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Linke Turbidity Modelling for Braşov Urban Area

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Abstract. An important factor in the solar radiation attenuation is Linke turbidity factor which has a specific value for every area; to model and simulate the solar radiation this key parameter must be determined.

Key words

Solar radiation, Linke turbidity factor, RES-systems.

1. Introduction

Nowadays, due to the technological breakthroughs that occurred during the last two centuries, the energy production has moved from fossil fuels to renewable energy based on to less pollutant sources. A significant percentage of these new types of green energy come from direct or indirect transformation of solar radiation into electricity, heat and biomass.

Designing a reliable solar renewable energy system for a specific area requires knowing the geographical, meteorological, climatological and pollution parameters and their variation in time, also the helioenergetic potential of the area. The solar energetic potential can be obtained from a correct determination of solar energy that a specific site can receive and then used to a properly design of RES system and also in studies or research. Among the solar radiation that reaches the earth surface and the climatological parameters, it exists a direct dependence through the Linke turbidity factor, the relative optical air mass and the optical depth.

Solar radiation passing through the atmosphere is scattered and absorbed by molecules and particles, and also it interacts with larger particles such as water droplets, dust and aerosols when these are present in the air. Scattering refers to processes in which photons change direction after an interaction, while absorption occurs when photons are removed from a beam light, and their energy is converted to an excitation of atoms or molecules.

Therefore, the Linke turbidity factor is a very convenient approximation to model the atmospheric absorption and scattering of the solar radiation under clear sky. It describes the optical thickness of the atmosphere due to both the absorption by water vapour and the absorption and scattering by the aerosol particles relative to a dry and clear atmosphere. The increase of the T_L leads to the larger attenuation of the radiation by the clear sky atmosphere.

The branch literature offers numerous models to simulate solar radiation and its components: global, direct and diffuse. These models, in order to be simple, have few variables and are very easy to use. Using these empirical models for simulating the global, direct and diffuse solar radiations, for Braşov urban area, the results did not offer a real and satisfactory approximation in comparison with the diagrams obtained using the real solar radiation (the real data were recorded with a Delta-T local weather station).

One of the inconvenient is that the curve obtained with the simulated values is sensitively higher than the real curve.

Other inconvenient is the curve's symmetry towards twelve o'clock solar time and the fact that simulated curves have both zero watt solar radiation for sun rise and sun set; in realty, in clear sky condition, it can be observed that due to the particular relief form of the Braşov area, namely a mountainous basin, and due to an interesting and highly important meteorological phenomenon, namely: the temperature inversion, the radiation curve symmetry obtained with the empirical models does not correspond with the real measurements and observations.

The value for Linke turbidity factor specifically recommended by the branch literature for Europe is 3 [1]. But, at a local level the value of Linke turbidity factor can vary with the geographical coordinates, meteorological parameters and climatic conditions.

Therefore, to obtain a radiation simulation according to reality, it is necessary the accurate determination of the Linke turbidity factor. As mentioned before, a major input parameter in the correct estimating of solar radiation income is the Linke turbidity factor.

2. Experimental Meteorological Data

The data sets, used in calculations and simulations, have been recorded by a Delta-T local weather station, which is positioned on the roof of the ’’Transilvania’’ University of Braşov (Romania), according to the standard mounting conditions.

The weather station is equipped with an environmental data logger (Delta-T Logger), which initiates the readings, controls the sensors and stores data related to 10 minutes range.

Delta-T Logger records data since October 2005 until now and they comprise the following parameters:

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

3. Braşov Area, Geographic and Climatic Factors

Braşov area, altitude: 790m, longitude: 25.35^o and latitude 45.39^o, is a medium size town with a high pollution level. The basin area is characterised by a continental temperate climate more precisely a transition type between oceanic and temperate climate of the temperate continental, more humid and cool in high mountainous area that surrounds the entire urban area with relatively generous liquid and solid precipitations and slightly decreased temperatures in the lower areas.

Because Braşov is situated in an intra mountainous basin formed between two mountain chains, it experiments an interesting phenomenon, namely, the temperature inversion, and as consequences fogs and cloudiness that reduce the solar sunshine period; the temperature inversion is also, an important factor in the local solar potential. We mention that due to these climatological and geographical features of Braşov location, during the winter, the basin low regions get cooler than the surrounding slops and warmer in the summer.

