COMPUTER PROGRAM FOR CLIMATOLOGICAL PARAMETERS CALCULATION AND RADIATION SIMULATION

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Abstract: *The paper presents software developed for the determination of the basic input data used to design a renewable solar energy system. The computer program calculates the angles that describe the apparent movement of the Sun in the sky. It allows the user an interactive selection of both the site and the period of time desired, as well as the calculation of various elements, such as: solar angles, air mass, Linke turbidity factor, and solar radiation received on a horizontal or tilted surface. The computer program also permits a graphical display of the variation in solar elevation and azimuth angles during equinoxes and solstices, as well as of the sunchart diagrams.*

Key words: *Linke turbidity factor, air mass, optical depth, direct radiation.*

1. Introduction

In a good design of renewable energy systems, the objectives that must be reached are the minimisation of the overall cost and the maximisation of the energy performance of the system.

In order to calculate the performance of an existing system or one that is being designed, appropriate and accurate weather and climatological data must be collected and analysed for the specific geographic area. This task requires the handling and processing of a significant volume of data.

In this respect, both an analysis of the influence of the measurement interval of solar radiation and wind speed, as well as a good fit for the data measured in a typical hybrid energy system are of paramount importance, not only with regard to technical reliability, but also in the minimisation of the system's total costs (i.e. power consumption).

Nature offers a variety of freely available options for producing energy.

It is mainly a question of how to convert sun radiation, wind, biomass or water into electricity, heat or power as efficiently, sustainably and cost-effectively as possible.

On average, the energy of the sunshine that reaches the Earth is about one kilowatt per square meter worldwide. According to the Research Association for Solar Power, the power is gushing from renewable energy sources at a rate of 2.850 times more energy than is needed in the world today.

In one day, the sun radiation which reaches the Earth produces enough energy to satisfy the world's current power requirements for eight years. Even though only a percentage of that potential is technically accessible, this is still enough to provide just under six times more power

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than the world currently requires.

To meet the necessities and requirements of the renewable energy systems designer, numerous software programs have been developed, with particular or large applicability.

The software developed by the authors was programmed in Visual FoxPro to obtain the basic input data used by the solar energy systems designers: solar angles, climatological parameters, simulation of the solar radiation on a horizontal or a tilted surface and the sun chart. The computer program provides a friendly interface, from which the user can choose the data to be displayed, allows of the tabular and graphical display of the calculated climatological parameters (the optical air mass, the optical Rayleigh depth, Linke turbidity factor, and the simulated global, diffuse and direct radiations, on both horizontal and tilted surface).

Further on, the direct link between the climatological parameters and the quantity of solar radiation received by a horizontal or tilted surface will be discussed.

2. Computer Program's Objectives

The computer program designed takes into consideration the following objectives [3]:

- the use of an advanced software that permits the processing of a large volume of data;
- the program must display a high degree of generality and applicability;
- the program's structure must allow of further development;
- the modelling of the climatological parameters for more sites in Romania using a default list, but also for any other location, for which the latitude or geographical coordinates must be typed in;
- the computer program should allow of both numerical (tabular data presentation) and graphical display;
- the program should calculate the following elements: solar angles, Linke turbidity factor, solar radiation received on a horizontal or tilted surface, air mass, optical depth and sunchart for a selected site.

The computer program uses original procedures developed for database computer modelling.

The program is run and the simulation performed for Braşov area, but due to its flexible structure, it can also be used for any desired site.

3. Computer Program's Theoretical Basis for Climatological Parameters

The correct determination of solar energy that a specific site can receive in clear sky condition is important for studies and research to find the characteristic climatological parameters of the area.

There is a direct dependence between the solar radiation that reaches the Earth's surface and the climatological parameters, mainly through Linke turbidity factor, the relative optical air mass and Rayleigh optical depth.

3.1. Linke Turbidity Factor (T_L)

Solar radiation passing through the atmosphere is scattered and absorbed by molecules and particles. It also interacts with larger particles such as water droplets and dust when these are present in the air [1].

Information about the quantity and the properties of these particles is needed to accurately estimate the radiation in clear sky conditions. Linke turbidity factor T_L helps to quantify this information.

The turbidity factor represents the number of clear dry atmospheres necessary to produce the observed attenuation.

Several atmospheric turbidity coefficients have been introduced during the past decades in order to quantify the influence of atmospheric aerosol content on direct radiation received at the Earth's surface.

