EVALUATION OF DISTRIBUTIONAL SOLAR RADIATION PARAMETERS OF ČAČAK USING LONG-TERM MEASURED GLOBAL SOLAR RADIATION DATA

by

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Serbia is becoming more dependet on imported primary energy to meet its increasing energy demand. The ratio of indigenous primary energy production to primary energy consumption is decreasing. Therefore, it is of great importance for Serbia to make use of its indigenous energy resources more effectively, including its solar energy potential. Knowledge of global solar radiation is essential in the prediction, study, and design of the economic viability of systems which use solar energy.
In this paper, the solar radiation data on Čačak (lat 43.87° N, long 20.33° E) are analyzed based on 4 years of global solar radiation data measured on a horizontal surface. The distributional solar radiation parameters are derived from the available data and analyzed. The available solar radiation data on a horizontal surface are converted to that of various tilt angles and the yearly and monthly optimum tilt angles are determined.

Key words: *renewable energy, solar radiation, optimal tilt angle*

Introduction

Energy in the period after the "energy crisis", has acquired a global significance and this fact should be respected by every country. The multi-side linkage of energy, economic development and living conditions of the population, limited fossil fuels, unfavourable foreign payment balance, high investment costs for energy production and consumption, imperfect world energy market, environmental constraints to energy consumption, *etc*. require from the governments to show a greater interest in the field of energy. The goal of all countries is to substitute the imported energy sources by domestic ones and to preserve the energy sources by their rational use. Now it is generally accepted that attention should be focused on renewable energy sources (RES), since they are an opportunity for reducing the use of conventional energy resources, as well as for environmental protection and increase of local energy sources use. The specific characteristics of the RES (availability in unlimited quantities, periodical occurrence, changeability, difficulties in appropriate storage, *etc*.) require their definition and appropriate evaluation.

Solar energy technologies offer a clean, renewable, and domestic energy sources, and are capital components of a sustainable energy future. The design of a solar energy conversion system require precise knowledge regading the availability of solar radiation and its components at the location of interest. Since the solar radiation reaching the earth's surface depends upon climatic conditions of the place, a study of solar radiation under local climatic conditions is essential. Information on global solar radiation received at any site (preferably gained over a long period) should be useful not only to the locality where the radiation data is collected but also for the wider community [1]. A global study of the world distribution of global solar radiation requires knowledge of the radiation data in various countries and for the purpose of world wide marketing, the designers and manufactures of solar equipment will need to know the average global solar radiation available in different and specific regions. Obviously, measured data is the best form of this knowledge.

The main objective of this paper is analysis of Čačak's exposure to solar radiation and determination of distributional solar radiation parameters from the available global solar radiation data measured on a horizontal surface. In this study, 4 years were selected in the available data (January 2003 – December 2006). Čačak is a city located 140 km south from Belgrade in Serbia, at lat 43.87° N, long 20.33° E, with an altitude 250 m. The climate in Čačak is moderate continental, with an average daily temperature of 10.47 °C. Čačak is mostly exposed to west and north-west wind. The average speed of west wind is 2.3 m/s, and of north-west wind 1.4 m/s. The average annual insolation is about 4 hours. The highest insolation of about 12 hours a day is in June and July, while December and January are the cloudiest months.