4. Linke Turbidity Factor - Theoretical Considerations

Atmospheric turbidity is associated with atmospheric aerosol load, dust particle and water vapour content. In a pure Rayleigh atmosphere the turbidity factor is equal to one (T_L=1). The closest value to this ideal value is achieved in extremely clear, cold air at high latitudes, (T_L=2). However, for a heavy polluted atmosphere the turbidity factor can increase to 8 [1].

An increase in the concentration of aerosols, caused by human activity in some urban regions, has a significant impact on the environmental quality of the cities, that makes the air more turbid with lower visibility, the atmospheric optic-chemistry faster, and the air polluted.

Aerosols are solid and liquid particles suspended in the atmosphere which interferes with the path of the solar radiation through the atmosphere, depending on the chemical components and the size of these; they can absorb, attenuate or scatter the radiation at a different percentage for different wave lengths.

In order to quantify this influence of atmospheric aerosol content on the direct radiation received by the earth’s surface, several atmospheric turbidity coefficients have been introduced during the past decades: Linke turbidity factor T_L (Linke, 1922), the Ångström turbidity parameters α and β (Ångström, 1929), the Shüepp coefficient B (Shüepp, 1949), the Unsworth-Monteith turbidity factor T_U (Unsworth and Monteith, 1972) [2]. Among them, Linke turbidity factor is commonly used.

In order to calculate the Linke turbidity factor and determine a method to simulate it’s variation through a certain period, measurements of the direct solar radiation and diffuse solar radiation recorded with the weather station sensors, for three years period, were considerate.

For the Linke turbidity factor calculation, it will be used the following relation [3]:

$$T_L = -\frac{\ln\left(\frac{I_0 \cdot \varepsilon \cdot \sin(\alpha)}{B_h}\right)}{\delta_r \cdot m}, \qquad (1)$$

where:

- $I_0\varepsilon$ is the solar constant (1367W/m^2) corrected by the eccentricity factor (ε);
- B_h is the beam horizontal irradiance;
- α is the solar altitude angle;
- δ_r is the integrated Rayleigh optical thickness, due to pure molecular scattering (clear and dry atmosphere);
- m is the relative optical air mass (the ratio of the optical path length of the solar beam through the atmosphere to the optical path through a standard atmosphere at sea level with the sun at the zenith).

In the equation (1) the Rayleigh optical thickness (δ_r) and the relative optical air mass (m), are at this moment unknown. For the calculation of these two parameters, the present paper will use two models:

- ✓ the first model uses for the optical air mass and the optical thickness, the relations of Kasten and Young [2], [4];
- ✓ the second model uses for the optical air mass and the optical thickness, the relations of Remund-Page [5].

All the data simulations and calculations will be made in consideration of clear sky conditions.

A. Kasten and Young Model

The first model uses for the optical air mass, the relation of Kasten and Young 1989, equation (2):

$$m = \frac{p}{p_0} \cdot \left(\sin\left(\alpha^c\right) + 0.50572\left(\alpha^c + 6.07995\right)^{-1.6364} \right)^{-1}. \tag{2}$$

According to the equation (2) the air mass depends only on two parameters, namely a correction for altitude angle (3) and another correction for site elevation (4):

$$\alpha_c = \alpha + 0.61359 \cdot \frac{0.1594 + 1.123\alpha + 0.065656\alpha^2}{1 + 28.9344\alpha + 277.3971\alpha^2}, \tag{3}$$

$$\frac{p}{p_0} = \exp\left(-\frac{z}{8435.2}\right). \tag{4}$$

Using the corrections from equations (3) and (4) the model Kasten-Young becomes particular for a specific area. To avoid a range of meteorological phenomena that can happen at sunrise, like thin haze and fog (when the air mass is very high), equation (5) proposes two relations for the optical depth in terms of the air mass value:

$$\begin{cases} \delta_r = \left(6.6296 + 1.7513\,m - 0.1202\,m^2 + 0.0065\,m^3 - 0.00013\,m^4\right)^{-1}, & m \le 20, \\ \delta_r = \dfrac{1}{10.4 + 0.718\,m}, & m > 20. \end{cases} \tag{5}$$

B. Remund and Page Model

The second model uses for the optical air mass and the optical depth, the equations proposed by Remund – Page in 2002 [5]. The relative optical air mass is calculated using relation (6):

$$m = \frac{p}{p_0} m_0 = \exp\left(-\frac{z}{8435.2}\right) \cdot \left(\sin(\alpha) + 0.50572(\alpha + 6.07995)^{-1.6364}\right)^{-1}, \tag{6}$$

where m_0 represents the optical air mass at the sea level and z represents the altitude of the site.