Some of these are: Linke turbidity factor, T_L (Linke, 1922), Ångström turbidity parameters, α and β (Ångström, 1929), Shüepp coefficient, B (Shüepp, 1949), Unsworth-Monteith turbidity factor, T_U (Unsworth and Monteith, 1972) and horizontal visibility. Of all them, Linke turbidity factor is most commonly used.

The computer program designed proposes different values of Linke turbidity factor calculated for Braşov urban area (for an air mass equal to 2).

Linke turbidity is a very convenient approximation to model the atmospheric absorption and scattering of solar radiation under clear sky conditions. This factor denotes the transparency of the cloudless atmosphere:

$$T_L = -\frac{1}{0.8662\,\delta_r\,m_a}\ln\left(\frac{E_0\,\varepsilon}{B}\right), \qquad (1)$$

where: δ_r - optical thickness of water- and aerosol-free atmosphere (clear and dry atmosphere); m_a - air mass; B - normal incidence direct irradiance and $E_0\varepsilon$ - solar constant (1367 W/m^2) corrected by the eccentricity factor:

$$\varepsilon = 1 + 0.03344\cos\left(\frac{2\pi\,day\_no}{365.25} - 0.048869\right). \qquad (2)$$

A typical value of Linke turbidity for Europe is 3 [1]. However, this value exhibits strong fluctuations in space and time, depending on the geographical and climatic conditions. Linke turbidity factor represents a key input to several models assessing the radiation modelling under clear skies. The computer program calculates all the climatolagical parameters under clear sky conditions.

Considering the above-mentioned facts, it is very important to determine Linke turbidity factor with respect to the real conditions of a particular site (Figure 1).

Day_no	T_l_kasten	T_l_remund
189	3.530	3.966
190	3.509	3.963
191	3.957	4.460
193	3.854	4.333
194	3.770	4.241
195	3.898	4.379
196	4.199	4.727
197	3.621	4.079
198	4.360	4.905
199	4.574	5.141

Fig. 1. *Linke turbidity factor*

It has been determined using two models:

A. The first model is based on Kasten and Young formula for the optical air mass (1989) and the improved Kasten formula for Rayleigh optical depth (1996) [4].

B. The second model is based on Remund-Page corrections (2002) for the relative optical air mass and Rayleigh optical depth [5].

The expressions of beam and diffuse radiations are dependant on turbidity factor variation. Thus, considering the studies conducted with a view to determining Linke turbidity for Braşov area, the present simulations will use the daily means variation of the turbidity factor corresponding to the variation presented in Figure 2.

3.2. Relative Optical Air Mass (m_a) and Rayleigh Optical Depth (δ_r)

In order to calculate the turbidity factor values (T_L) with equation (1), the values of air mass (m_a) and Rayleigh optical thickness in clean dry atmosphere (δ_r) must be known.

The relative optical air mass is the length of the optical pathway along which solar radiation travels through the Earth's atmosphere.

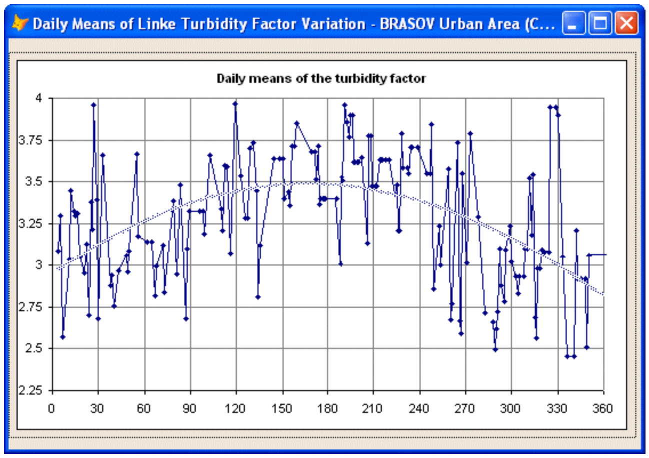


Fig. 2. *Daily means of Linke turbidity factor for Braşov area*

The computer program does the calculation of relative optical air mass and Rayleigh depth using two modelling relations, respectively. The first one proposes the classical formula - relations (3) and (4) - for relative air mass (m_a) and optical depth.