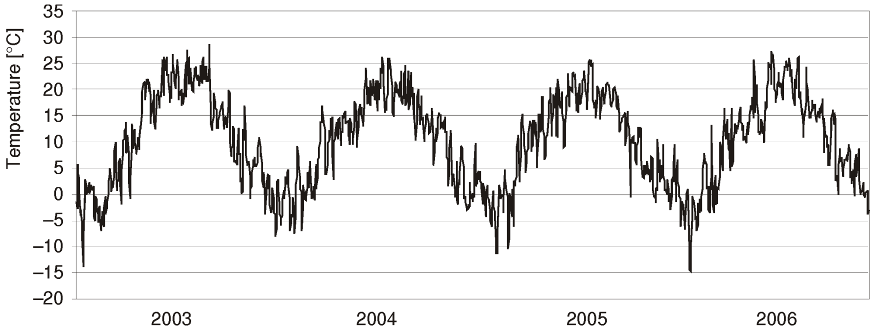

Figure 1. Air temperature during measured period 2003-2006

The available data reported in this paper were supplied by the Fruit Research Institute Meteorological station of Cacak. The meteorological station is installed in the centre of town, away of industrial zone, near the city park. Instaled weather station Vaisala Milos 200 provides measurements data on a 10-min. basis of wind speed and direction, humidity, air temperature, rain detector, solar radiation, and temperature. METNET dispersed system was developed for automated meteorological measurements and data processing, display, archiving, and transferring to the measurement network. The system consists of multiple remote measurement heads deployed in the measurement area according to the needs of the user and connected by a communication network. The performance of the system is controlled by a master station in local network of the meteorological office, which gives access to the data for other elements of meteorological support system.

Extraterrestrial radiation and clearness index

The declination δ is the angluar position of the sun at solar noon, with recpect to the surface of the equator. Its value in degree is given by equation [2]:

$$\delta = 23.45 \sin \left(360 \frac{284 + n}{365} \right) \tag{1}$$

where n is the day of year.

The sunset hour angle ω_s is the solar hour angle corresponding to the time when the sun sets, and it is given by the following equation:

$$\omega_s = -\mathrm{tg}\phi \mathrm{tg}\delta \tag{2}$$

where ϕ is the latitude of the site.

Solar radiation outside the earth's atmosphere is called extraterrestrial radiation. The extraterrestrial solar radiation on a horizontal surface is a function only of a horizontal surface alatitude and independent of other location parameters. Daily extraterrestrial radiation on a horizontal surface H_o, can be computed for the day of year n [3, 4]:

$$H_o = \frac{24 \cdot 3600 \cdot G_{SC}}{\pi} \left(1 + 0.033 \cos \frac{360n}{365} \right) \left(\cos\phi \cos\delta \sin\omega_s + \frac{\pi \omega_s}{180} \sin\phi \sin\delta \right) \tag{3}$$

where G_{SC} is the solar constant equal to 1367 [W/m^2]. The monthly mean daily extraterrestrial radiation is a useful quantity. For latitudes in the range +60 to –60 it can be calculated with eq. (3) using n and δ for the mean day of the month from tab. 1.

Before reaching the surface of the earth, radiation from the sun is attenuated by the atmosphere and the clouds. The ratio of solar radiation at the surface of the earth to extraterrestrial radiation is called the clearness index. Thus the monthly average clearness index K_T is defined as:

$$K_T = \frac{H}{H_o} \tag{4}$$

The clearness index depends on the location and the time of year. They are usually between 0.3 (for very overcast climates) and 0.8 (for very sunny location).

Table 1. Recommended average days for months and values of *n*

Month	*n* for i^{th} day of month	For average day of month		
		Date	*n*	δ [°C]
January	*i*	17	17	–20.9
February	31 + *i*	16	47	–13.0
March	59 + *i*	16	75	–2.4
April	90 + *i*	15	105	9.4
May	120 + *i*	15	135	18.8
June	151 + *i*	11	162	23.1
July	181 + *i*	17	198	21.2
August	212 + *i*	16	228	13.5
September	243 + *i*	15	258	2.2
October	273 + *i*	15	288	–9.6
November	304 + *i*	14	318	–18.9
December	334 + *i*	10	344	–23.0

The theoretically calculated extraterrestrial solar radiation data, and the monthly clearness index values calculated for Čačak from both the available measured and theoretically calculated extraterrestrial solar radiation data are presented in tab. 2. The monthly clearness index values varied between 0.13 and 0.58, while the yearly average values ranged from 0.31 to 0.37 between the years 2003-2006.

