H = -0.0942(n/N)^2 - 0.6142(n/N) + 0.8606$
December	$H_{dif}/H = -0.5845(n/N)^2 - 0.2119(n/N) + 0.9045$

5.2 Estimation of the daily solar irradiation using for the global component two regressions (depending on the variation range of sunshine fraction) specific to every month – the M2 model

The second estimation model of daily global irradiation proposes the use of different regressions according to the values of sunshine fraction; the proposed regressions are dependent on sunshine

fraction, air temperature (maximum and minimum daily values of the air temperature) and the precipitable water amount (Table 5).
Depending on the values of daily global irradiation, two types of regressions for estimation of the daily diffuse irradiation were determined (Table 6 and Table 7).

Table 5. Regressions for estimation of the daily global irradiation – the M2 model.

Month	n/N	Regression
Jan.	n/N<0.2	$H/H_0 = 0.2745 + 1.2684(n/N) + 0.0421(T_{max} - T_{min})^{0.5} - 0.1932\,w$
	n/N≥0.2	$H/H_0 = 0.3046 + 0.4161(n/N) + 0.0642(T_{max} - T_{min})^{0.5} - 0.1534\,w$
Feb.	n/N<0.2	$H/H_0 = 0.0412 + 1.1145(n/N) + 0.0859(T_{max} - T_{min})^{0.5} - 0.0134\,w$
	n/N≥0.2	$H/H_0 = 0.3784 + 0.4855(n/N) + 0.0008(T_{max} - T_{min})^{0.5} - 0.0593\,w$
Mar.	n/N<0.2	$H/H_0 = 0.1051 + 0.6443(n/N) + 0.0951(T_{max} - T_{min})^{0.5} - 0.1084\,w$
	n/N≥0.2	$H/H_0 = 0.2565 + 0.4617(n/N) + 0.0346(T_{max} - T_{min})^{0.5} - 0.0616\,w$
Apr.	n/N<0.2	$H/H_0 = -0.0312 + 0.9346(n/N) + 0.0854(T_{max} - T_{min})^{0.5} + 0.0069\,w$
	n/N≥0.2	$H/H_0 = 0.1846 + 0.4716(n/N) + 0.0462(T_{max} - T_{min})^{0.5} - 0.0345\,w$
May	n/N<0.2	$H/H_0 = 0.0615 + 1.1428(n/N) + 0.055(T_{max} - T_{min})^{0.5} - 0.0081\,w$
	n/N≥0.2	$H/H_0 = 0.239 + 0.4972(n/N) + 0.0311(T_{max} - T_{min})^{0.5} - 0.0387\,w$
Jun.	n/N<0.2	$H/H_0 = 0.00261 + 0.7878(n/N) + 0.08694(T_{max} - T_{min})^{0.5} - 0.0071\,w$
	n/N≥0.2	$H/H_0 = 0.26288 + 0.48412(n/N) + 0.02677(T_{max} - T_{min})^{0.5} - 0.03082\,w$
Jul.	n/N<0.2	$H/H_0 = -0.03986 + 0.8664(n/N) + 0.106(T_{max} - T_{min})^{0.5} - 0.00652\,w$
	n/N≥0.2	$H/H_0 = 0.26712 + 0.43406(n/N) + 0.03295(T_{max} - T_{min})^{0.5} - 0.02872\,w$
Aug.	n/N<0.2	$H/H_0 = -0.18691 + 0.91488(n/N) + 0.07998(T_{max} - T_{min})^{0.5} + 0.073759\,w$
	n/N≥0.2	$H/H_0 = 0.26715 + 0.47987(n/N) + 0.01163(T_{max} - T_{min})^{0.5} - 0.01558\,w$
Sep.	n/N<0.2	$H/H_0 = 0.018613 + 0.964207(n/N) + 0.051911(T_{max} - T_{min})^{0.5} + 0.017222\,w$
	n/N≥0.2	$H/H_0 = 0.259429 + 0.412306(n/N) + 0.03125(T_{max} - T_{min})^{0.5} - 0.02129\,w$
Oct.	n/N<0.2	$H/H_0 = 0.119421 + 1.191278(n/N) + 0.047935(T_{max} - T_{min})^{0.5} - 0.03671\,w$
	n/N≥0.2	$H/H_0 = 0.374648 + 0.468461(n/N) + 0.006497(T_{max} - T_{min})^{0.5} - 0.05612\,w$
Nov.	n/N<0.2	$H/H_0 = 0.075841 + 1.056499(n/N) + 0.044562(T_{max} - T_{min})^{0.5} + 0.026519\,w$
	n/N≥0.2	$H/H_0 = 0.282354 + 0.478946(n/N) + 0.00665(T_{max} - T_{min})^{0.5} - 0.01361\,w$
Dec.	n/N<0.2	$H/H_0 = 0.151144 + 1.16346(n/N) + 0.033173(T_{max} - T_{min})^{0.5} - 0.02569\,w$
	n/N≥0.2	$H/H_0 = 0.420509 + 0.470092(n/N) - 0.01111(T_{max} - T_{min})^{0.5} - 0.11861\,w$

The analysis of diagrams by type: Observed values versus estimated values, emphasizes a good approximation of the daily global irradiation regardless of the chosen estimation model (Figure 4).
As regards the estimation models of the daily diffuse irradiation (Figures 5 and 6) it is recorded a higher spreading of the estimated values compared to the observed values, especially for values of the daily diffuse irradiation higher than 1.5kWh/m^2/day (namely, for cloudy days with low and very low values of the sunshine fraction n/N). If for estimating the daily global irradiation, the M2 model is used, it can be noted a closeness – to a lesser extent – of the estimated values towards the observed daily diffuse