The second modelling relations suggest, for relative air mass, the use of two relations depending on the solar elevation angle; for solar elevation angles $\alpha > 25^{o}$, air mass is calculated with relation (3), while for solar elevation angles $\alpha \leq 25^{o}$, relation (5) is used. Rayleigh optical depth (δ_r) is calculated with relation (6):

$$m_a = \frac{1}{\sin\alpha}, \tag{3}$$

$$\delta_r = \frac{1}{9.4 + 0.9 m_a}. \tag{4}$$

These second modelling relations use the equations developed by F. Kasten and A. Young [4]:

$$m_a = \frac{1.002432\sin^2\alpha + 0.148386\sin\alpha + 0.0096467}{\sin^3\alpha + 0.149864\sin^2\alpha + 0.0102963\sin\alpha + 0.000303978}, \tag{5}$$

$$\delta_r = \frac{1}{6.6296 + 1.7513 m_a - 0.1202 m_a^2 + 0.0065 m_a^3 - 0.00013 m_a^4}. \tag{6}$$

3.3. Solar Radiations on a Horizontal or Tilted Surface

In the branch literature there are numerous models that simulate solar radiation on horizontal or tilted surface, along with its components: beam solar radiation (or direct solar radiation) (*B*), diffuse solar radiation (*D*) and global solar radiation (*G*), under clear sky or normal conditions.

The quantity of solar radiation received on a horizontal or tilted surface is conditioned by various factors, such as: season (day of the year, declination, altitude), hour (hour angle), time of day, climatological conditions and parameters (clouds, rain, the atmosphere's turbidity, relative optical air mass, optical thickness), geographical coordinates, relief configuration, and degree of pollution.

Thus, a model that simulates solar radiation and its components must include all these factors and the interdependence established among them.

In order to simulate global, direct (beam), and diffuse radiations on a horizontal surface, the computer program uses the formulas proposed by Bason [1]:

$$B = E_0 \varepsilon \sin\alpha \cdot \exp(-0.8662 T_L m_a \delta_r)\,, \quad (7)$$

$$D = (49.04 T_L - 42.32)[1 - \exp(0.1 T_L - 0.0908\alpha)]\,, \quad (8)$$

where T_L, m_a and δ_r formulas have been presented in subchapters 3.1 and 3.2 above.

Global solar radiation on a horizontal surface is calculated as the sum of its components (diffuse radiation and beam radiation).

In order to simulate global, direct (beam), and diffuse radiations on a tilted surface, the following equations are used [2]:

$$B_\beta = B\frac{\cos\theta}{\cos\theta_z}\,, \quad (9)$$

where θ and θ_z represent the incidence angle of the solar beam on a tilted and horizontal surface, respectively, and are expressed by the following relations:

$$\cos\theta = \cos(\varphi - \beta)\cos\delta\cos\omega + \sin(\varphi - \beta)\sin\delta, \quad (10)$$

$$\cos\theta_z = \cos\varphi\cos\delta\cos\omega + \sin\varphi\sin\delta, \quad (11)$$

where φ - site latitude; δ - declination angle; ω - hour angle.

The diffuse component on a tilted surface is given by relation:

$$D_\beta = D\frac{1}{2}(1 + \cos\beta)\,, \quad (12)$$

where β - inclination angle of the surface.

Relations (9) and (12) are used to calculate solar radiation when plane-surface, non-tracking solar systems are employed. These are south oriented and set at an optimum angle towards horizon (β), for the given site and the working period during a year.

4. Computer Program's Interface

On the user-friendly program interface, the dialog between program and user is carried out through input data fields, areas 2, 3, 4, 5, and 6 (Figure 3). The default list, area 1, contains predefined cities in Romania for which the program runs implicitly.

By clicking one of the buttons 7 to 15, the corresponding required data will be displayed in area 16 (Figure 4).

The program's interface enables the user to choose the type of data needed (e.g. solar angles, tilted angle, solar radiation or climatological parameters) as well as to select the manner in which the output data will be displayed (either in a tabular or graphical fashion).

If the location required by the user is in the default list, the program calculates the latitude and longitude that can be seen in areas 3 and 4; otherwise, the latitude of the site can be typed in the 'Enter latitude' field (area 5).

The user can also choose the time interval (area 6) for which the program will calculate the selected data.

By clicking button 7, a set of basic input data for designing a solar energy system will be shown in tabular form in the output data display area, see Figure 4.

