SOLAR RADIATION ESTIMATION UNDER CLEAR SKY CONDITIONS FOR BRASOV AREA (ROMANIA) – MODELS PERFORMANCE ESTIMATION

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Abstract. The literature in this field offers a high number of models for estimating total solar radiation, because the world's most weather stations measure total solar radiation. However, it must be mention, diffuse radiation estimation models are few and these can be applied only to a specific geographic and climate location of which these have been determined. This paper proposes the determination of solar radiation estimation models (diffuse, direct and total components) for the urban area of Brasov. In this respect, the achieved study proposes a unitary approach of the solar radiation components modelling, in order to obtain models that can be used together. It is taken into account the fact that, in literature, models for estimating solar radiation are studied only for one component of it (often total radiation); thus the combination of direct radiation patterns with those of diffuse radiation, leads to high estimation errors. Models performance is analyzed using the Root Mean Square Error (RMSE), the Mean Bias Error (MBE), the Mean Percentage Error (MPE) and t-statistic.

Keywords: diffuse radiation, direct radiation, Mean Bias Error MBE, Root Mean Square Error RMSE, t-statistic

1. Problem description

Among all the estimation models for solar radiation, the diffuse radiation estimation is facing the greatest difficulties, given the fact that we refer to an urban valley (Braşov urban area). Given this, there is need to develop urban climatology (and establish the role of the city as a generating factor of own climate) and statistical modelling of specific atmosphere parameters (especially the diffuse fraction – the ratio of diffuse radiation and total radiation). It is envisaged that, the diffuse fraction has a distribution specific to analyzed location, showing a significant influence on the radiation quantity on an absorber surface.

Also stated – from the application of models offered in the literature for specific geographical conditions of Braşov area (790 m altitude, 25˚35 'E longitude and 45˚39' N latitude) and from the study of the performance of these models – that the existing empirical models in the literature do not approximate in a satisfactory manner the real variation of solar radiation [3, 4].

The present paper is structured in two parts: the first was designed to the Linke turbidity factor determination and the present one to the solar radiation estimation (considering the obtained values of turbidity factor) and models performance estimation.

2. Results and discussion

2.1. Estimating clear-sky solar radiation

Considering the values obtained for the Linke turbidity factor (the first part of the paper), the next stage consisted in the solar radiation estimation.

Therefore, in Figure 1 measured direct radiations versus estimated direct radiations are presented. The diagrams are plotted for all clear-sky days considering the entire year (Figure 1, a) but also for all clear-sky days from June and July (Figure 1, b). From the study of these diagrams, it can be noticed that the proposed models work correctly for direct radiation values over 300 W/m^2; the graph reveals a greater spreading of the real recorded values, especially for lower values.

The points that correspond to direct radiation values that are higher than 800 W/m^2, approximate very well the real values.

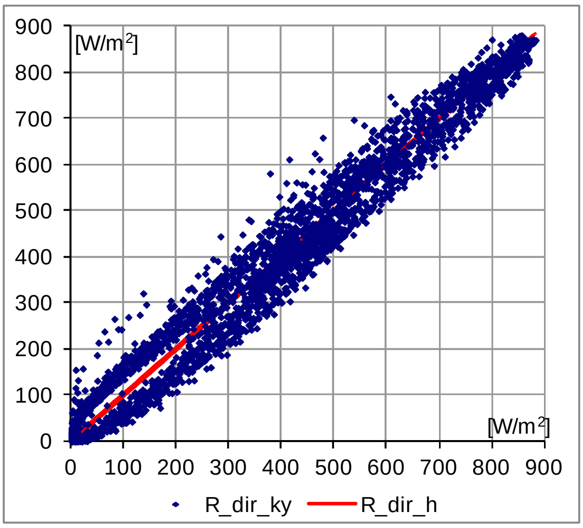
For a complete study of the proposed estimation models, it is also necessary the analysis of the real and estimated values variation during a day. In this way, it can be noticed, the use of the turbidity factor, the monthly mean values, does not lead to a good approximation of the real data for clear sky conditions.