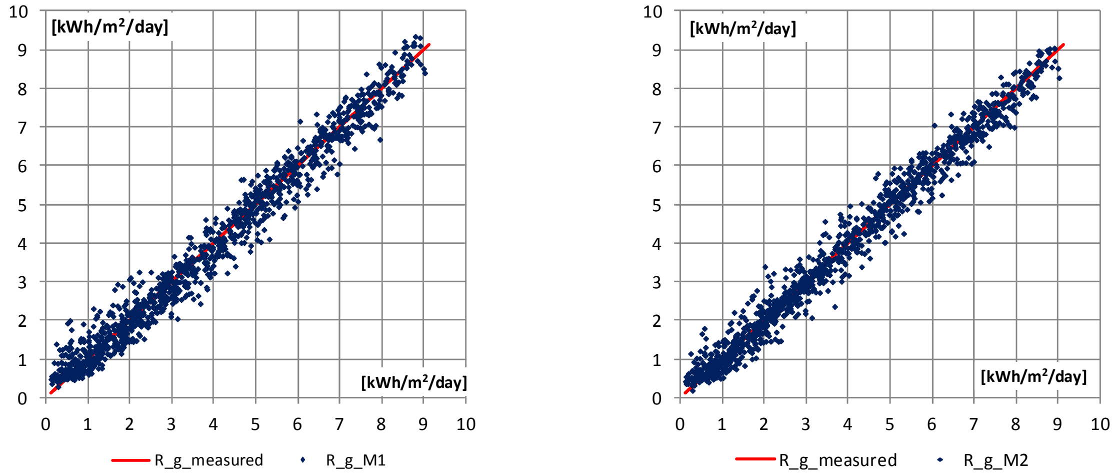
irradiation. This closeness is more obvious when for the estimation of daily diffuse irradiation are used the regressions by type $H_{dif}/H(n/N)$ (Figure 6,(b)), especially for high values of the daily diffuse irradiation.

Table 6. Regressions for estimation of the daily diffuse irradiation (estimation of daily global irradiation with the M2 model).

Month	Regression
January	$H_{dif}/H = -1.0574(H/H_0)^2 - 0.1291(H/H_0) + 0.9871$
February	$H_{dif}/H = -1.4623(H/H_0)^2 + 0.167(H/H_0) + 0.9631$
March	$H_{dif}/H = -0.6984(H/H_0)^2 - 0.6991(H/H_0) + 1.1121$
April	$H_{dif}/H = 0.0707(H/H_0)^2 - 1.3835(H/H_0) + 1.1978$
May	$H_{dif}/H = -0.1698(H/H_0)^2 - 1.1445(H/H_0) + 1.1376$
June	$H_{dif}/H = 0.2083(H/H_0)^2 - 1.5609(H/H_0) + 1.2116$
July	$H_{dif}/H = -0.0435(H/H_0)^2 - 1.3472(H/H_0) + 1.1804$
August	$H_{dif}/H = -0.0516(H/H_0)^2 - 1.2791(H/H_0) + 1.1449$
September	$H_{dif}/H = -0.8781(H/H_0)^2 - 0.4695(H/H_0) + 1.0081$
October	$H_{dif}/H = -0.4663(H/H_0)^2 - 0.9261(H/H_0) + 1.1375$
November	$H_{dif}/H = -0.5537(H/H_0)^2 - 0.8013(H/H_0) + 1.0939$
December	$H_{dif}/H = -1.2628(H/H_0)^2 - 0.0898(H/H_0) + 0.9969$

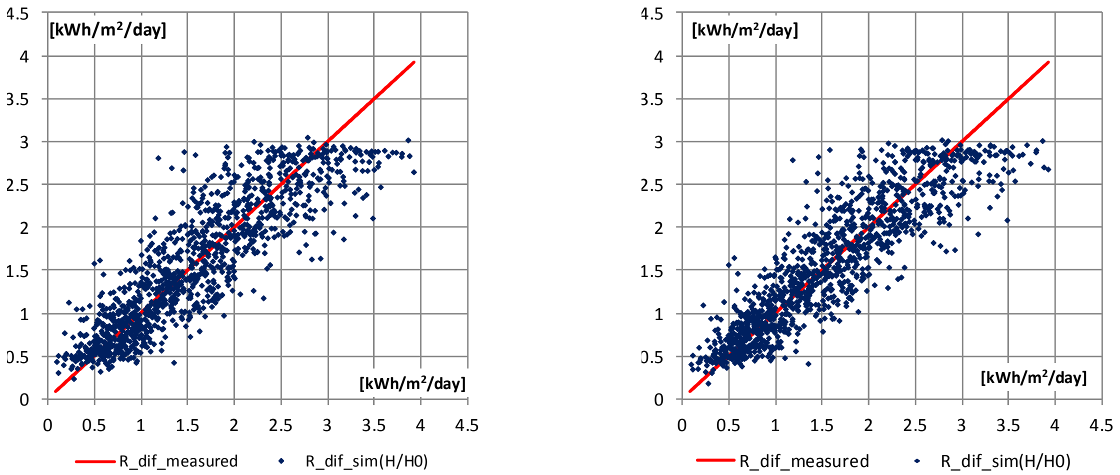
Table 7. Regressions for estimation of the daily diffuse irradiation (estimation of daily global irradiation with the M2 model).

Month	Regression
January	$H_{dif}/H = 0.1567(n/N)^2 - 0.8801(n/N) + 0.95$
February	$H_{dif}/H = 0.1399(n/N)^2 - 0.9261(n/N) + 0.9523$
March	$H_{dif}/H = 0.2417(n/N)^2 - 1.0506(n/N) + 0.965$
April	$H_{dif}/H = 0.3487(n/N)^2 - 1.1576(n/N) + 0.9683$
May	$H_{dif}/H = 0.2854(n/N)^2 - 1.0733(n/N) + 0.9422$
June	$H_{dif}/H = 0.4446(n/N)^2 - 1.2469(n/N) + 0.9526$
July	$H_{dif}/H = 0.2729(n/N)^2 - 1.0345(n/N) + 0.9132$
August	$H_{dif}/H = 0.2539(n/N)^2 - 1.0017(n/N) + 0.9082$
September	$H_{dif}/H = 0.1365(n/N)^2 - 0.8769(n/N) + 0.9131$
October	$H_{dif}/H = 0.1801(n/N)^2 - 1.0222(n/N) + 0.9668$
November	$H_{dif}/H = 0.4321(n/N)^2 - 1.1577(n/N) + 0.9495$
December	$H_{dif}/H = 0.0744(n/N)^2 - 0.8(n/N) + 0.9453$



