Analysis and determination of the optimal collector array orientation characteristics in solar systems

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Abstract. This paper presents results analysis for the distribution of direct and diffuse solar radiation for a specific climatic zone in Bulgaria. The influence of the slope angle of the collector array over monthly solar radiation incident is studied and regression dependencies regarding incident total, direct and diffuse specific annual solar radiation are derived. Based on the obtained dependencies, the optimal value of the solar collectors slope angle, that guarantees maximum value of the annual solar radiation, is determined. The ratio of direct radiation on an inclined to that on a horizontal surface depending on the azimuth of collector arrays with different slope angle is investigated using a dynamic simulation software. Graphical dependencies, allowing the determination of the total annual solar radiation at different values of the azimuth and the slope angle of the collector array are obtained.

1 Introduction

The eccentric nature of the Earth's ecliptic and the change in the geometric angles characterizing the position of the sun in a daily interval, associated with the rotational movement of the Earth around its axis, are the reasons for the non-stationary nature of the intensity of solar radiation. Additional influence on the available potential of the solar energy is exerted by the specific features of the geographical area, the atmosphere and the earth's surface. In engineering practice, the choice of a certain orientation of the solar collectors array is governed by the requirement to achieve maximum value of the solar energy over them and utilized by the systems in a different time interval, usually for a year or a series of months during the summer period.

For the conditions of the northern hemisphere, the orientation of the solar collectors in the direction of the geographical south is natural and logical, and their slope relative to the horizon β must be consistent with the change in the solar elevation angle α_s and with the condition for ensuring maximum duration of the periods in which the solar incidence angle ϑ is equal or close to 0^o. The recommended values of β and the orientation of the solar collectors, characterized by its azimuth angle γ, are summarized by Duffie J. A., W.

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Beckman [1] and subsequently cited in other specialized sources. The criteria for choosing the angle β specified therein is to account for the annual period of operation of the solar systems and the geographical latitude of the region φ , as the indicated values are $\beta = \varphi + (10^o \div 15^o)$ during operation in the winter period; $\beta = \varphi - (10^o \div 15^o)$ during summer operation and $\beta = \varphi$ during all year-round operation. At the same time, a number of authors are doing research and analysis on the most suitable orientation of solar collectors under different climatic conditions [2, 3].

The aim of the presented research is to analyse the influence of the orientation of solar collectors on the efficiency of conversion of solar radiation and to determine optimal values of collector array slope angle, ensuring maximum value of the annual solar energy on it under the climate conditions in Bulgaria.

Increasing the efficiency of solar radiation utilization will create objective prerequisites for making renewable energy sources an alternative to conventional fuels and for eliminating significant problems that arise from their combustion [4, 5].

2 Methods

Annually, the criteria for determining the optimum inclination angle β of solar collectors is to ensure maximum annual value of the total solar radiation, $H_{T,a}\ kWh/a$, incident on them. A possible approach to estimate $H_{T,a}$ is to determine its monthly average daily integral values $\overline{H}_T$. In this instance the baseline is monthly average statistical data for total daily solar radiation on a horizontal surface $\overline{H}$ and the index of average daily cloudiness $\overline{K}_T$.

Various model relations are used to calculate $\overline{H}_T$ which characterize, to a certain degree of approximation, the transfer of its direct, diffuse and reflected components from a horizontal to an inclined surface.

The methodology developed by Lui and Jordan [6] for determining $\overline{H}_T$ on an unshaded surface inclined at angle β is widely used. Assuming an isotropic model for the diffuse and reflected from the Earth's surface solar radiation, the monthly average total daily radiation is given by:

$$\overline{H}_T = \overline{H} \cdot \left(1 - \frac{\overline{H}_d}{\overline{H}}\right) \cdot \bar{R}_b + \overline{H}_d \cdot \left(\frac{1+\cos\beta}{2}\right) + \overline{H} \cdot \rho_g \cdot \left(\frac{1-\cos\beta}{2}\right), \quad (1)$$

where $\bar{R}_b = \overline{H}_T / \overline{H}$ is the ratio of the radiation on an inclined to that on a horizontal surface; $\overline{H}_d / \overline{H} = f(\overline{K}_T)$ – ratio of diffuse to monthly average total daily radiation; ρ_g - terrain reflection coefficient.