Figure 2 proposes the daily diagrams for direct and diffuse horizontal radiations. The diagrams of the theoretical and real (direct and diffuse) horizontal radiations are plotted for a specific day of the month, day that keeps to clear sky conditions.

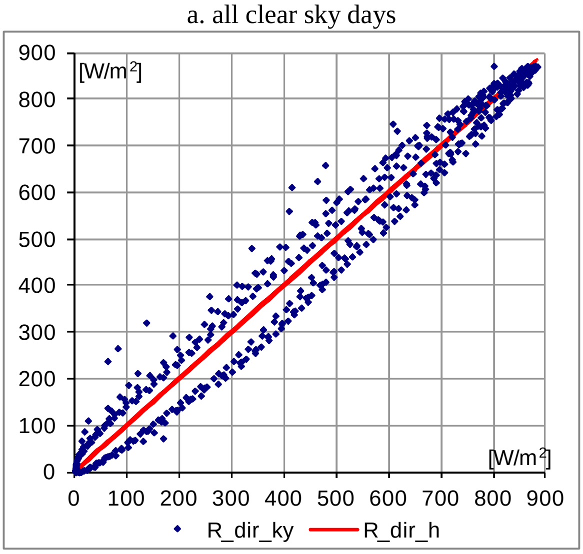
There can be noticed from the presented diagrams, the estimated values of the direct and diffuse horizontal radiation during a day are very close to the real recorded values, but is recorded an underestimation during the mornings and an overestimation during the afternoons.

These underestimations and overestimations of the theoretical radiation estimations are predictable if the real direct radiation variation is analysed. There were taken into consideration the following aspects:

- during a day, the direct radiation variation records the maximum value at 12 solar time but it is not really symmetrical toward 12 solar time (the estimated direct radiation is a symmetrical function towards 12 solar time); it can be noticed that during the morning the real direct radiations values are higher than those during the afternoon (theoretically the direct solar radiation values should be the same for solar hours placed at the same duration time towards 12 solar time);
- if it is taken into consideration the fact that the analysed area is an urban basin, the direct solar radiation diminution during the afternoon is obvious.



a. all clear sky days

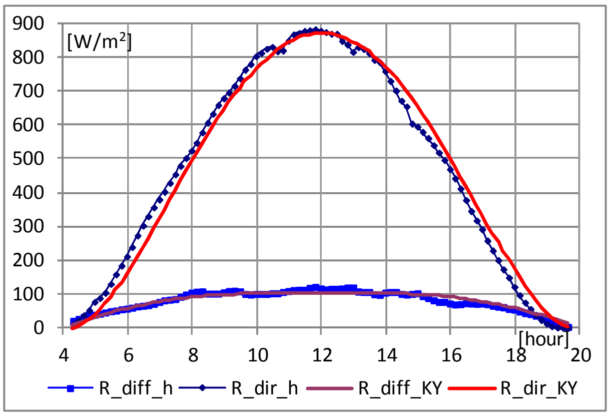


b. clear sky days – June and July

Figure 1. Theoretical versus real values for the horizontal direct radiation

All these reasons lead to the need for a correction factor in the relation of direct radiation (C_{dir}); in this context the direct radiation becomes:

$$B_h = I_0 \cdot \varepsilon \cdot \sin(\alpha) \cdot \exp(-T_L \cdot C_{dir} \cdot m \cdot \delta_r(m)) \quad (1)$$