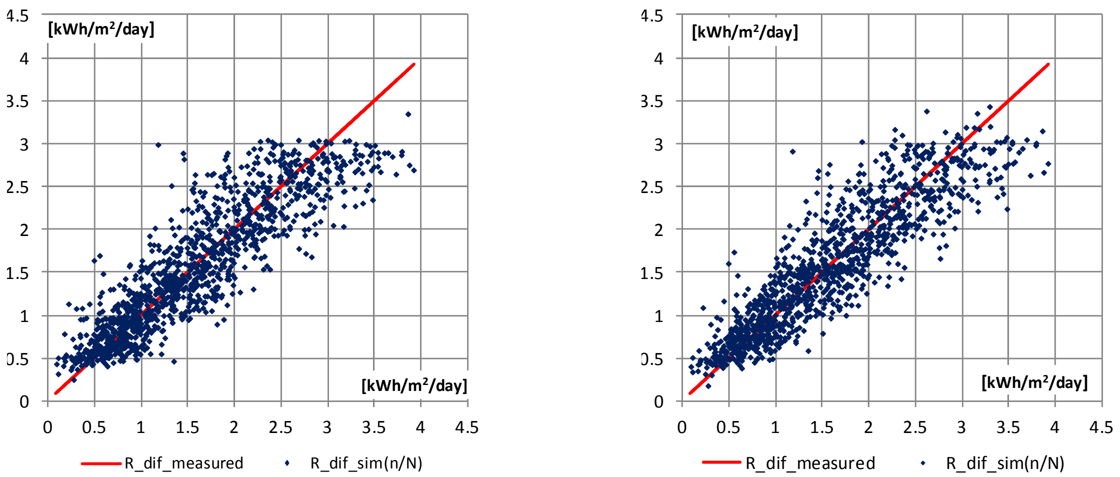
(a) (b)

Figure 4. Estimated values versus observed values of the daily global irradiation: (a) daily global irradiation estimated with the M1 model; (b) daily global irradiation estimated with the M2 model.



(a) (b)

Figure 5. Estimated values versus observed values of the daily diffuse irradiation – regressions by type $H_{dif}/H(H/H_0)$: (a) daily global irradiation estimated with the M1 model; (b) daily global irradiation estimated with the M2 model.



(a) (b)

Figure 6. Estimated values versus observed values of the daily diffuse irradiation – regressions of type Hdif/H(n/N): (a) daily global irradiation estimated with the M1 model; (b) daily global irradiation estimated with the M2 model.

In order to validate the estimation models of the daily solar irradiation, it is required, in addition to a statistical analysis of their performances evaluation parameters, also a visual graphical analysis of variation diagrams of the daily irradiation. Thus Figures 7 and 8 show the diagrams of daily variation of observed radiation values and estimated radiation values, but for days of the year 2014; therefore it is proposed a validation of the estimation models for days that have not formed the basis of determining the presented regressions. To highlight the importance of using different estimation models for cloudy days ($n/N<0.2$) – of estimation models that use two regressions dependent on sunshine fraction value n/N – Figure 8 presents the variation diagrams of daily solar irradiation for a series of days in 2014, for what the sunshine fraction is less than 0.2 ($n/N <0.2$).

6. Quantification of the correlations intensity

As has been previously mentioned, the criterion that led to the obtaining of estimation models of the daily solar irradiation that to approximate as much as possible the observed values, was represented by the increase of Pearson's coefficient values. For this reason, the analysis of this indicator values is proposed separately, at this stage. Therefore, to determine the interdependence between the estimated variables and the observed variables, and to measure the degree of correlation between them, further, there will be made an analysis of the Pearson's coefficients obtained for each of the proposed models. This coefficient has values between -1 and 1, but in these situations this takes positive values indicating a direct correlation (the two correlated variables vary in the same direction).

Pearson's coefficient values calculated for estimation model of the daily global irradiation M1 (Table 8) indicate a very strong correlation between the observed values and estimated values ($r>0.8$). The minimum value of the correlation coefficient is of 0.933 and this was obtained for estimations of February. If the estimation of daily global radiation is made using model M2, an increase of Pearson's coefficient values is observed, especially for estimations made for the periods of the cold months. For the estimations made with this model, the minimum value of Pearson's coefficient is of 0951 and this value is also obtained for February.

In the case of estimation models of the daily diffuse irradiation the Pearson's coefficient values are significantly smaller than those obtained for estimating the daily global irradiation (Table 9).

Using the M1 model for the daily global irradiation and regressions of type $H_{dif}/H(H/H_0)$ for the daily diffuse irradiation, the values of the correlation coefficient indicate a strong correlation ($r\in 0.6, 0.8]$) for the months of January and March to October; the estimations for February, November and December indicate a reasonable correlation between estimated values and observed values ($r\in [0.4, 0.6]$). The weakest correlation is given by the estimation model for December. For regressions of type $H_{dif}/H(n/N)$, the Pearson's coefficient values are higher than in the previous case. Thus, during the months of January to October, the correlation coefficient values indicate a strong correlation ($r\in [0.6, 0.8]$), and during a period of two months, November and December, a reasonable correlation. The minimum value of Pearson's coefficient was obtained for the estimations of the month December.

When the estimation of the daily global irradiation is achieved with the model M2, the Pearson's coefficient values for the estimation models of daily diffuse irradiation are significantly higher (compared to the use of model M1), the values being corresponding to a strong correlation for the months from January to November and only in December the correlation coefficient value is corresponding to a reasonable correlation.

For regressions of type $H_{dif}/H(H/H_0)$, the correlation coefficient values for the period January to November, is within the range of 0.605 – 0.806, and for regressions of type $H_{dif}/H(n/N)$, for the same period, between 0.657 – 0.801.

It is noted that during the months of July to September, Pearson's coefficient values for the estimations using regressions of type $H_{dif}/H(H/H_0)$ are higher than when using regressions of type $H_{dif}/H(n/N)$.