The adoption of an isotropic model for the diffuse radiation, according to which it falls on the sun-receiving surfaces uniformly from all sky directions, allows the orientation influence to be estimated unambiguously by analysing the effect of the azimuthal angle γ only on the direct component of the radiation G_b. For a surface inclined at an angle β relative to the horizon, the geometric transfer factor R_b of the direct radiation G_b from a horizontal to an inclined surface $G_{b,T}$ is given by:

$$R_b = G_{b,T} / G_b = G_{b,n} \cdot \cos\vartheta \,/ G_{b,n} \cdot \cos\vartheta_z, \quad (2)$$

where ϑ and ϑ_Z are the angles of incidence of the sun's rays on the inclined and horizontal surface.

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3 Results and discussions

3.1 Solar collectors' inclination angle

In certain geographical areas, the "rule of thumb" for choosing the slope angle of the collectors array relative to the horizon β defined in [1] could be ambiguous, due to the multicomponent nature of the solar radiation, expressed by the sum:

$$G=G_b+G_d+G_r,\ W/m^2 \quad , \quad (3)$$

where G_b, G_d G_r is the intensity of direct, diffuse and reflected solar radiation, W/m^2.

The ratio of diffuse to total solar radiation $\overline{H}_d/\overline{H}$ has been studied by various authors [6, 7, 8] and the resulting functional dependencies $\overline{H}_d/\overline{H} = f(\overline{K}_T) = f(\overline{K}_T)$ are summarized in [9]. The monthly distribution of the $\overline{H}_d/\overline{H}$ ratio for Climate Zone 1 of Bulgaria, obtained with the data published in [10, 11] for the factor of average monthly daily cloudiness $\overline{K}_T$ is shown in Figure 1.

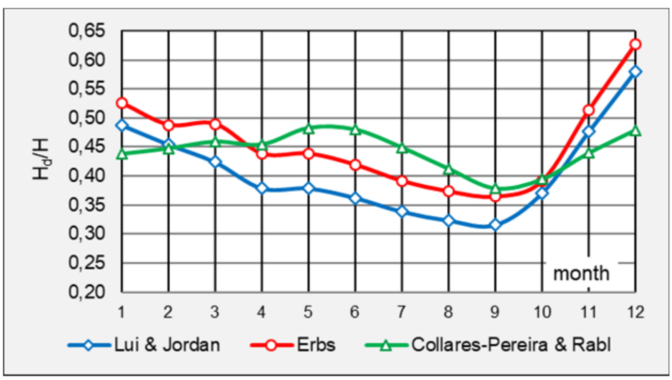

Fig. 1. Annual change in the proportion of monthly average daily diffused solar radiation for Climate Zone 1 in Bulgaria.

Figure 2 shows the annual evolution of the specific solar radiation over surfaces with different angles to the horizon β for Climate Zone 1, obtained with the Lui & Jordan model for $\overline{H}_d/\overline{H} = f(\overline{K}_T)$. The graph illustrates the monthly values of incident radiation $H_{T,m\,i}$ as the angle of the solar collectors changes in the interval $\beta \in [0° \div 90°]$, determined by the relation:

$$H_{T,m\,i} = N_{m\,i} \cdot \overline{H}_{T,m\,i}, \quad (4)$$

where $N_{m\,i}$ is the number of days in a month i $(i = 1..12)$.

The plots in Figure 2 confirm the expected nature of the annual variation of solar radiation $H_{T,m\,i} = f(\beta)$. The increase in $H_{T,m\,i}$ as the angle β decreases during the months of March to September/October and the opposite trend during the winter period warrants consideration of the hypothesis of the existence of an optimal value of β_{opt} which meets the requirement of achieving $\max(H_{T\,a})$ and can be determined by examining the functional relation $H_{T\,a} = \sum_{i=1}^{12} H_{T,m\,i} = f(\beta)$.