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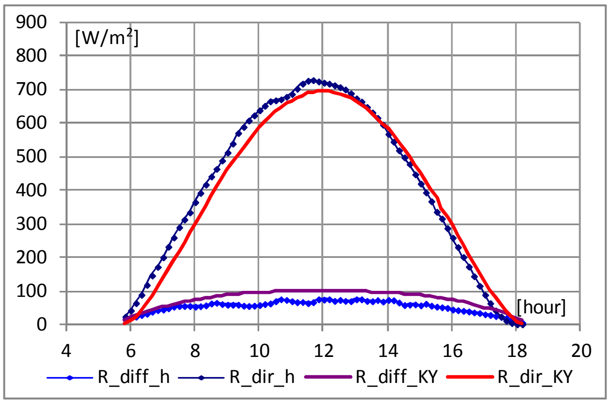

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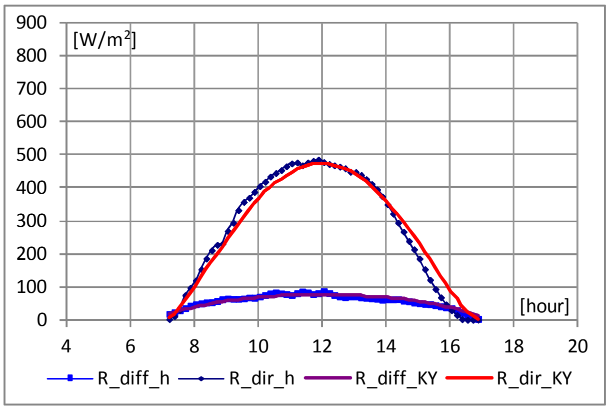

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Figure 2. Theoretical and real curves of the direct and diffuse horizontal radiations during a day

The correction factor C_{dir} is dependent on solar time, which makes necessary the determination of its daily variation (variation specific to every month).

As a result of the mathematical modelling achieved on the basis of the direct radiation measurements, the correction coefficient curves were determined (values specific to the urban area of Braşov).

Figure 3 presents the correction coefficient variation for direct radiation, during a clear-sky day, specific to December, March, June and September months. It can be noticed:

- the correction coefficient has an increasing variation during a day;
- during the morning, the minimum values of the correction coefficient are obtained and consequently the estimated direct solar radiation will have higher values;
- during the afternoon, the correction coefficient has higher values; this fact will lead to lower values of the estimated direct radiation values that draws the estimated radiation curve near the real one.

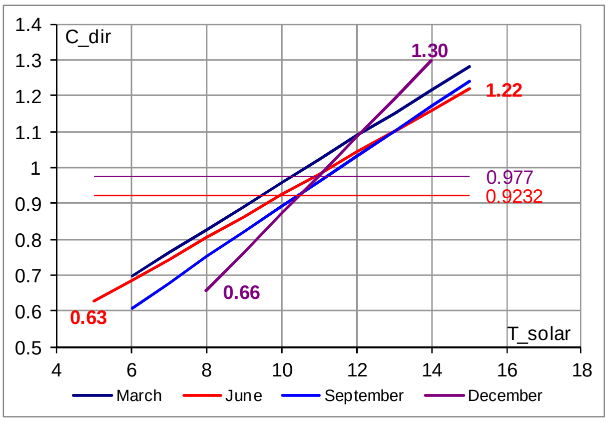


Figure 3. Correction coefficient of the direct radiation

The mathematical modelling of the correction coefficient was achieved for every month; thus for every month were determined the correction coefficient functions depending on solar time. All the functions of the correction coefficient for direct radiation – specific to Braşov urban area – are systematised in Table 1.

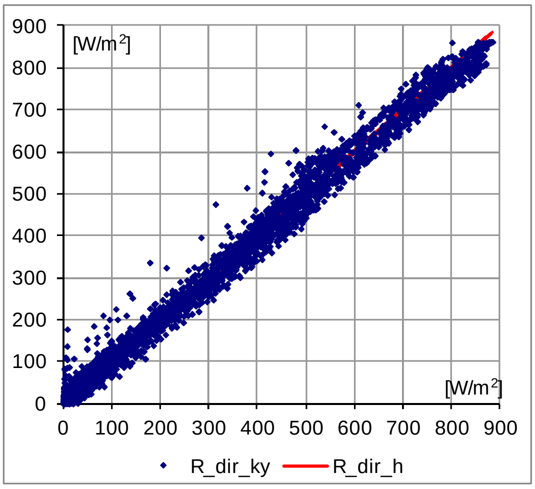
Therefore, a more accurate mathematical modelling of the correction coefficient curves can lead to the obtaining of some direct radiation estimations that to approximate in a great extend reality. In this way, for every month, the determined correction coefficient was replaced in Eqn. (1).