In case of the estimations for the month of December, although the regression of type $H_{dif}/H(n/N)$ (for the M2 estimation model of the daily global irradiation) leads to a value of the Pearson's coefficient that corresponds to a reasonable correlation, however this value is the maximum value of Pearson's coefficient (0.579) that could be obtained for the estimation of daily diffuse irradiation for December.

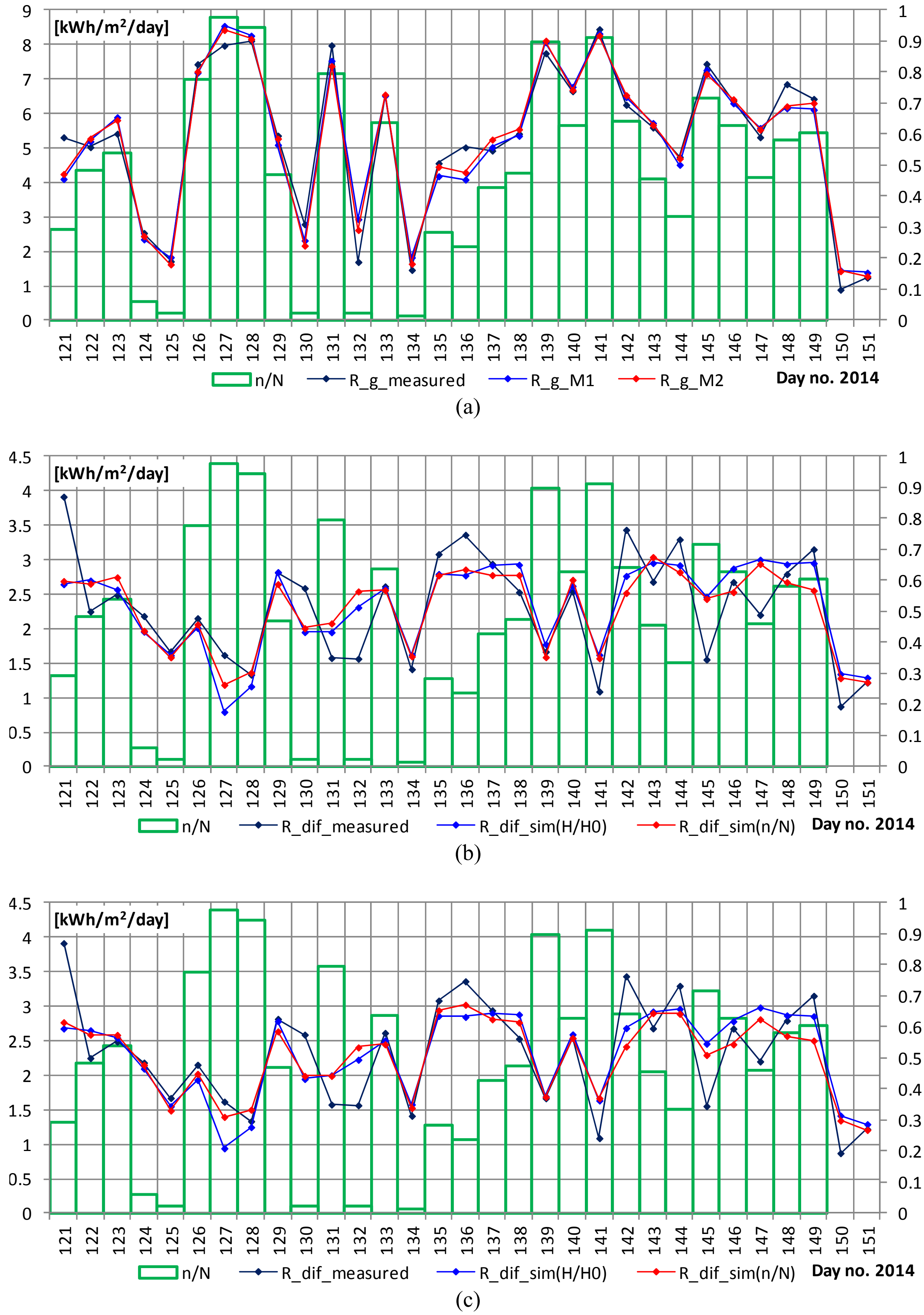
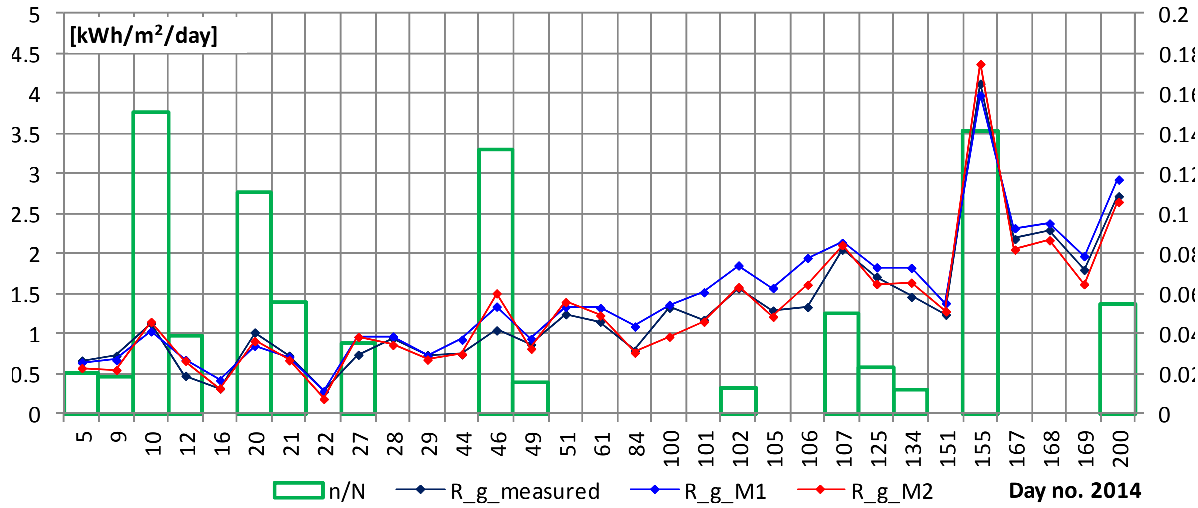
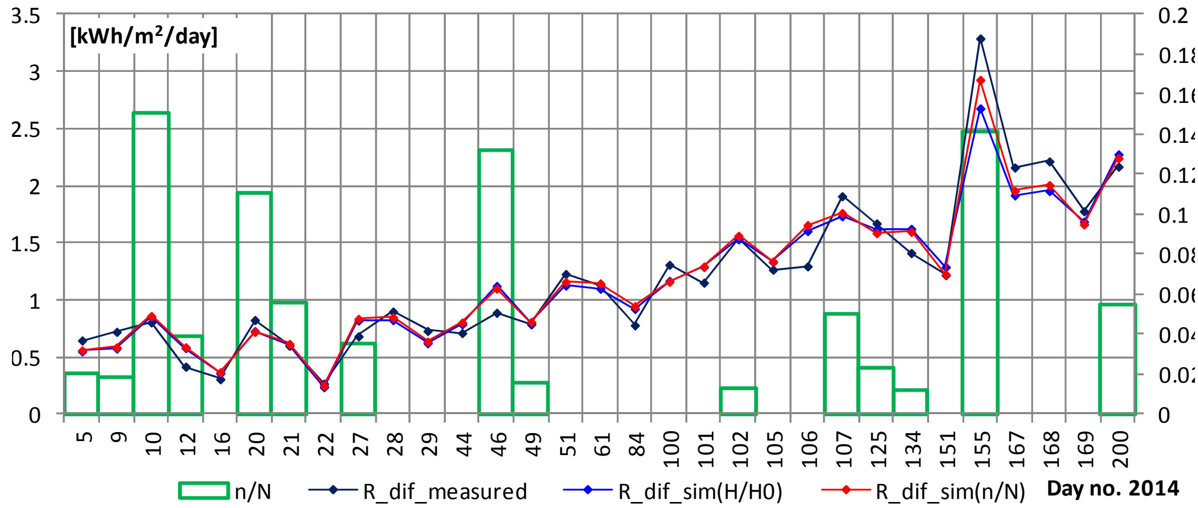