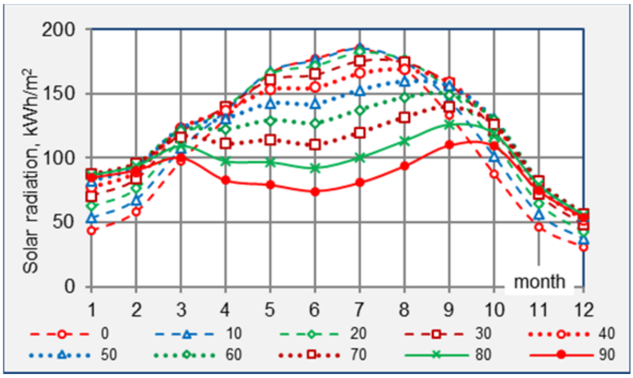

Fig. 2. Total monthly specific solar irradiance for surfaces with different angle relative to the horizon for Climate zone 1.

Summary results of the variation of annual specific total, direct and diffuse solar radiation with solar collector angle for the studied climatic conditions, obtained with a distribution model $(\overline{H}_d/\overline{H}) = f(\overline{K}_T)$ by Lui & Jordan, are shown in Figure 3. The graphical relations for total and direct solar radiation have an identical variation described by second-degree polynomials with pronounced maxima at values of angle β in the range 30 to 35 . The resulting functional relationships with the distribution model of $(\overline{H}_d/\overline{H}) = f(\overline{K}_T)$ of the above cited authors are summarized in Table 1. The table also shows the results obtained by simulation modelling with Transol software [12] based on calculations with hourly climate parameter data.

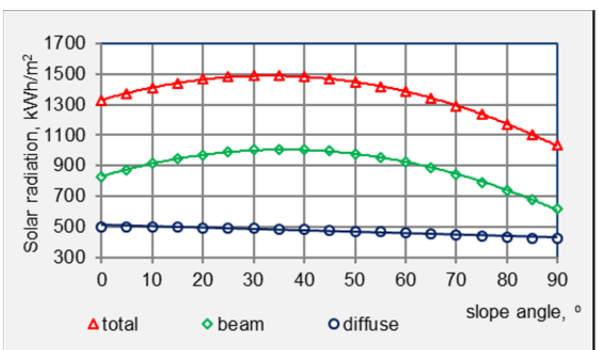

Fig. 3. Specific annual total, direct and diffuse radiation relative to the angle to the horizon for Climate zone 1.

3.2 Azimuth of the solar collectors

The nature of the variation of the monthly values of the factor R_b in the solar noon, at the angle of the solar collectors $\beta = 43° \approx \varphi$ is shown in Figure 4 and in Figure 5 - at an angle equal to the one defined as optimal for the climatic conditions of Climatic zone 1 with the Transol model ($\beta_{opt} = 32$ °). The analysis of the obtained results shows that at angle $\beta = 32°$ and azimuthal angle variation in the interval $\gamma = [-30° \div 30°]$ during all months of the year, the incident direct solar radiation is greater than that on a horizontal surface. At $\beta = 43° \approx \varphi$ for the same interval of variation of γ during the months of June and July an insignificant decrease in the R_b factor is observed. In the remaining months of the year R_b decreases with increasing $|\gamma|$, with minimum values ($R_b = 0.85$ by $\beta = 32°$) and ($R_b = 0.73$ by $\beta = 43°$) being reached in December at $|\gamma| = 90°$.

Table 1. Dependencies for determining the solar radiation and optimum collector tilt angle for Climate Zone 1 (φ=43.2°).