Figure 4 presents the new diagrams of the measured direct radiations versus estimated direct radiations and Figure 5 presents the real and theoretical curves of the direct and diffuse horizontal radiations during the same days as in Figure 2.

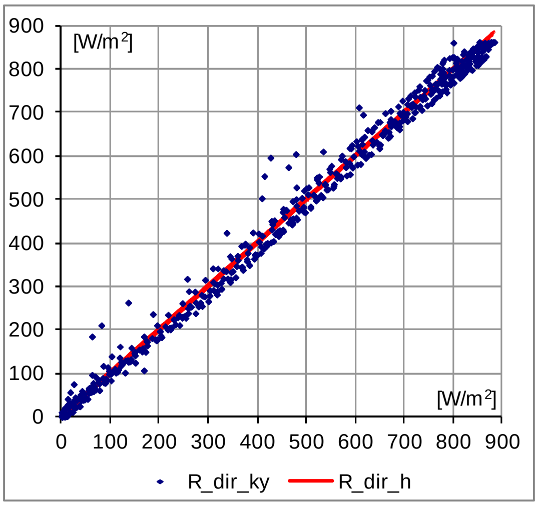
By correcting the direct radiation relation with the coefficient C_{dir}, the estimated values are closer to the line 1:1 (Figure 4); it can be also noticed that the proposed models work correctly for all direct radiation values; in addition, the graph reveals a lower spreading of the estimated values.

Table 1. Correction coefficient functions of direct radiation for Braşov area

Month	**C_{dir}**	**C_{dif}**
January	$C_{dir} = 0.05T_{solar} + 0.36$	1.35
February	$C_{dir} = 0.11T_{solar} - 0.3$	1.35
March	$C_{dir} = 0.06T_{solar} + 0.3$	1.3
April	$C_{dir} = 0.07T_{solar} + 0.15$	1.1
May	$C_{dir} = 0.09T_{solar}$	1.15
June	$C_{dir} = 0.06T_{solar} + 0.33$	0.95
July	$C_{dir} = 0.05T_{solar} + 0.34$	1
August	$C_{dir} = 0.08T_{solar} + 0.05$	1
September	$C_{dir} = 0.07T_{solar} + 0.19$	1.05
October	$C_{dir} = 0.07T_{solar} + 0.05$	1.15
November	$C_{dir} = 0.07T_{solar} + 0.2$	1.25
December	$C_{dir} = 0.107T_{solar} - 0.2$	1.25

