SOLAR RADIATION ESTIMATION UNDER CLEAR SKY CONDITIONS FOR BRAŞOV AREA (ROMANIA) – LINKE TURBIDITY FACTOR

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Abstract. The determination of solar radiation is important for solar renewable systems design. The solar radiation is dependent on several factors such as, latitude and altitude location, season, day, time, content of dust, water vapour and aerosols in the atmosphere. In addition, mounting of solar energy systems in urban areas requires the determination of solar radiation, because in urban areas there is a more significant attenuation of solar radiation due to atmospheric pollution. However, the development of some methods to estimate the solar radiation assumes the knowledge of some climatological parameters (the optical air mass, Rayleigh optical depth, Linke turbidity factor, etc.). Among all these parameters, one of the most important is represented by the atmospheric turbidity, due to the relationship existing between aerosols and attenuation of solar radiation reaching the Earth's surface.

In this context, this paper proposes a study of the Linke turbidity factor, for Braşov urban area, with the purpose of more accurate solar radiation estimation. In addition, this study recommends the use of some correction coefficients for the direct and diffuse radiations; these coefficients are empirically determined and they depend on the specific geographical and climatic conditions of the considered site.

Keywords: clear sky conditions, direct radiation, Linke turbidity

1. Problem description

The main climatic parameters, with an important influence in the design of solar energy conversion systems are: solar radiation, wind speed, temperature and humidity. Among these, solar radiation is the main input parameter, both in the design of solar energy conversion systems in heat or electricity energy, and the building energy simulation. In this context, the objective of this study is to develop solar radiation estimation models, adequate models for an optimum design of solar energy conversion systems. The present study proposes a unitary approach of the solar radiation components modelling, in order to obtain models that can be use together.

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

2. Method used

2.1. Experimental meteorological data

The proposed study uses the meteorological data collected by an automatic weather station type Delta-T. The weather station is automatic with a flexible structure consisting of a variable set of sensors that measure various meteorological parameters (total and diffuse solar radiation, temperature and humidity, wind speed and direction) and a data logger which records data. Meteorological data readings are made every minute, a value representing the average readings being recorded every 10 minutes [2].

2.2. Depression of Braşov, geographical and climate description

Braşov has a temperate continental climate, specific to transition between oceanic temperate climate and that continental temperate climate. Temperature variations are high, the average temperature recorded with Delta-T weather station (Braşov basin) during 2006-2011 being 9.39 °C; the lowest temperature was recorded in January 2010 (-20.03 °C) and the maximum one in July 2007 (35.85 °C). Braşov basin area is characterized by temperature inversions; temperatures in the surrounding mountains are higher than those of depression, and the cold air masses accumulate them here because of the surrounding mountains, which prevent their movement.

2.3. Sunshine duration

Before calculating the Linke turbidity factor and proceeding to solar radiation estimation, in Table 1, a few monthly measured parameters (daily average) that characterize Braşov urban area are presented. It can be noticed that fractional sunshine ($\overline{n}/\overline{N}$) is less than 50 percent throughout the periods December, January-April and about 70 percents during August and September, in these months the clearness index ($\overline{H}_g/\overline{H}_0$) is also recording the maximum values (higher than 0.60).

Table 1. Monthly average – daily parameters characteristic to Braşov urban area

Month	$\overline{n}/\overline{N}$	$\overline{H}_g \overline{H}_0$	$\overline{H}_{diff}/\overline{H}_0$	$\overline{H}_{diff}/\overline{H}_g$
January	**0.20**	**0.34**	0.22	**0.65**
February	0.26	0.41	0.26	**0.64**
March	0.47	0.49	0.22	0.45
April	0.46	0.47	0.19	0.41
May	0.51	0.51	0.21	0.42
June	0.51	0.49	0.19	0.38
July	0.58	0.53	0.20	0.37
August	**0.75**	**0.61**	0.16	**0.27**
September	**0.76**	**0.62**	0.20	0.32
October	0.57	0.54	0.20	0.36
November	0.59	0.53	0.23	0.43
December	**0.21**	**0.31**	0.20	**0.65**

It can be also noticed, the diffuse radiation represents, during a year, at least 27 percents from total radiation (this value represents the minimum value recorded in August). The lower contribution of the diffuse radiation in the total radiation is also recorded during June, July, September and October (32÷38%) when the clearness index has higher values. The highest values of the ratio $\overline{H}_{diff}/\overline{H}_g$ are recorded during December and January-February (over 60%) when the clearness index $k_t = \overline{H}_g/\overline{H}_0$ records the minimum values.