Table 2. Extraterrestrial and measured monthly solar radiation values and clearness indexes

Month	Total solar radiaiton [MJ/m²]					Clearness indexes			
	H_o	2003	2004	2005	2006	2003	2004	2005	2006
January	12.52	2.10	2.30	2.84	3.21	0.17	0.18	0.23	0.26
February	18.09	2.30	2.84	3.21	3.93	0.13	0.16	0.18	0.22
March	25.64	5.34	4.82	3.93	8.86	0.21	0.19	0.15	0.35
April	34.01	8.39	8.80	8.86	10.24	0.25	0.26	0.26	0.30
May	40.38	11.20	10.38	10.24	15.10	0.28	0.26	0.25	0.37
June	43.14	13.19	13.62	15.10	15.41	0.31	0.32	0.35	0.36
July	41.71	15.40	16.02	15.41	15.60	0.37	0.38	0.37	0.37
August	36.34	15.45	14.90	17.61	12.15	0.43	0.41	0.48	0.33
September	28.37	14.66	11.06	14.24	9.59	0.52	0.39	0.50	0.34
October	19.96	10.46	8.90	11.48	6.08	0.52	0.45	0.58	0.30
November	13.58	6.31	5.95	8.18	4.90	0.46	0.44	0.60	0.36
December	10.94	3.69	3.06	4.88	2.87	0.34	0.28	0.45	0.26
Average	**27.06**	**9.04**	**8.55**	**9.66**	**9.00**	**0.33**	**0.31**	**0.37**	**0.32**
Total	**324.68**	**108.49**	**102.65**	**115.97**	**107.95**				

The optimal tilt angle of a collector

Solar energy systems are usually installed at an angle from the horizontal surface to increase the solar energy angle of incidence on the surface of the collectors. The aim of the present study is to determine the monthly optimal tilt angle for Cacak, based on measured radiation data, and to compare it to theoretically obtained optimal tilt angles. The solar radiation on a horizontal surface is converted to different tilt angles so that the optima tilt angle can be determined. As the available hourly data for Cacak were measured on a horizontal surface as global radiation, it first needs to be split into its beam and diffuse component. The beam and diffuse component are not only essential for calculating the total solar radiation on tilted surfaces, but also the ratio of diffuse to total radiation has an important effect on the performance of solar energy systems.

Adopting the isotropic diffuse model, the solar radiation on a tilted surface can be calculated on an hourly basis based on the following well-known equations [5]:

$$H_{\mathrm{T}} = H_{\mathrm{b}} R_{\mathrm{b}} + H_{\mathrm{d}} \frac{1 + \cos\beta}{2} + H\rho_{\mathrm{g}} \frac{1 - \cos\beta}{2} \tag{5}$$

The first term on the right-hand side of eq. (5) represents solar radiation coming directly from the sun, the second term represents the contribution of monthly average diffuse radiation, and the last term represents reflection of radiation on the ground in front of the collector.

The ratio of global radiation on a tilted surface to that on a horizontal surface is denoted by R:

$$R = \frac{H_T}{H} = \frac{H_b}{H} R_b + \frac{H_d}{H} \frac{1 + \cos\beta}{2} + \rho_g \frac{1 - \cos\beta}{2} \tag{6}$$

where H is hourly total radiation on a horizontal surface, H_{b} is the hourly beam radiation, H_{T} is hourly total radiation on a tilted surface, H_{d} is the hourly diffuse radiation, β is the angle of tilt, and ρ_{g} is the ground reflectance factor. The geometric factor R_{b} is the ratio of beam radiation on the tilted surface to that on a horizontal surface at any given time. For surface facing directly towards the equator in the northern hemisphere, R_{b} is given by the following equation:

$$R_{\mathrm{b}} = \frac{\cos(\phi - \beta)\cos\delta\cos\omega + \sin(\phi - \beta)\sin\delta}{\cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta} \tag{7}$$

The ratio of tilted to horizontal solar radiation on a monthly basis for 4 years of Cacak data is shown in fig. 2. The tilt angle, in this case, is equal to the latitude of Cacak. The monthly ratio of tilted to horizontal radiation shows little variation from April to August. In the remaining months, the ratio varies relatively from year to year. In May, June, and July the ratio is below the unity, meaning that a horizontal surface receives more solar radiation than a surface tilted 43.87°. From August to December, the surface tilted 43.87° receives more solar radiation than the horizontal surface.