Figure 7. Variation of the observed values and the estimated values for the daily irradiation during May 2014: (a) variation of the daily global irradiation; (b) variation of the daily diffuse irradiation – estimation of the daily diffuse irradiation is based on estimation model M1 of the daily global radiation; (c) variation of the daily diffuse irradiation – estimation of the daily diffuse irradiation is based on estimation model M2 of the daily global radiation.



(a)



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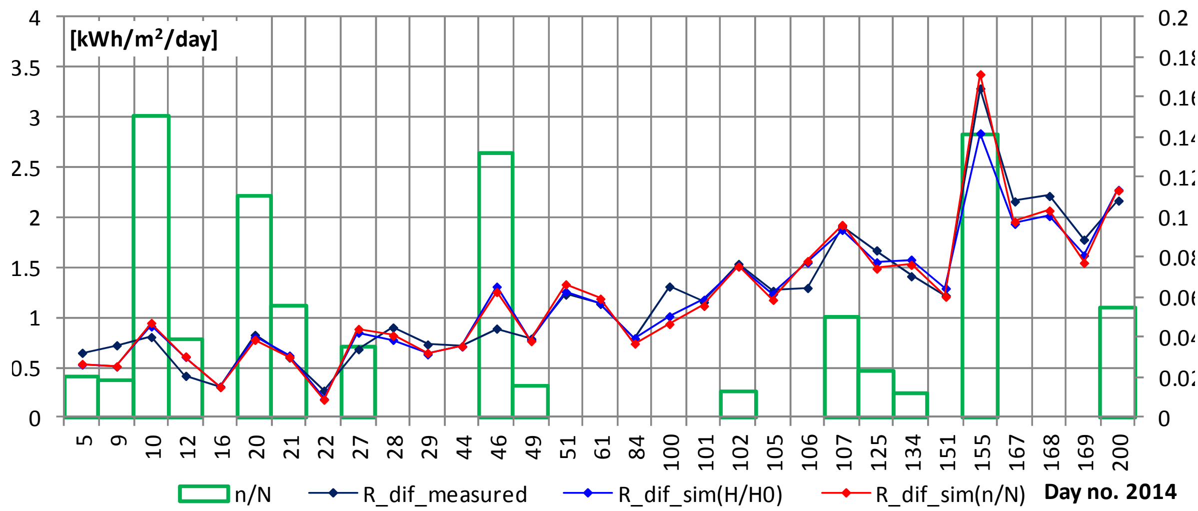


(c)

Figure 8. Variation of the observed values and the estimated values for the daily irradiation for a series of days in 2014, in which n/N<0.2: (a) variation of the daily global irradiation; (b) variation of the daily diffuse irradiation – estimation of the daily diffuse irradiation is based on estimation model M1 of the daily global radiation; (c) variation of the daily diffuse irradiation – estimation of the daily diffuse irradiation is based on estimation model M2 of the daily global radiation.

Table 8. Pearson's coefficients and correlation coefficients (R^2) calculated for the two estimation models of the daily global irradiation.

Month	Model M1		Model M2	
	R	R^2	R	R^2
January	0.951	0.904	**0.961**	0.924
February	0.933	0.870	**0.951**	0.905
March	0.967	0.936	**0.973**	0.946
April	0.972	0.945	**0.977**	0.954
May	0.981	0.962	**0.984**	0.967
June	0.973	0.947	**0.978**	0.957
July	0.968	0.937	**0.973**	0.946
August	0.975	0.950	**0.980**	0.960
September	0.977	0.955	**0.985**	0.970
October	0.970	0.942	**0.979**	0.958
November	0.973	0.947	**0.982**	0.963
December	0.946	0.895	**0.955**	0.913

Table 9. Pearson's coefficients (r) and correlation coefficients (R^2) calculated for the estimation models of the daily diffuse irradiation.