When the available solar radiation is analysed the sunshine duration must be considered (Figure 1). As a result of the multiple periodic and non-periodic cloud variations and the frequency of different types of clouds, the sunshine duration varies from year to year and from month to month.

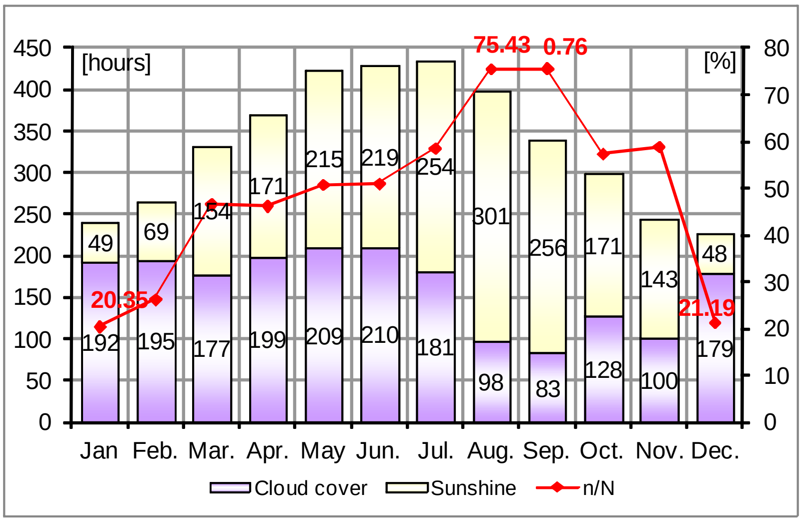

Figure 1. Sunshine duration average for Braşov

From the analysis of the data recorded with the weather station Delta T, assembled on the roof of the Product Design and Environment Department, it results for the period March 2011-February 2012 (Figure 1), the annual mean duration of sunshine is 2051 hours, that representing 51.2% from the total number of sunshine hours possible in Braşov. Usually, the maximum sunshine duration is recorded for July and August months, the minimum sunshine duration corresponding to December

2.4. Selecting clear-sky records

The models for the radiation estimation proposed by this paper refer to clear sky conditions. In this way, the first stage of the study consisted in the selection from the entire six-year database (2006-February 2012) only the records suitable for a clear sky model.

The clear-sky conditions assume meeting several conditions, so that clouds do not influence beam values [1, 2]:

- The normal incident direct radiation exceeds 200 W/m^2;
- Mention should be made of the meteorological data for which conditions of clear sky were ambiguous, such as thin haze in early morning or in late afternoon – sometimes they could be wrongly selected as clear-sky data; this is another reason to consider only the data records for solar elevation greater than 10°;
- With regard to the clearness index, (this parameter is defined as the ratio of the total radiation at ground level on a horizontal surface to the horizontal radiation outside the atmosphere) only days with a daily clearness (it is defined from

daily irradiations) of at least 0.7 are taken into consideration;

- Only hourly values with a corrected clearness value k_t' (Eq. (1)) of at least 0.7 are taken into consideration [1]

$$k_t^{'} = \frac{k_t}{1.031 \cdot \exp\left(\frac{-1.4}{0.9 + 9.4m} + 0.1\right)} \quad (1)$$

3. Results and discussion

3.1. Linke turbidity factor

In the first stage of this study, modelling of Linke turbidity factor is proposed, considering the specific geographical and climate characteristics of the Braşov urban area (clear sky conditions).

Linke turbidity factor determination will be based on measurements of direct solar radiation. In this purpose, Linke turbidity factor (T_L) is defined and the climatological factors involved in calculating T_L – that the air mass and optical air depth – are described. To quantify the level of atmosphere turbidity and its effect on the direct solar radiation received by the Earth's surface, several turbidity coefficients have been defined [3]; among them the most appreciated and widely used is the Linke turbidity factor.

Turbidity factor T_L was proposed and defined by Linke in 1922, as the number of clean and dry atmosphere necessary to obtain the same effect on direct solar radiation, as that produced by the real atmosphere. Turbidity factor T_L depends on the optical depth of the clean and dry atmosphere, in its turn this being influenced by air mass (which itself depends on the angle of altitude).

Linke turbidity factor describes the optical depth of the atmosphere, due to both the processes of scattering caused by aerosols and air molecules and the absorption processes caused by ozone, water vapour, oxygen and carbon dioxide.