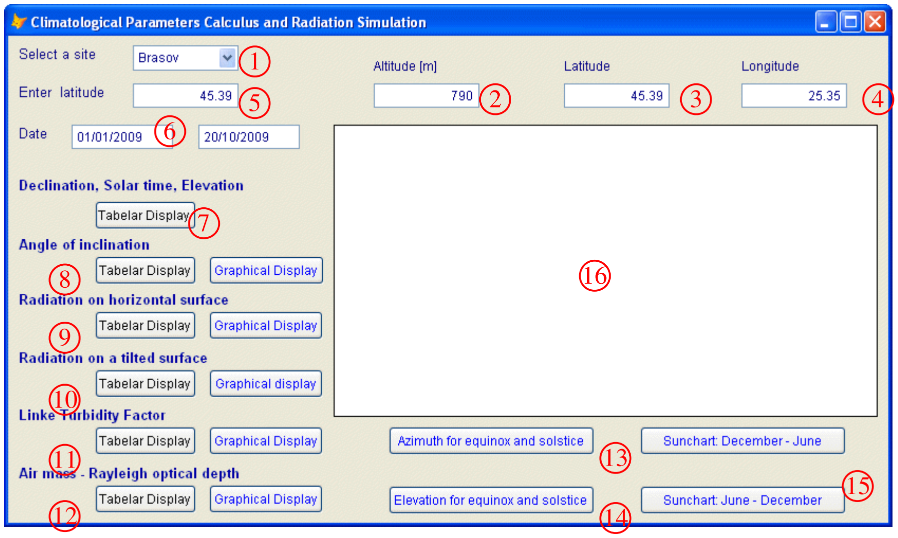


Fig. 3. *User-computer program interface*

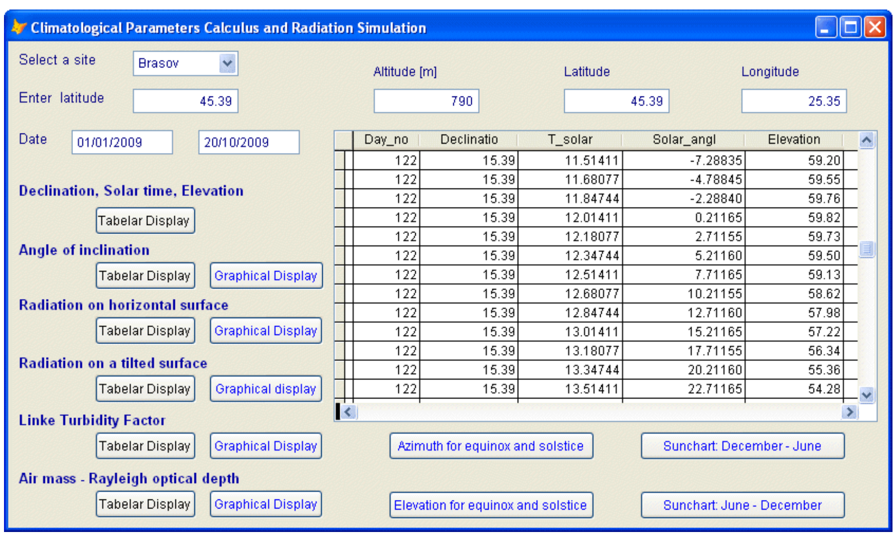


Fig. 4. *Basic data - tabular display*

By clicking button 9, the solar radiation on a horizontal surface can be shown in either tabular or graphical form, see Figure 5.

The average per day values of solar radiation on a horizontal surface have been calculated (the authors have opted for an average-per-day approach, as a more suggestive and representative graphical display can be obtained in this fashion, see Figure 5). By clicking button 10, the solar radiation on a tilted surface can be shown in a tabular or graphical display (Figure 6).

It should be mentioned that all data displayed can be exported and saved in a file for later use (e.g. comparative analysis or different graphs displaying).