Month	Global radiation estimated with the M1 model				Global radiation estimated with the M2 model			
	$H_{dif}/H(H/H_0)$		$H_{dif}/H(n/N)$		$H_{dif}/H(H/H0)$		$H_{dif}/H(n/N)$	
	r	R^2	r	R^2	R	R^2	r	R^2
January	0.641	0.411	0.727	0.529	0.705	0.497	0.783	0.612
February	0.584	0.341	0.611	0.374	0.656	0.430	0.694	0.481
March	0.701	0.492	0.759	0.576	0.745	0.555	0.773	0.599
April	0.702	0.492	0.757	0.572	0.729	0.531	0.765	0.585
May	0.753	0.567	0.785	0.616	0.752	0.565	0.789	0.606
June	0.733	0.537	0.740	0.548	0.750	0.563	0.754	0.571
July	0.763	0.582	0.744	0.553	0.786	0.617	0.776	0.601
August	0.777	0.603	0.790	0.624	0.806	0.650	0.801	0.642
September	0.789	0.623	0.788	0.620	0.802	0.643	0.785	0.616
October	0.719	0.517	0.737	0.544	0.745	0.555	0.764	0.584
November	0.556	0.309	0.542	0.294	0.605	0.365	0.657	0.432
December	0.481	0.231	0.517	0.267	0.530	0.281	0.579	0.336

7. Assessment of performances for the proposed estimation models

The statistical testing of the performances for the proposed estimation models consisted of:

- achieving of the models comparison based on the values of Mean Percentage Error (MPE [%]);
- testing the models' tendency to underestimate or to overestimate the observed values and the obtaining of information on long-term regarding the performances of these models (analysis of the Mean Bias Error indicator (MBE [kWh/m^2]));
- quality analysis of the models on short-term and testing of the scattering level of these, by achieving a comparison of the actual deviation between the observed and estimated values (analysis of the Root Mean Square Error indicator (RMSE [kWh/m^2]));
- statistical testing to determine if the models are statistically significant (t-distribution test).

The calculation relations for the used statistical indicators are according to those presented in [33, 29].

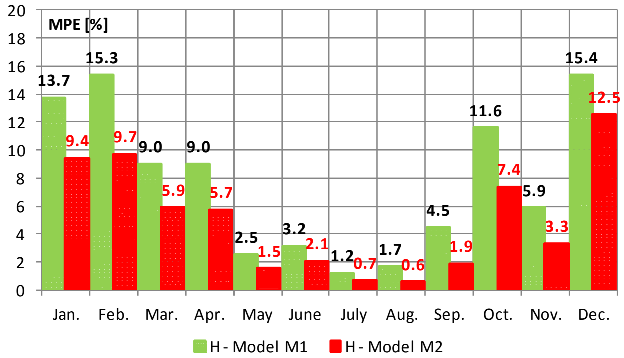
Therefore, in the first stage of statistical testing, the analysis of the MPE indicator values is proposed, the calculated values for estimation models of the daily global irradiation being shown in Figure 9,(a) and those for estimation models of the diffuse daily irradiation in Figures 9,(b) and 9,(c).

The highest values of the MPE indicator are recorded during the cold months, from October to December, respectively from January to April, both at estimation of the daily global radiation as well as at estimation of the daily diffuse irradiation; this conclusion highlights the need to develop different estimation models for cloudy days, characterized by low values of sunshine duration (and implicitly, low values of sunshine fraction).

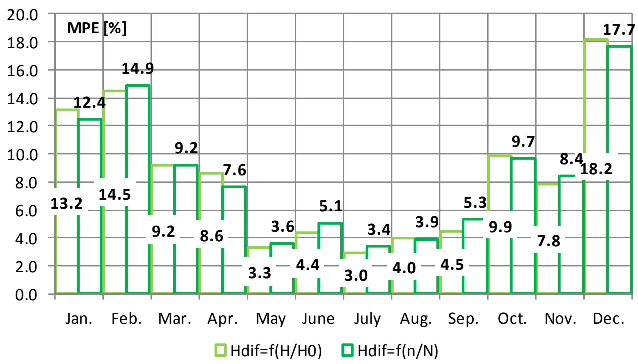
The use of the estimation model of the daily global irradiation, M2, leads to values of the MPE indicator significantly lower than those obtained when using the estimation model, M1 (the differences are more pronounced for the cold months from October to December and respectively from January to April).

In the case of estimations for the daily diffuse irradiation (regardless the estimation model M1 or M2, for the daily global irradiation), for six months of the year, namely February, May, June, July, August, September, the MPE values are lower at the use of regressions of type $H_{dif}/H(H/H_0)$ compared to regressions of type $H_{dif}/H(n/N)$.

It is also noted that the use of M2 model of the daily global irradiation is justified to estimation of the daily diffuse irradiation, especially for estimations corresponding to cold periods, January to March respectively November to December, Figure 10 (the M2 model uses different regressions for the estimation of daily global irradiation, these models being dependent of the variation interval of sunshine fraction values, n/N<0.2, respectively n/N≥0.2).



(a)



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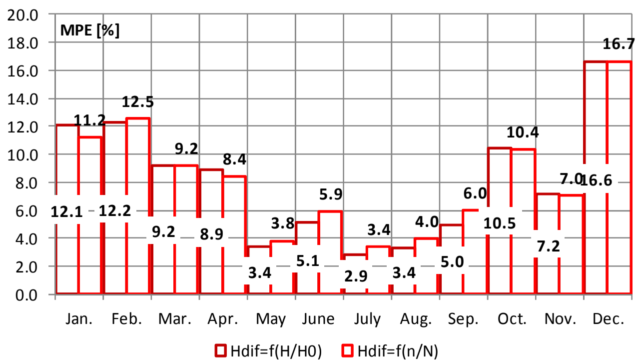

(c)

Figure 9. Monthly values of the MPE indicator: (a) MPE values for estimation of the daily global irradiation; (b) MPE values, for estimation of the daily diffuse irradiation – the daily global irradiation estimated with the M1 model; (c) MPE values, for estimation of the daily diffuse irradiation – the daily global irradiation estimated with the M2 model.