The values given in the literature, for turbidity factor T_L specific to Braşov urban area, do not correspond to real values; these recommendations ignore that Braşov is a lowland area, plus it is an urban area [6]. To obtain more accurate values of the turbidity factor T_L, the determination and accurately modelling of all climatic parameters that appear in its calculation are necessary.

Linke turbidity factor may provide a good estimate for the direct radiation reaching the Earth's surface for the real atmosphere that contains particles, mists, fumes, mist or other impurities [1, 3, 4]. To calculate the T_L factor, from the direct radiation measurements (for clear sky conditions), the relation of direct radiation on a horizontal surface is re-written [1],

$$T_L = 1/(\delta_r \cdot m) \cdot \ln(I_0 \cdot \varepsilon \cdot \sin(\alpha)/B_h) \quad (2)$$

where: $I_0 \cdot \varepsilon$ is the solar constant (1367 W/m^2) corrected by the eccentricity factor; B_h is the beam horizontal radiation; 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).

For the optical air mass (m) and Rayleigh optical depth (δ_r), the literature recommends a large number of calculation relationships. This paper proposes to calculate the Linke turbidity factor, using for air mass and optical air thickness, the relations proposed by Kasten and Young (1989 and 1996) [4, 5],

$$m = p/p_0 \cdot m_0 = \\ = p/p_0 \left(\sin(\alpha_c) + 0.5057(\alpha_c + 6.079)^{-1.6364}\right)^{-1}, \quad (3)$$

$$\alpha_c = \alpha + 0.6136 \frac{0.159 + 1.123\alpha + 0.06565\alpha^2}{1 + 28.9344\alpha + 277.397\alpha^2} \quad (4)$$

$$\delta_r = \left(6.6296 + 1.7513m - 0.1202m^2 + \\ + 0.0065m^3 - 0.00013m^4\right)^{-1}, \quad m \le 20, \quad (5a)$$

$$\delta_r = (10.4 + 0.718m)^{-1}, \quad m > 20. \quad (5b)$$

The relative optical air mass (Eq. (3)) is dependent on the corrected solar altitude given by the Eq. (4) and the correction for a given elevation z (Eq. (6)),

$$p/p_0 = \exp(z/8435.2). \quad (6)$$

Note that the use of the two relationships (Eq. (3) and Eq. (5)) takes into account the altitude of the site for which the calculation is achieved (this being the reason why these models were chosen). For geographical location of Braşov, the highest value the altitude angle is obtained on the summer solstice and it is about 68°.

Thus, considering the two calculation relations for air mass and optical depth, in the next step, turbidity values (T_L) will be calculated, for each record – extracted from the database – corresponding to the clear sky days.

The annual variation of the Linke turbidity factor was analyzed over a six-year period: January 2006 - February 2012. Figure 2 presents the monthly means values for the turbidity factor, these values representing the monthly mean for all six years analyzed.

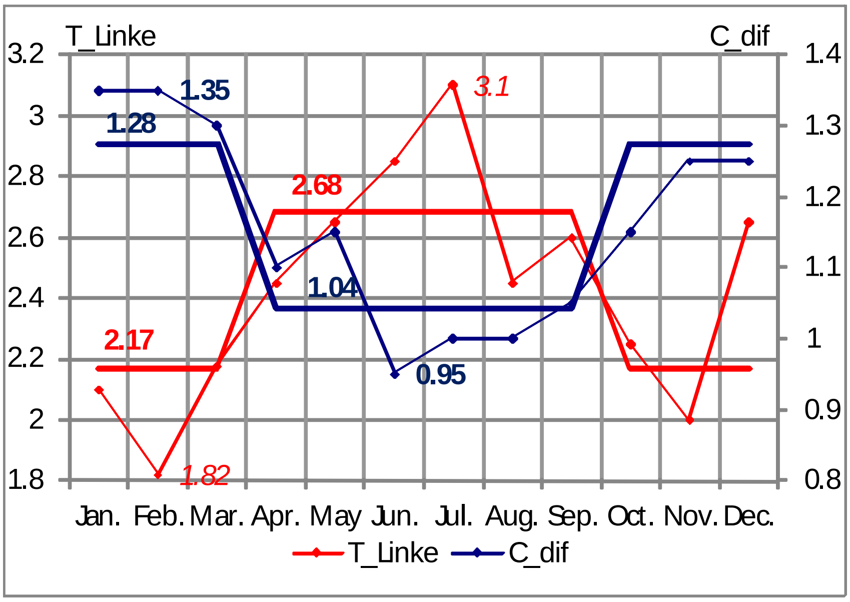

Figure 2. Monthly means of the Linke turbidity factor and correction coefficient for diffuse radiation (six-year period)

The main feature of the turbidity factor variation is a seasonal cycle divided into two year periods. The first one (from October to March) is characterized by low values of turbidity and the second one (from April to September) is characterized by high values of turbidity. March and October can be regarded as transition months between the two periods.