For the optical Rayleigh depth, the equation (7) is proposed:

$$\delta_r = \frac{1}{p_c}\left(6.625928 + 1.92969 m_0 - 0.170073 m_0^2 + 0.011517 m_0^3 - 0.000285 m_0^4\right)^{-1}, \tag{7}$$

where p_c represents the pressure level correction determined for Braşov area, and it is expressed by the equation (8):

$$p_c = 1.08879307 - 0.004282756\,m_0 + 0.000132327\,m_0^2. \tag{8}$$

We mention, the relation (8), of the pressure level correction, was determined particularly for the specific geographical coordinated of Braşov [6].

The turbidity factor values for the Braşov urban area were calculated after the elimination of the cloudy-sky periods from the three years database [6]. In this way, for this study, there were extracted (from the entire three years database) only the records suitable for a clear sky model.

5. Linke Turbidity Factor for Braşov Urban Area

Considering the two models proposed for the optical air mass and the optical Rayleigh depth, in this section there will be presented the values of the Linke turbidity factor for Braşov urban area.

In the first stage, there were calculated the monthly mean values of the Linke factor but, also the monthly means of the hourly minimum values recorded during a month. These values, for the two models proposed, are presented in Table 1.

From the analysis of the results centralised by Table 1, it can be seen, the values resulted with the Remund-Page formulas lead to higher values of the turbidity factor.

Although the air mass formulas (2) and (6) lead to very close values, the optical Rayleigh depth calculated with Kasten-Young formula (5) has higher values than the optical depth calculated with Remund-Page formula (7).

The optical depth has a significant influence on the turbidity factor and consequently higher values of this lead to lower values of the turbidity factor.

The use of the Linke turbidity factor (the monthly mean values or the monthly means of the hourly minimum values) for the radiation calculation, does not lead to a very accurate simulation of this.

Table 1. Linke Factor for Braşov Urban Area

Month	Monthly means: $T_{LKasten\_Young}$	Monthly means of the hourly minimum values: $T_{L\_Kasten\_Young}$
January	3.11	2.75
February	3.18	2.73
March	3.44	2.72
April	3.62	3.07
May	3.79	3.26
June	3.79	3.33
July	3.82	3.37
August	3.81	3.48
September	3.53	2.91
October	3.00	2.50
November	3.14	2.90
December	3.44	2.89
Month	Monthly means: $T_{L\_Remund\_Page}$	Monthly means of the hourly minimum values: $T_{L\_Remund\_Page}$
January	3.51	3.10
February	3.59	3.08
March	3.88	3.06
April	4.08	3.45
May	4.26	3.67
June	4.26	3.75
July	4.30	3.79
August	4.29	3.92
September	3.97	3.28
October	3.38	2.82
November	3.54	3.27
December	3.88	3.26

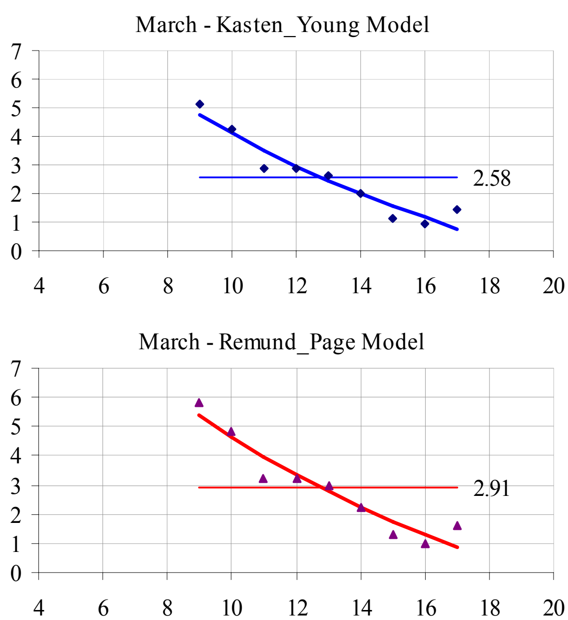

Fig.1. Linke Turbidity Factor determined for the spring equinox, Braşov urban area