Model	**Solar radiation**	**Functional dependence**	β_{opt}, °
Lui & Jordan	Total	$H_{T,a} = -0.14 \cdot \beta^2 + 9.51 \cdot \beta + 1\,331$	33
	Direct	$H_{T,b\,a} = -0.14 \cdot \beta^2 + 9.69 \cdot \beta + 831$	35
	Diffuse	$H_{T,d\,a} = -0.90 \cdot \beta + 510$	-
Erbs	Total	$H_{T,a} = -0.14 \cdot \beta^2 + 8.72 \cdot \beta + 1\,331$	32
	Direct	$H_{T,b\,a} = -0.12 \cdot \beta^2 + 8.98 \cdot \beta + 763$	36
	Diffuse	$H_{T,d\,a} = -1.29 \cdot \beta + 583$	-
Collares-Pereira & Rabl	Total	$H_{T,a} = -0.14 \cdot \beta^2 + 9.38 \cdot \beta + 1\,330$	34
	Direct	$H_{T,b\,a} = -0.13 \cdot \beta^2 + 9.66 \cdot \beta + 739$	38
	Diffuse	$H_{T,d\,a} = -1.42 \cdot \beta + 607$	-
Transol	Total	$H_{T,a} = -0.15 \cdot \beta^2 + 9.66 \cdot \beta + 1\,301$	32
	Direct	$H_{T,b\,a} = -0.09 \cdot \beta^2 + 7.57 \cdot \beta + 619$	42
	Diffuse	$H_{T,d\,a} = -3.10 \cdot \beta + 751$	-

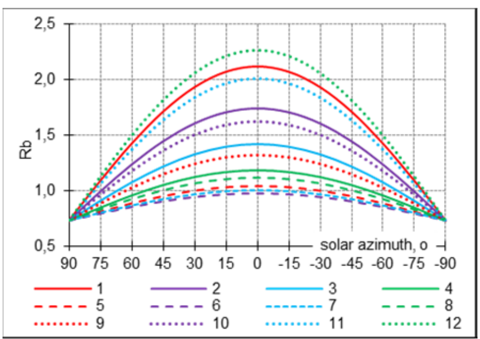

Fig. 4. Monthly transfer factor of direct solar radiation R_b at angle $\beta = 43° \approx \varphi$

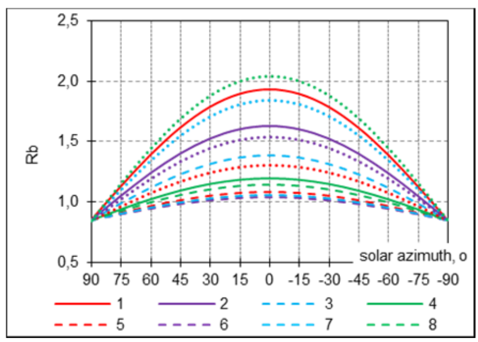

Fig. 5. Monthly transfer factor of direct solar radiation R_b at angle $\beta = 32° \approx \varphi$

The influence of the surface orientation on the incident solar radiation can be estimated using the orientation factor $F_{\gamma,a}$, defined annually by the relation:

$$F_{\gamma,a} = \frac{\sum_{i=1}^{12} H_{T,\gamma,i}}{\sum_{i=1}^{12} H_{T,\gamma=0,i}}, \tag{5}$$

where $H_{T,\gamma=0,i}$, kWh/m^2 is the specific total radiation for month i, on a solar radiation receiving surface with a southern orientation ($\gamma = 0°$); $H_{T\gamma,i}$, kWh/m^2 - specific total radiation for the month i, on a solar radiation receiving surface with azimuth $\gamma \neq 0°$.

The orientation factor of the surface can take values $F_{\gamma,a} \leq 1$ and provides information about the degree of reduction of the solar radiation incident on it during the corresponding time period due to $\gamma \neq 0°$. Its variation for the Climate Zone 1 conditions for surfaces with inclination angle $\beta = \beta_{opt} = 32°$ and $\beta \approx \varphi = 43°$ when the azimuth angle of the surface varies in the interval $\gamma = [-90° \div 90°]$ is shown in Figure 6, and the annual solar radiation incident on the surface - in Figure 7.