By analyzing Figure 2, it can be seen that the mean values of the turbidity factor vary for the October-March period, around the value of 2.17 and for the period April-September around the value of 2.68. The smallest values of the T_L turbidity factor were obtained for February (1.82) and November. The highest values of the turbidity factor for the Braşov urban area were registered for June and July (3.1).

3.2. Estimating Clear-Sky Solar Radiation – Theoretical Considerations

Knowing the Linke turbidity values the most used relationships to calculate solar radiation components are those recommended by WMO through ESRA handbook [1]; thus, for the direct radiation on a horizontal surface, is recommended the following relation

$$B_h = I_0 \cdot \varepsilon \cdot \sin(\alpha) \cdot \exp(-T_L\, m\, \delta_r(m)). \qquad (7)$$

Diffuse radiation, for clear sky conditions, is calculated with relation

$$D_h = C_{dif} \cdot I_0 \cdot \varepsilon \cdot T_{rd}(T_{Lam2}) \cdot F_d(\alpha, T_{Lam2}), \qquad (8)$$

where:

- $T_{rd}(T_{Lam2})$ is the atmospheric transmission function (when the sun is at zenith),

$$T_{rd}(T_{Lam2}) = -0.015843 + 0.030543\,T_{Lam2} + 0.00033797\,T_{Lam2}^2, \qquad (9)$$

- $F_d(\alpha, T_{Lam2})$ – solar altitude correction,

$$F_d(\alpha) = A_0 + A_1 \sin(\alpha) + A_2 (\sin(\alpha))^2, \qquad (10)$$

where

$$A_0 = 0.2646 - 0.06158\,T_L + 0.0031\,T_L^2, \qquad (11)$$

if $A_0 T_{rd} < 0.0022$, then

$$A_0 = 0.0022/T_{rd}, \qquad (12)$$

$$A_1 = 2.04 + 0.018945\,T_L - 0.01116\,T_L^2, \qquad (13)$$

$$A_2 = -1.3025 + 0.0392\,T_L - 0.008507\,T_L^2, \qquad (14)$$

- T_{Lam2} – Linke turbidity factor for air mass 2,
- C_{dif} – correction coefficient for diffuse radiation.

The coefficient C_{dif} is determined empirically and it is specific to the urban area of Braşov. This coefficient value varies between 0.95 and 1.35 depending on the month (Figure 2).

This coefficient takes into account the fact that, the radiation estimation is performed for lowland urban areas and in depression areas the diffuse radiation values are higher than usually, even under clear sky day conditions. This factor has a cyclic seasonal variation, which divides the year into two periods: October-December-January-March period characterized by high values of this coefficient (these values vary around 1.28) and April-September period characterized by low values (around 1.04). The highest values of this coefficient are recorded for January and February (1.35) and the lowest for the summer months (0.95 for June and 1 for July and August).

Total radiation is obtained by summing the two components, namely direct and diffuse radiations (Eqns. (7) and (8)). Considering the obtained values of the Linke turbidity factor, the next stage consists in the solar radiation estimation and the models performance estimation, topic that will be covered in the second part of this paper.

4. Conclusions

The obtaining of some precise radiation estimations (direct, total and diffuse radiations) requires the accurate mathematical modelling of all the climatological parameters that intervene in the radiation relation. Among these climatological parameters, the atmospheric turbidity (by Linke turbidity factor) is an important parameter for assessing the air pollution in local areas, respectively then aerosol total burden.

It must be mentioned, the turbidity factor values given by the technical literature for the Braşov area [6], do not correspond to the real values calculated on the basis of the real recorded meteorological data (these values do not take into consideration at least the urban condition of Braşov). The turbidity factor values from literature are too low and the use of some too low values for the turbidity factor, with the purpose to estimate the radiation variation, leads to significant differences between the real curves and the theoretical ones. In this context, due to the lack of information concerning the turbidity values for the urban basin area of Braşov and taking into consideration the specific variation of direct radiation for this area, the present paper proposed the determination of Linke turbidity factor.

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