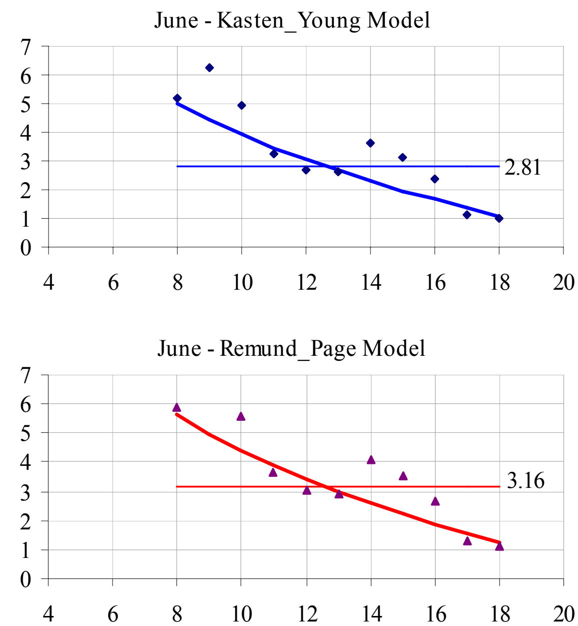

Fig.2. Linke Turbidity Factor determined for the summer solstice, Braşov urban area

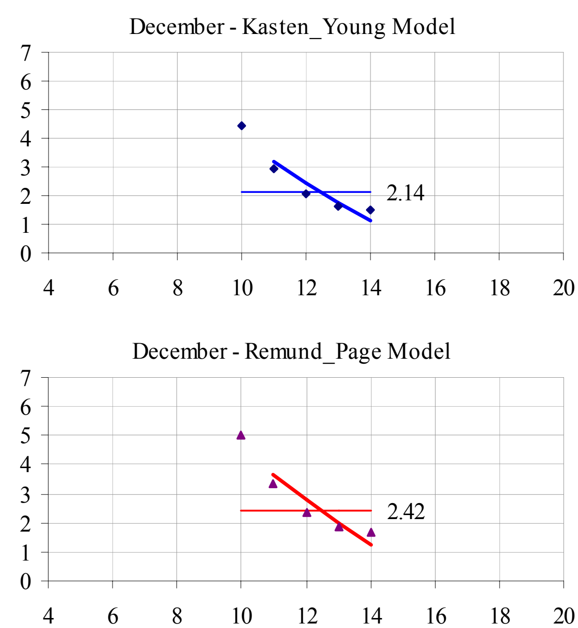

Fig.3. Linke Turbidity Factor determined for the winter solstice, Braşov urban area

It was ascertained, the use of some constant values during a month for the turbidity factor is reflected in the radiation diagrams as follows:

- ✓ around the noontime, lower values of the theoretical radiations were obtained, compared to those real;
- ✓ similarly, at the sunset time, the recorded radiation measurements have higher values than those theoretical.

Considering the aspects above mentioned, in the next step, the study of the variation of Linke turbidity factor during a day (depending on the solar time) is proposed.

Table 2. Linke Factor Functions for Braşov Urban Area

Month	$T_{LKasten\_Young}$
January	$T_L = -5.185\ln(T_{solar}) + 15.386$
February	$T_L = -5.504\ln(T_{solar}) + 16.104$
March	$T_L = -6.255\ln(T_{solar}) + 18.499$
April	$T_L = -5.398\ln(T_{solar}) + 16.328$
May	$T_L = -4.234\ln(T_{solar}) + 13.584$
June	$T_L = -4.811\ln(T_{solar}) + 14.997$
July	$T_L = -5.689\ln(T_{solar}) + 17.204$
August	$T_L = -5.605\ln(T_{solar}) + 17.457$
September	$T_L = -6.840\ln(T_{solar}) + 20.030$
October	$T_L = -7.760\ln(T_{solar}) + 21.954$
November	$T_L = -5.597\ln(T_{solar}) + 16.363$
December	$T_L = -8.635\ln(T_{solar}) + 23.911$
Month	$T_{L\_Remund\_Page}$
January	$T_L = -5.895\ln(T_{solar}) + 17.471$
February	$T_L = -6.296\ln(T_{solar}) + 18.393$
March	$T_L = -7.080\ln(T_{solar}) + 20.928$
April	$T_L = -6.119\ln(T_{solar}) + 18.407$
May	$T_L = -4.744\ln(T_{solar}) + 15.237$
June	$T_L = -5.409\ln(T_{solar}) + 16.861$
July	$T_L = -6.573\ln(T_{solar}) + 19.879$
August	$T_L = -6.448\ln(T_{solar}) + 19.871$
September	$T_L = -7.853\ln(T_{solar}) + 22.948$
October	$T_L = -8.776\ln(T_{solar}) + 24.825$
November	$T_L = -6.321\ln(T_{solar}) + 18.480$
December	$T_L = -9.784\ln(T_{solar}) + 27.090$