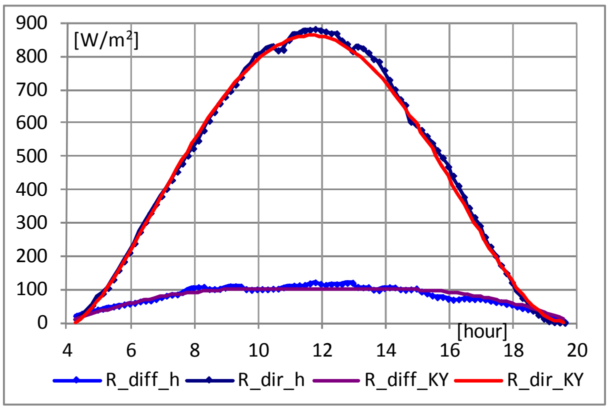


a. all clear sky days



b. clear sky days – June and July

Figure 4. Theoretical versus real values for the horizontal direct radiation



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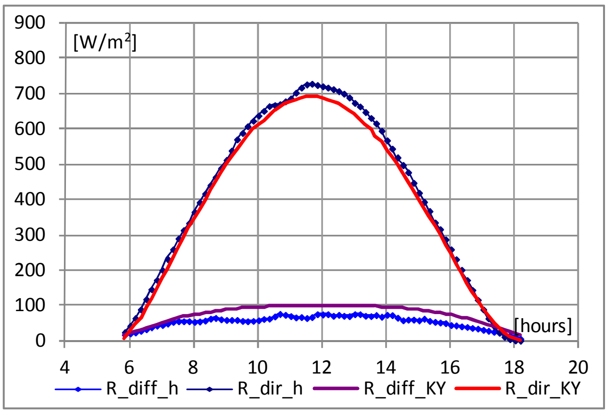

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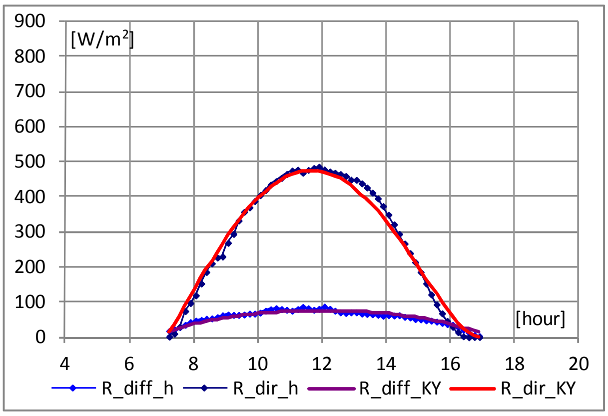

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Figure 5. Theoretical and real curves of the horizontal direct and diffuse radiations during a day

There can be noticed from the diagrams presented in Figure 5, the estimated values of the direct radiation during a day are very close to the real recorded values.

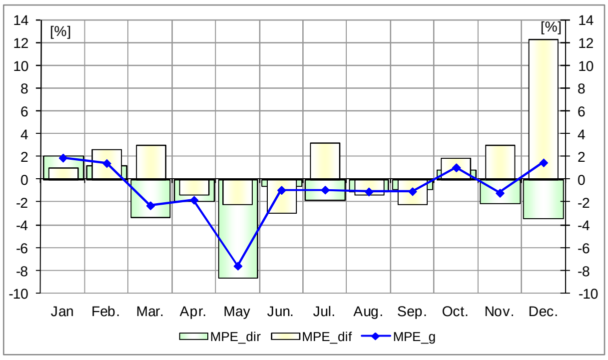
2.2. Model performance estimation

In the next stage of this study, the paper proposes the model performance estimation that consists of statistical indicators analysis; in this way, the Root Mean Square Error (RMSE), Mean Bias Error (MBE), the Mean Percentage Error (MPE) and t-values are calculated [1, 2, 3, 5].

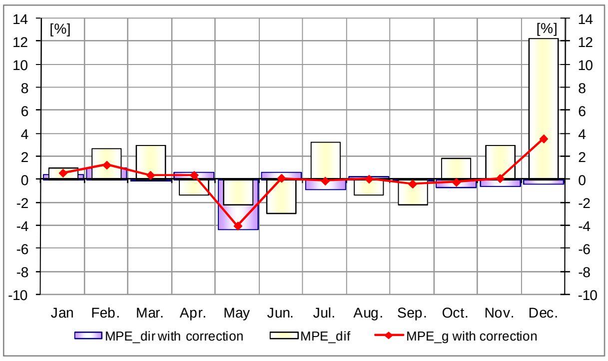
The MBE, MPE, RMSE and t-values were determined using measured data of total, direct and diffuse solar radiations on horizontal surface and considering for the estimation of direct radiation both the relation – without correction coefficient, and – with correction coefficient, Eqn. (1).

Thus, the statistical indicators were calculated for all radiation components, because there were desired the models validation for all components; in this way, an unitary approach of the solar radiation components modelling was obtained, in order to obtain estimation models that can be used together.