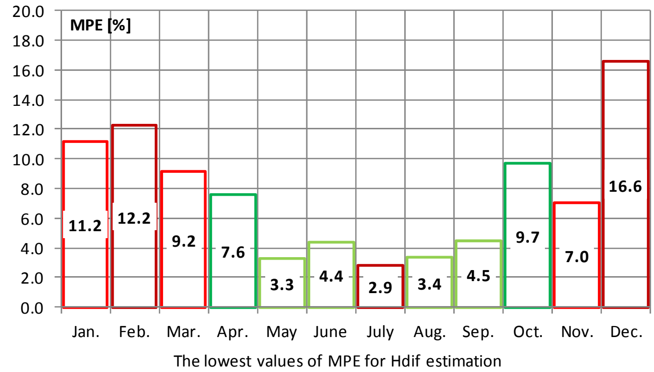

Figure 10. Recommendations for estimation models of the daily diffuse irradiation considering the lowest values obtained for the MPE indicator.

However, for the period from May to September, for the simplification of estimation models, a single monthly regression can be used to estimate the daily global irradiation (model M1) and regressions of the type $H_{dif}/H(H/H_0)$ for estimations of the daily diffuse irradiation (although from Figure 9, for July it is recommended the use of estimation model M2 for the daily global irradiation, the MPE value at estimation of the daily diffuse irradiation is only with 0.1% lower compared to the recommended situation).

In practice, the most used indicators of measuring the error of estimation are: Root Mean Squared Error (RMSE) and Mean Bias Error (MBE).

The monthly values of the MBE indicator obtained for estimation of the daily global irradiation are within the values -0.00449 and 0.0057, when using the model M1 and between -0.00439 and 0.0163 when using the model M2 (Table 10). The minimum monthly values of the MBE indicator are obtained for estimations made with the M1 model for seven months of the year, and respectively for five months of the year for estimations made with the M2 model.

When estimating the daily diffuse irradiation, the lowest values of the MBE indicator are obtained if estimation of the daily global irradiation was performed with model M1 (for eight months).

When referring to the type of regression used to estimate the daily diffuse irradiation ($H_{dif}/H(H/H_0)$ or $H_{dif}/H(n/N)$) it can be seen that the minimum values of the MBE indicator are obtained for 6 months for each type regression (Table 10).

Table 10. Monthly values of Mean Bias Error (MBE).

Month	MBE [kWh/m^2]					
	Daily global irradiation		Daily diffuse irradiation			
			Model M1 for estimation of the daily global irradiation		Model M2 for estimation of the daily global irradiation	
	Model M1	Model M2	$H_{dif}/H(H/H_0)$	$H_{dif}/H(n/N)$	$H_{dif}/H(H/H_0)$	$H_{dif}/H(n/N)$
Jan.	**-0,00157**	-0,00402	**-0,00513**	-0,00939	-0,00515	-0,00657
Feb.	-0,00449	**-0,00439**	0,01017	**-0,00023**	0,00811	-0,00063
Mar.	**-0,00012**	-0,00066	**-0,00011**	-0,00851	-0,00078	0,00101
Apr.	0,00179	**-0,00104**	**0,00138**	-0,00389	0,00258	0,00555
May	-0,00239	**-0,00218**	0,00285	-0,00121	0,00251	**0,00068**
June	**0,00068**	0,01630	**-0,00025**	-0,00069	0,00769	0,01643
July	**0,00376**	0,00953	0,00314	0,00480	**0,00296**	0,00452
Aug.	**-0,00273**	-0,00303	**0,00018**	-0,00287	-0,00088	-0,00218
Sep.	**0,00075**	0,00214	0,00187	**-0,00030**	0,00394	0,00647
Oct.	0,00570	**0,00335**	0,00271	**0,00048**	0,00332	0,00348
Nov.	**-0,00089**	-0,00180	0,00354	0,00493	0,00488	**0,00223**
Dec.	0,00099	**0,00088**	0,00113	0,00144	0,00115	**0,00001**

Another indicator commonly used for the validation and the comparison of the estimation models is the Root Mean Squared Error (RMSE).
According to the obtained values of the RMSE indicator, for the estimation of the daily global irradiation, the lowest values of this were obtained for the estimations made using the M2 model; it is noted that, the same as in the analysis of monthly values of Pearson's coefficient, from the RMSE indicator point of view, for estimation of the daily global irradiation, the use of regressions corresponding to model M2 is recommended (Table 11).
Also, in the case of estimation models of the daily diffuse irradiation – similarly with the recommendations resulted from the Pearson's coefficient analysis – the lowest values of the RMSE indicator were obtained at the use of model M2 for estimating the daily global irradiation, and for the months from July to September at the use of regressions of the type $H_{dif}/H(H/H_0)$.
Regardless of the estimation model – of the daily global irradiation or the daily diffuse irradiation – the greatest values of the spreading degree were obtained for the period from March to July.
However, there are situations in which, although performances testing of an estimation model with the indicators: MPE, MBE and RMSE, leads to low absolute values of these parameters, the estimation model does not validate in a satisfactory measure the real variation of analyzed parameter.
In view of a trustful testing of an estimation model, it is recommended the corroborating of results obtained with statistical indicators: MPE, MBE and RMSE, with results of t-distribution testing.
The t-distribution test is not introduced to replace the testing with the statistical indicators: MPE, MBE and RMSE, but as an additional criterion that allows a more complete assessment and a rapid and efficient testing of performances of an estimation model.
The introduction of this test as validation stage for the estimation models of the daily solar irradiation is extremely popular among researchers because of the rapid and rigorous results that can be obtained; such, the calculated values of t-distribution indicator, in view of tested model validation, must be less than the t-distribution critical values (values provided by statistical tables, depending on the number of performed measurements and the confidence level adopted for proposed model [33]).
The obtained values for the t-distribution indicator are systematized in Table 12.
The proposed models for estimation of the daily global irradiation are validated after applying the t-distribution test, its calculated monthly values being smaller than the t-distribution critical values, for a model confidence level of 95% (the maximum value of the t-distribution indicator is 0.38 obtained for the M2 model, for the month of June, the value that is much lower than the t-distribution critical value).
Also, the t-distribution indicator values calculated for estimation models of the daily diffuse irradiation, lead to the validation of these models (the maximum value of 0.40 is much lower than the t-distribution critical value recommended for a confidence level of 95%).
So, all proposed models for estimation of the daily solar irradiation have statistical significance.