The minimum values of $F_{\gamma,a}$ are detected at $\gamma = -90°$ with $F_{\gamma,a}^{\beta_{opt}} = 0.82$. At $\beta = \varphi = 43°$ the minimum value of $F_{\gamma,a}$ is ~ 4% lower ($F_{\gamma,a}^{\beta=\varphi} = 0.79$). In annual aspect at $\gamma = -90°$ and $\beta_{opt} = 32°$ the reduction of radiation incident on the collector field $\Delta H_{T,\gamma\ \beta=\beta_{opt}} = H_{T,\gamma=0°} - H_{T,\gamma=90°}$ amounts to $265\ kWh/m^2$ while at surface orientation angle $\beta = \varphi = 43°$ and at azimuth $\gamma = -90°$ to $308\ kWh/m^2$.

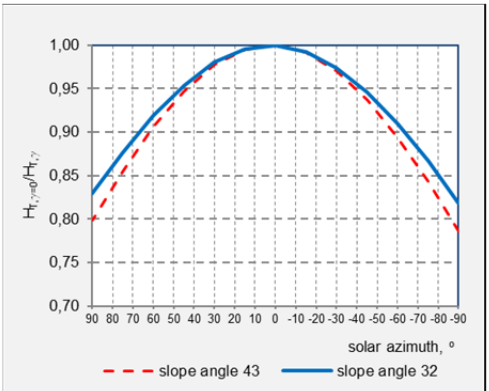

Fig. 6. Dependence of annual orientation factor $F_{\gamma,a}$ on azimuth angle for surfaces with slopes $\beta = 32^{\circ}$ and $\beta = 43^{\circ}$ for Climate Zone 1

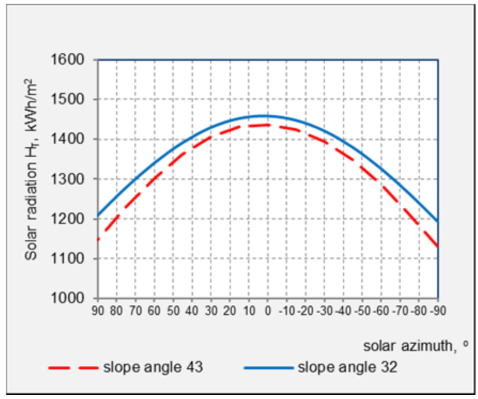

Fig. 7. Dependence of annual solar radiation on azimuth angle for surfaces with slope $\beta = 32^{\circ}$ and $\beta = 43^{\circ}$ for Climate Zone 1

4 Conclusion

The current paper presents a study of the distribution of direct and diffuse solar radiation for the town of Varna, considered as representative for Climate Zone 1 in Bulgaria.

Regression dependencies for the annual total $H_{T,a} = f(\beta)$, direct $H_{T,b,a} = f(\beta)$ and diffuse $H_{T,d,a} = f(\beta)$ incident on solar collectors are derived.

Regression dependencies for the annual total $H_{T,a} = f(\beta)$, direct $H_{T,b,a} = f(\beta)$ and diffuse $H_{T,d,a} = f(\beta)$ radiation incidents on solar collectors are acquired. The resulting regression for $H_{T,a} = f(\beta)$ are examined to determine the surface angle values β_{opt}, at which a maximum value of annual incident solar radiation is achieved. Study results show that the maximum value of $H_{T,a}$ is achieved at an angle β_{opt}, significantly lower than the value generally accepted in practice ($\beta = \varphi$).

Using dynamic simulation software, the variation of the monthly transfer factor of direct solar radiation $R_b = f(\gamma)$ is investigated in dependence on the azimuth of surfaces with angles β_{opt} and $\beta = \varphi$ under the conditions of Climate Zone 1 in Bulgaria.

The influence of the azimuth angle of the surface on the radiation incident on it is estimated by the annual orientation factor $F_{\gamma,a}$ for which graphical dependencies $F_{\gamma,a} = f(\gamma)$ are obtained for surfaces with angle β_{opt} and $\beta = \varphi$ under the conditions of Climate Zone 1 in Bulgaria. For the specific climate zone, the annual specific solar radiation data on surfaces with an angle of β_{opt} and $\beta = \varphi$ are defined and summarized.

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