Considering the models proposed, the paper presents the MBE (MPE) and RMSE monthly values, for diffuse, direct and total radiations (Table 2 and Figure 6).



a. estimated radiations without the use of the correction coefficient for the direct radiation



b. estimated radiations without the use of the correction coefficient for the direct radiation

Figure 6. Monthly values of the MPE calculated for direct, diffuse and total solar radiation

These values indicated that the percentage error for a single month is between -7.6% and 2% for the estimation model that does not use the correction C_{dir} and between -4% and 3.5% when the correction C_{dir} is used for estimation. The highest MBE monthly values are recorded for May.

The comparison between the estimated radiation components (total, diffuse and direct) and the measured ones, leads to the conclusion that, the highest MBE values were obtained for the diffuse solar radiation during December (the same conclusion can be worded when the errors are expressed as percentages (MPE)).

Table 2. Monthly RMSE and MBE

Month	RMSE_Bh kWh/m^2	RMSE_Dh kWh/m^2	RMSE_Gh kWh/m^2	MBE_Bh kWh/m^2	MBE_Dh kWh/m^2	MBE_Gh kWh/m^2
	Estimated radiations without the use of the correction coefficient for the direct radiation					
January	0.0256	0.0070	0.0306	**0.0060**	0.0008	**0.0068**
February	0.0296	0.0049	0.0332	0.0040	0.0018	0.0058
March	0.0497	0.0123	0.0500	-0.0141	0.0025	-0.0116
April	0.0585	0.0111	0.0570	-0.0099	-0.0011	-0.0110
May	**0.1257**	0.0168	**0.1149**	**-0.0426**	-0.0021	**-0.0446**
June	0.0496	0.0144	0.0490	-0.0033	**-0.0025**	-0.0058
July	0.0620	0.0207	0.0514	-0.0087	0.0033	-0.0055
August	0.0550	0.0088	0.0568	-0.0052	-0.0010	-0.0062
September	0.0464	0.0226	0.0449	-0.0035	-0.0017	-0.0053
October	0.0445	0.0145	0.0432	0.0030	0.0013	0.0044
November	0.0352	0.0157	0.0330	-0.0064	0.0020	-0.0044
December	0.0274	**0.0274**	0.0487	-0.0067	**0.0108**	0.0041
	Estimated radiations using the correction coefficient for the direct radiation					
January	0.0153	0.0070	0.0181	0.0013	0.0008	0.0021
February	0.0163	0.0049	0.0157	0.0034	0.0018	0.0052
March	0.0330	0.0123	0.0310	-0.0006	0.0025	0.0019
April	0.0300	0.0111	0.0240	**0.0035**	-0.0011	0.0024
May	**0.0740**	0.0168	**0.0677**	**-0.0216**	-0.0021	**-0.0236**
June	0.0218	0.0144	0.0171	0.0032	**-0.0025**	0.0007
July	0.0301	0.0207	0.0171	-0.0040	0.0033	-0.0007
August	0.0272	0.0088	0.0244	0.0013	-0.0010	0.0003
September	0.0273	0.0226	0.0189	-0.0001	-0.0017	-0.0019
October	0.0310	0.0145	0.0254	-0.0023	0.0013	-0.0010
November	0.0253	0.0157	0.0165	-0.0016	0.0020	0.0004
December	0.0054	**0.0274**	0.0268	-0.0008	**0.0108**	**0.0100**

Regarding the level of scatter the models produce, the maximum RMSE values are obtained for direct and total radiations during May.

This study indicates that the percentage error for a single month never exceeds ± 15% for the direct or total radiation, especially if the correction C_{dir} is used.

The comparison between the estimated and the real solar radiations (direct, diffuse and total components) was also carried out according to the t-value.

The monthly t-values obtained for all clear sky days during the period 2006 – February 2012 are presented in Figure 7. The t-values are calculated for both proposed models (without and with the use of the correction coefficient).