Table 11. Monthly values of the Root Mean Square Error (RMSE [kWh/m^2]).

Month	Daily global irradiation		Daily diffuse irradiation			
			Model M1 for estimation of the daily global irradiation		Model M2 for estimation of the daily global irradiation	
	Model M1	Model M2	$H_{dif}/H(H/H_0)$	$H_{dif}/H(n/N)$	$H_{dif}/H(H/H_0)$	$H_{dif}/H(n/N)$
Jan.	0,22680	**0,20150**	0,25100	0,22124	0,22862	**0,20132**
Feb.	0,36620	**0,31280**	0,38943	0,36547	0,35481	**0,32944**
Mar.	0,39725	**0,36331**	0,43441	0,39171	0,40151	**0,38154**
Apr.	0,50367	**0,45821**	0,48808	0,44597	0,46710	**0,43882**
May	0,42659	**0,39572**	0,45528	0,42135	0,43615	**0,41714**
June	0,51387	**0,46346**	0,50404	0,49501	0,48618	**0,48378**
July	0,40752	**0,37456**	0,41994	0,43483	**0,40097**	0,40871
Aug.	0,36192	**0,32214**	0,35270	0,34249	**0,33081**	0,33445
Sep.	0,33885	**0,27994**	0,31407	0,31080	**0,30148**	0,31227
Oct.	0,30871	**0,26111**	0,29061	0,27919	0,27176	**0,26225**
Nov.	0,17772	**0,14850**	0,20949	0,21014	0,20014	**0,18494**
Dec.	0,20182	**0,18391**	0,21648	0,21067	0,20952	**0,19821**

Table 12. Monthly t-distribution values.

Month	Daily global irradiation		Daily diffuse irradiation			
			Model M1 for estimation of the daily global irradiation		Model M2 for estimation of the daily global irradiation	
	Model M1	Model M2	$H_{dif}/H(H/H_0)$	$H_{dif}/H(n/N)$	$H_{dif}/H(H/H_0)$	Hdif/H(n/N)
Jan.	**0,0663**	0,1914	**0,1958**	0,4076	0,2159	0,3130
Feb.	**0,1124**	0,1285	0,2394	**0,0057**	0,2096	0,0174
Mar.	**0,0032**	0,0202	**0,0026**	0,2409	0,0216	0,0293
Apr.	0,0386	**0,0247**	**0,0307**	0,0951	0,0601	0,1380
May	0,0622	**0,0609**	0,0694	0,0319	0,0636	**0,0181**
June	**0,0144**	0,3838	**0,0054**	0,0151	0,1725	0,3707
July	**0,1010**	0,2787	0,0819	0,1208	**0,0808**	0,1212
Aug.	**0,0722**	0,0901	**0,0047**	0,0802	0,0254	0,0624
Sep.	**0,0209**	0,0721	0,0561	**0,0089**	0,1232	0,1955
Oct.	0,1770	**0,1231**	0,0895	**0,0163**	0,1170	0,1271
Nov.	**0,0470**	0,1142	0,1593	0,2212	0,2301	**0,1135**
Dec.	0,0469	**0.0459**	0.0499	0.0655	0.0525	**0.0004**

8. Conclusions

Valorization the benefits of renewable energy is motivated mainly by the environment degradation and the anticipated increases of prices for the non-renewable resources (coal, oil and gas), that are in the continuous decreasing. In the near future, the renewable energy industry will be one of the most important and performant economic branch.

Increasing the global interest in renewable energy production has led to the development of the technologies of capturing and capitalizing on solar radiation that enabled the adoption of solutions with a high efficiency.

Making a decision concerning the achievement of a project on renewable energy involves the demonstration of its feasibility. Regardless of the technology used to convert the solar energy, thermal or photovoltaic, different initial data are required and firstly, data on meteorological parameters specific to the area of implementation; of these solar radiation represents the main input in the design of solar energy conversion systems.

The paper proposes the estimation of the daily solar irradiation under real sky conditions in view of the obtaining some models that to ensure a better estimation of its real variation. The proposed estimation models were established using the database of the Department of Renewable Energy Systems and Recycling, from Transilvania University of Braşov, Romania.

In this regard, for estimation of the daily global irradiation have been proposed models that use regressions having as inputs the sunshine fraction, the air temperature (the maximum daily temperature and minimum daily temperature) and the precipitable water amount. For the daily diffuse irradiation were proposed two types of regressions (regressions dependent on the clearness index H/H0, respectively regressions dependent sunshine fraction n/N).

Based on the observed data processing, two precise models to estimate the daily global irradiation were developed. All the proposed estimation models for the daily global irradiation were validated after applying the statistical testing, the obtained values of statistical indicators confirming the high performances of these.

Of all estimation models of the daily solar irradiation, at estimation of the daily diffuse irradiation, there were encountered the greatest difficulties, given the fact that we refer to a depression urban area. Therefore, the deterministic nature of diffuse radiation by atmospheric conditions has led to the obtaining of weaker performances of the estimation models; we refer especially to the fact that the statistical testing of these models has led to the lowest values of Pearson's coefficient. The satisfactory results after the statistical testing were obtained for the eleven months from January to November.

Considering this last aspect, there appears the need to develop the urban climatology and to establish the city's role as a driving factor to its own climate.

In conclusion, a future research objective can be worded, respectively the statistical modeling of the parameters specific to atmosphere; it is envisaged especially the accurate modeling of the diffuse fraction that has a distribution specific to the analyzed area and has a significant influence on the amount of radiation on a capturing surface.

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