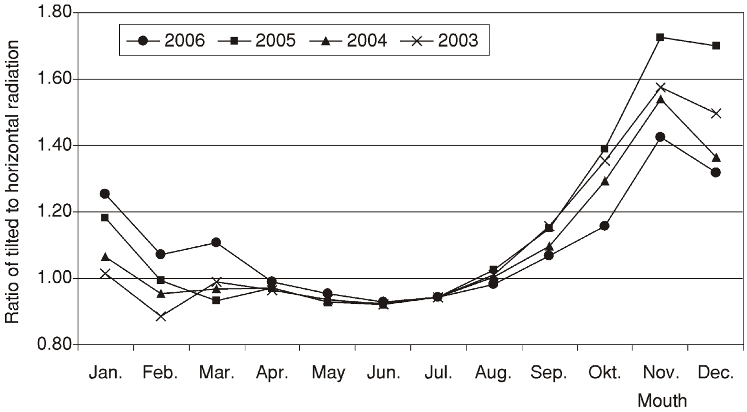

Figure 2. The ratio of tilted to horizontal solar radiation on a monthly basis for various years (the angle of the tilted surface is equal to the latitude of Čačak)

Detailed analysis was carried out based on the Čačak data of the calendar years 2003-2006 to study the effect of tilt angle on the total solar radiation incident on a surface. The yearly average daily solar radiation at different tilt angles is presented in fig. 3. If the solar radiation curves seen in fig. 3 is represented by a function of $f(x)$, the x satisfying the $f(x)/\ x = 0$ is the optimal tilt angle.

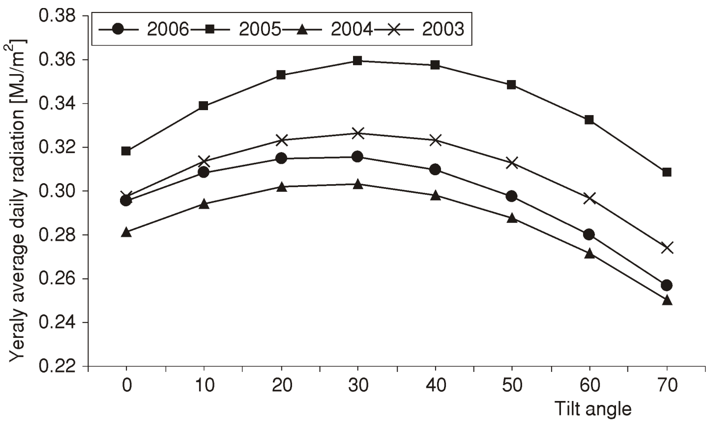

Figure 3. Yearly average daily solar radiation at different tilt angles

The monthly average daily solar radiation at different tilt angles for the year 2006 is shown in fig. 4.

When the monthly curves are represented by function and solved as described, the monthly optimal tilt angles can be determined. The optimal tilt angles determined in this way can be seen in fig. 5. The monthly optimal tilt angle can be determined theoretically for the beam radiation for a surface rotated about a horizontal east-west axis with a single daily adjustment, so that the beam radiation is normal to the surface at noon each day [5, 6]:

$$\cos\theta + \sin^2\delta + \cos^2\delta\cos\omega \tag{8}$$

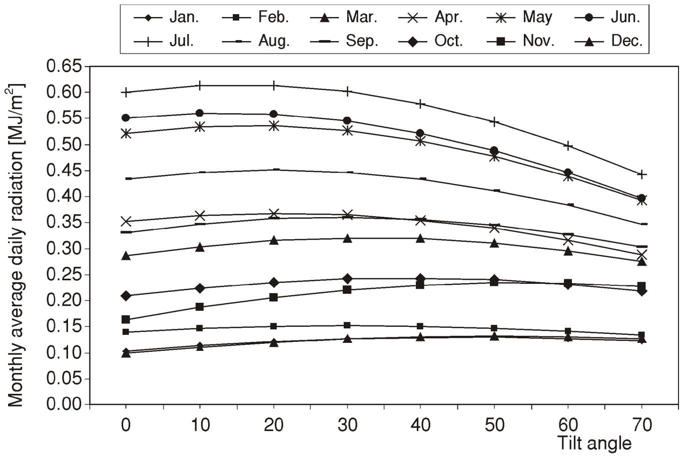

Figure 4. Monthly average daily solar radiation at different tilt angles

The slope of this surface will be fixed for each day and will be:

$$\beta = \phi - \delta \tag{9}$$

The monthly optimal tilt angles found theoretically, for the mid-day of each month *vs.* those derived from the measured data, using the method presented, are given in fig. 5. As can be seen from the fig. 5 theoretically calculated optimal tilt angles and those found from the measured data show a consistent relationship. The optimal tilt angles calculated from the measured data are lower those than found theoretically for April-September, whereas they are nearly equal for January-Mart and October-December.

In the northern hemisphere, the optimum orientation for solar collectors is south facing. As expected, different months of a year have different optimal tilt angles. As can be seen from fig. 5, the values of the monthly optimum tilt angle for month of March and be-

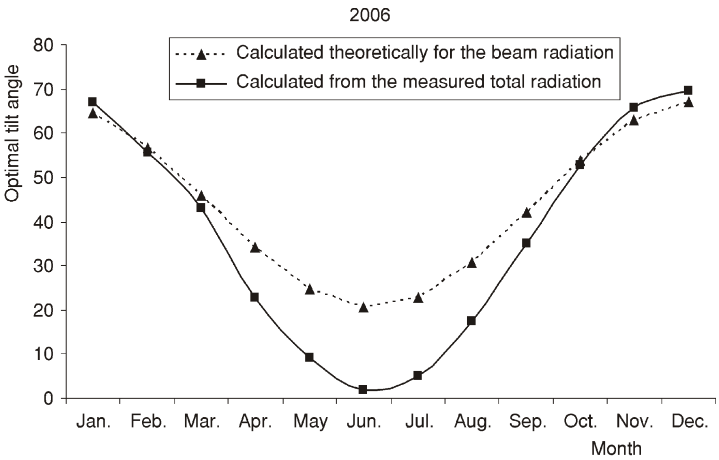

Figure 5. Monthly optimal tilt angles found theoretically for the beam radiation and those derived from measured total radiation

tween September and October are approximately equal to the latitude (|ϕ = 43.87°|). For these months, a solar collector tilted at an angle equal to the latitude will receive solar radiation nearly normally. It is also noted from fig. 5 that β_{opt} increases towards the beginning and end of the year. This indicates the times when greatest improvement is made on the amount of solar radiation incident on a solar collector tilted at an optimum angle. Further, the energy loss will occur if we take $\beta_{opt} = \phi$ throughout the year (for fixed collectors). Therefore the obtained values for β_{opt} from fig. 5 should be taken into account for receiving a maximum amount of solar energy. The yearly optimal tilt angle derived from measured data for Čačak is 37.10°, for winter months 58.96°, and for summer months 15.25°. Various investigators have carried out a number of studies in order to optimize the tilt angle around the world. For example, the yearly optimal tilt angle for Izmir, Turkey (|ϕ |) is 36.6° [2] or for Beijing (|ϕ |) is 39.2°, for winter months 58.5°, and for summer months 15.6° [5]. If seasonal adjustments can be made, some authors give advice that the optimal tilt angle for summer is $\beta_{opt} = \phi + 15°$, and for winter $\beta_{opt} = \phi - 15°$.

Other distributional parameters

The measured duration of sunshine hours on a monthly and yearly average daily basis for the available data from Čačak is presented in tab. 3. The yearly average daily sunshine durations vary between 3.69 and 4.44 hours. Overall, the monthly average daily measured sunshine duration is longest in July. The winter months have a relatively low duration of sunshine. However, it is noted that the monthly average daily sunshine duration varies from year to year. For example, see November of 2004 and 2005, and August of 2003 and 2005.