In this way for every month of the year there were extracted the minimum hourly values and these were plotted depending on the solar time. The diagrams of the minimum hourly values of the Linke turbidity factor were achieved for both models proposed before.

Figures 1, 2 and 3 present the Linke factor variation (during a clear-sky day), specific to three months, namely March, June and September. It can be noticed:

- the turbidity factor has a decreasing variation during a day;
- the daily mean values of the hourly minimum values have lower values than the monthly means of the minimum hourly values; thus, around 12-13 solar hours, lower values of the turbidity factor resulted (this leads to higher values of the simulated solar radiation around 12 solar time);
- at the sunset time, the minimum values of the turbidity factor were obtained (consequently the simulated solar radiation will have higher values);
- during the morning, the turbidity factor has higher values (this fact leads to smaller values of the solar radiation that draws the theoretical radiation curve near the real one).

The mathematical modelling of the turbidity factor was achieved for every month; thus, for every month the turbidity factor functions depending on solar time were determined. The mathematical modelling was applied for both mentioned models. All the functions of the Linke factor specific to Braşov urban area are systematised in Table 2. More accurate mathematical modelling of the turbidity factor curves can lead to solar radiation simulations that approximate in a great extend the reality.

In this way, Figures 4, 5 and 6 present the direct solar radiation simulated with the turbidity factor functions proposed by table 2 and with the two models proposed for the optical air mass and the optical depth. As it can be noticed, the use of the two models for the horizontal beam irradiance simulations, lead to very close curves.