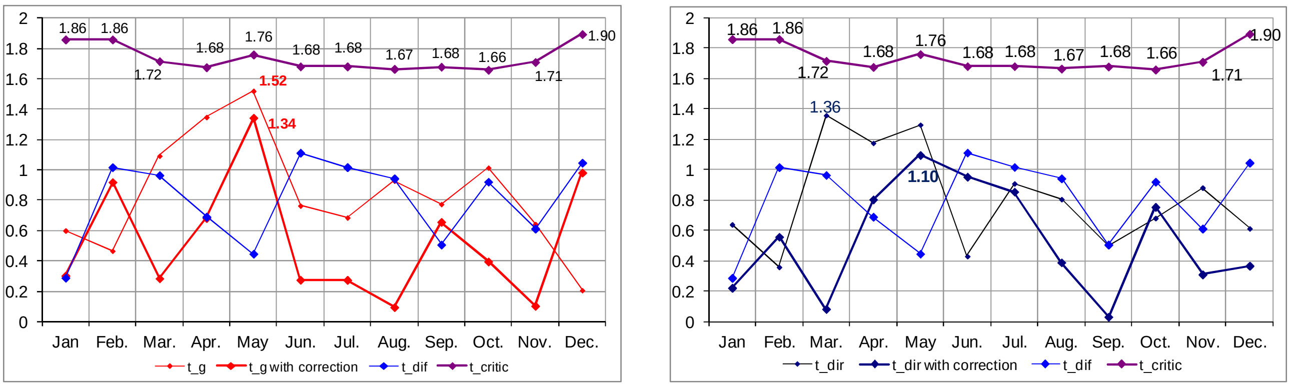


Figure 7. Monthly values of the t-statistic

The highest t-values were obtained when the direct radiation was estimated without the use of correction coefficient C_{dir}.

The highest value was 1.52 (for total radiation, estimation without C_{dir}) but this is lower than the critical t-value, obtained from standard statistical tables (t_critical at 5% is 1.76).

3. Conclusions

The calculated statistical indicators concerning the total, direct and diffuse radiations are very good for the estimation models proposed. As can be seen, the direct radiation estimation using relation without correction leads to validation of estimations for all components of solar radiation.

However for proper testing of the estimation models, a "visual" charts testing is necessary: estimated values versus real values (Figures 1 and 4) and that of the daily variation diagrams of real and estimated values (Figures 2 and 5).

Although from the statistical testing, the indicator values are low, still the charts study of real values versus estimated values leads to conclusion that direct radiation (and global radiation) is underestimated during the morning and overestimated during the afternoon; therefore, at statistical testing is possible a "compensation" of "underestimation with overestimation", that leads to low values of statistical indicators.

Correcting the relation of direct radiation with the coefficient C_{dir} (Eqn. 1) leads to a closeness of estimation curves (of the direct and total radiations) to the real variation curves, and calculated values of statistical indicators are much lower than those obtained when radiation estimations were made without correction for direct radiation (Figure 8).

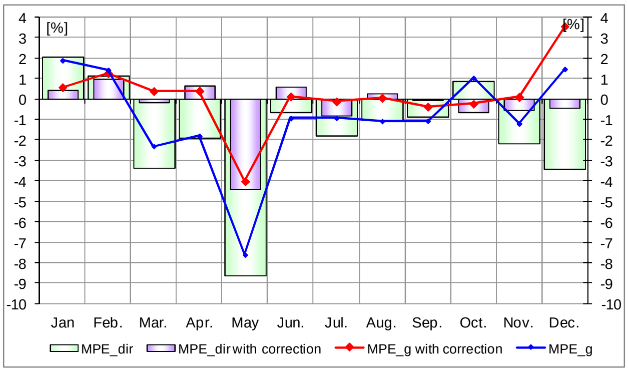


Figure 8. MPE values for direct and total radiation for both models (without and with the correction coefficient)

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