Table 3. Duration of sunshine on a monthly basis

Months	Sunshine duration [h]				Monthly average
	2003	2004	2005	2006	
January	0.60	0.76	0.90	1.22	**0.87**
February	–	2.38	2.43	1.45	**2.09**
March	–	3.99	4.42	3.76	**4.06**
April	–	4.87	4.74	3.96	**4.52**
May	7.02	5.69	5.97	6.78	**6.37**
June	8.20	6.90	7.18	6.46	**7.19**
July	7.74	7.00	6.65	7.46	**7.34**
August	8.39	7.34	4.69	5.67	**6.52**
September	4.34	4.19	4.15	5.39	**4.52**
October	2.38	2.52	2.29	3.74	**2.73**
November	0.82	3.68	0.66	1.50	**1.67**
December	0.49	0.41	0.14	0.40	**0.36**
Yearly average	**4.44**	**4.14**	**3.69**	**4.02**	

The ratio of diffuse to total radiation on a monthly and yearly average basis is summarized in tab. 4. Overall, the yearly average ratios vary between 0.6 and 0.66. The ratio on a monthly basis shows the following trend: decrease May-July, and increase November-February. In some months as low as 0.30, as observed in November 2005, and the highest ratio of diffuse to total radiation is seen in February 2003.

Table 4. Ratio of diffuse to total solar radiation

Months	Diffuse / total radiation			
	2003	2004	2005	2006
January	0.90	0.86	0.77	0.72
February	1.00	0.93	0.88	0.79
March	0.81	0.85	0.92	0.60
April	0.75	0.73	0.72	0.66
May	0.70	0.73	0.74	0.56
June	0.66	0.64	0.59	0.59
July	0.57	0.55	0.57	0.56
August	0.51	0.52	0.44	0.62
September	0.41	0.55	0.43	0.61
October	0.41	0.48	0.36	0.66
November	0.43	0.46	0.30	0.55
December	0.58	0.68	0.45	0.71
Average	**0.64**	**0.66**	**0.60**	**0.64**

Conclusions

The analysis of the energy situation in Serbia indicates that the ratio of indigenous primary energy production to primary energy consumption has been decreasing steadily during recent years. This declination is expected to continue. The use of renewable energy, in general, and solar energy in particular, has been negligible when compared to their economically exploitable potential. The solar radiation potential of Čačak was studied in the present paper based on 4 years of hourly global solar radiation data. This will contribute to the exploration of the potential of solar energy in Serbia. The most important findings arising from this study are:

- the yearly total solar radiation for Čačak varied 102.65-115.97 MJ/m^2 for the years analyzed,
- the yearly optimal tilt angle was 37.10° for the calendar year 2006; for winter months the optimal tilt angle was 58.96°, and for summer months 15.25°; the monthly optimal tilt angles were further calculated from the measured data, the smallest optimal tilt angle was 2° in June, and the largest was in December 69.52°, and
- the yearly average ratio of diffuse to total radiation varied 0.6-0.66, while the sunshine duration varied 3.69-4.44 hours.

Nomenclature

G_{SC} – solar constant, [= 1367 Wm^{-2}]
H – hourly total radiation on a horizontal surface, [MJm^{-2}]
H_b – hourly beam radiation, [MJm^{-2}]
H_d – hourly diffuse radiation, [MJm^{-2}]
H_T – hourly total radiation on a tilted surface, [MJm^{-2}]
H_o – daily extraterrestrial solar radiation on a horizontal surface, [MJm^{-2}]
K_T – monthly average clearness index, [–]
n – number of the day of the year starting from the first of January, [–]
R_b – geometric factor, [–]

Greek letters

β – optimum tilt angle, [deg]
δ – solar declination, [deg]
θ – angle of incidence, [deg]
ρ_g – ground reflectance factor [–]
ϕ – latitude of site, [deg]
ω_s – hour angle for sunset, [deg]

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