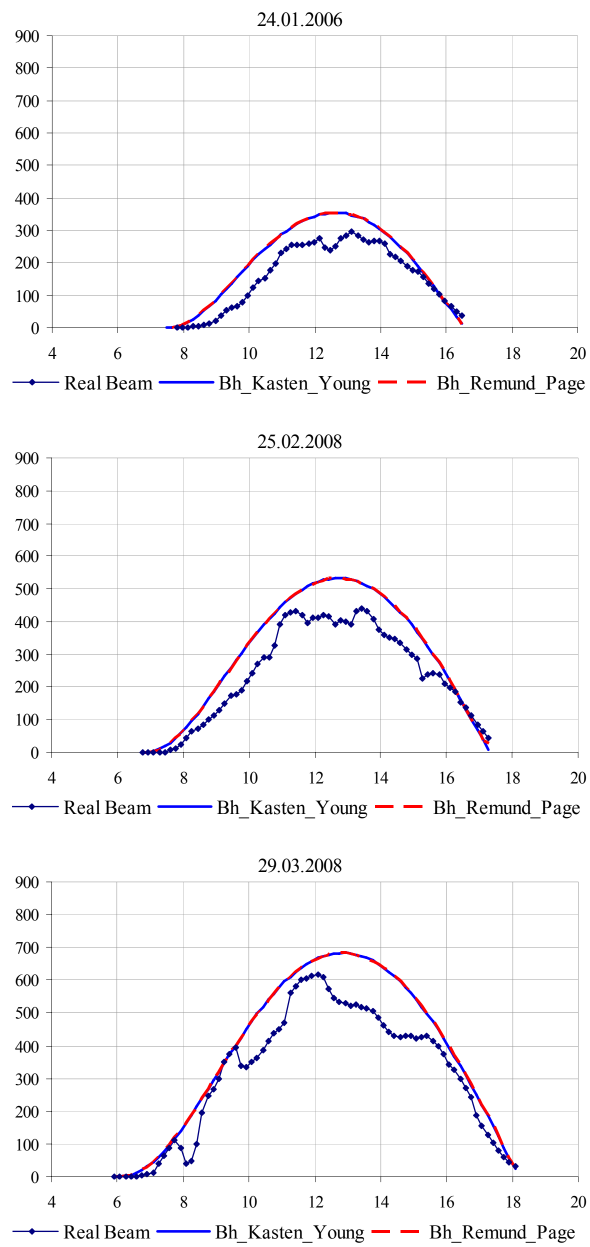

Fig.4. Theoretical simulation of the direct radiation for Braşov

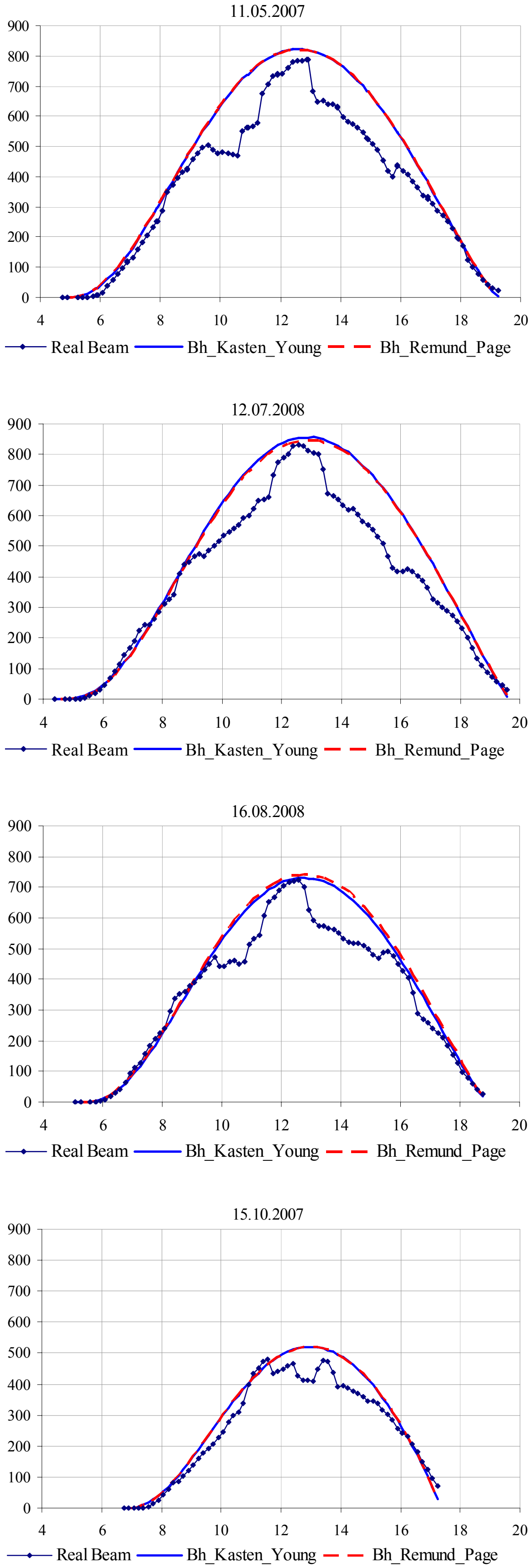

Fig.5. Theoretical simulation of the direct radiation for Braşov

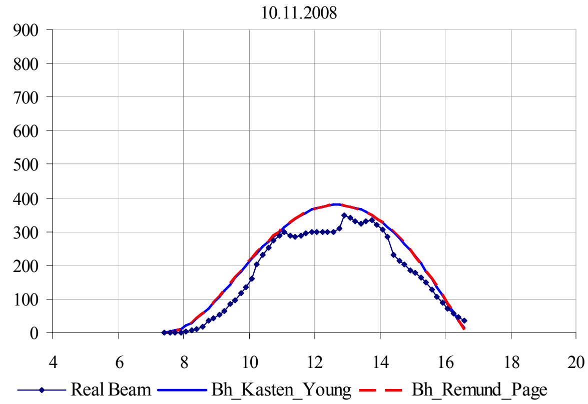

Fig.6. Theoretical simulation of the beam horizontal irradiance for Braşov Area

4. Conclusion

The obtaining of some more precise theoretical radiation simulation requires the accurate mathematical modelling of all climatological parameters that intervene in the beam relation. In the same time, the geographical and climatic features of every site as well the influence of the urban conditions on some climatological parameters must be taken into consideration.

The turbidity factor values, recommended by the technical literature for the Braşov area (these values do not take into consideration at least the urban condition of Braşov), do not correspond to the real values calculated on the basis of the recorded meteorological data.

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