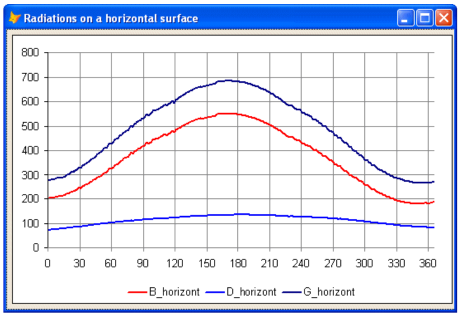


Fig. 5. *Solar radiation on a horizontal surface - graphical display*

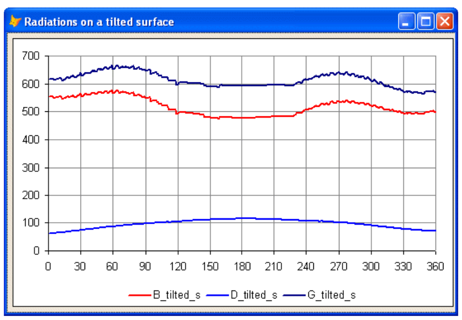


Fig. 6. *Solar radiation on a tilted surface - graphical display*

In order to view the difference between the solar radiation on a horizontal and a tilted surface, a graph has been plotted for direct radiation received in both cases, see Figure 7 (data exported from two files has been used).

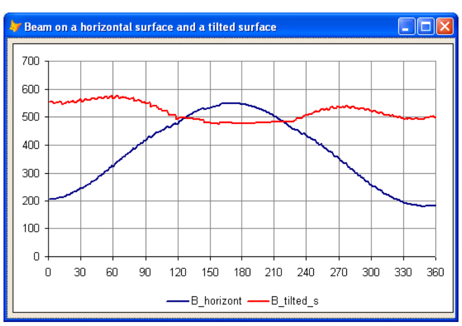


Fig. 7. *Direct solar radiation*

It can be noticed that, during the summer, the direct solar radiation received by a tilted surface is smaller as compared to that gathered by a horizontal surface, but through a correct orientation of a solar system, the direct solar radiation received can be maximised.

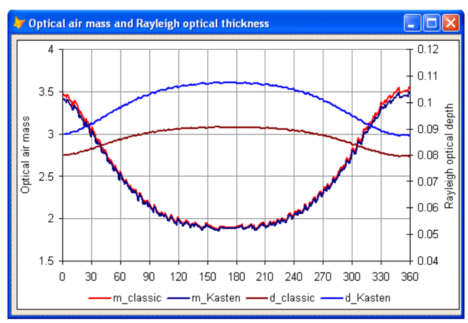
By selecting button 11, Linke turbidity factor can be shown in the output data area; for a tabular display, see Figure 1; for a graphical display, see Figure 2.

By selecting button 12, both optical air mass and Rayleigh optical depth are displayed in the output data area, see Figure 8.

Select a site

Date	Solar_t	M_classic	M_kasten	D_kasten
05/05/09	11.51924	1.15646	1.15646	0.11759
05/05/09	11.68590	1.15240	1.15240	0.11768
05/05/09	11.85257	1.15006	1.15006	0.11772
05/05/09	12.01924	1.14941	1.14941	0.11774
05/05/09	12.18590	1.15045	1.15045	0.11772
05/05/09	12.35257	1.15318	1.15318	0.11766
05/05/09	12.51924	1.15764	1.15764	0.11757
05/05/09	12.68590	1.16384	1.16384	0.11744
05/05/09	12.85257	1.17183	1.17183	0.11727
05/05/09	13.01924	1.18168	1.18168	0.11707
05/05/09	13.18590	1.19344	1.19344	0.11683

a)



b)

Fig. 8. *Optical air mass and Rayleigh optical depth: a) tabular display; b) graphical display*

5. Conclusions

The program presented in this paper is a very important tool for the determination of major climatological parameters used in the design of renewable energy systems.

Due to the comparative analysis of solar radiation available on both horizontal and tilted surfaces, the program makes it possible to determine the optimum inclination angle of the solar energy system (with respect to horizontal surface). Thus, according to the necessities of solar radiation during a year, the inclination angle can be determined. It is assumed that by using tilted surfaces the available radiation on them can be either maximised or minimised (for instance, during the summer the necessities of solar radiation can decrease).

The authors intend to conduct further research in order to enhance this software's versatility, by using the current models, such as: Adnot, Haurwitz and Kasten formulas for global radiation, Bugler formula for diffuse radiation and Hottel formula for direct radiation. Another model we have in mind is the European Solar Radiation Atlas (ESRA).

We also intend to develop more accurate radiation models for Braşov urban area. To achieve this, it is essential to take into consideration the geographical and climatological parameters, as well as any other conditions specific to an urban area (especially air pollution).

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