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ESTIMATION OF SOLAR IRRADIANCE ON TILTED SURFACE FACING SOUTH IN ČAČAK, SERBIA

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ABSTRACT

The performance of solar systems is affected by the value of its tilt angle with respect to the horizontal surface, where the variation of tilt angle changes the amount of incident solar radiation. In this paper, hourly extraterrestrial solar irradiance, beam, diffuse and solar radiation on the tilted surface is modeled and calculated based on measured data of the global solar radiation on horizontal surfaces for Čačak (lat 43.87° N, long 20.33° E). The computer program has been done to calculate the hourly solar irradiance for calculating different tilt angle setups. The calculation was based on experimental data of global solar radiation on the horizontal surface for the average day of April, July and September. Important trends of solar radiation on tilt surfaces as a function of time and the effect of surface tilt angles of the PV panel for achieving maximum collection of solar radiation in Čačak are presented. Most of the parameters modeled in this paper are essential in the design and study of solar energy conversion systems.

Keywords: Solar radiation, Beam and diffuse irradiation, Solar tilt angle.

INTRODUCTION

Solar energy technologies offer a clean, renewable and domestic energy sources, and are capital components of a sustainable energy future. 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 should be useful not only to the locality where the radiation data is collected but also for the wider community. 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.

Acquiring the solar radiation data at the location of interest at any given time is vital in the design of a PV system. 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. Čačak is a city located 140 km south from Belgrade in Serbia, at lat 43.87 ^{o}N, long 20.33 ^{o}E, with an altitude 250 m. The climate in Čačak is moderate continental, with an average daily temperature of 10.47^{o} C. Čačak is mostly exposed to north and north-east wind. The average speed of north wind is 2.3 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 (Dragićević, & Vučković, 2007).

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 (Alatarawneh, Rawadieh, Tarawneh, Alrowwad, & Rimawi, 2016; Wessley, Starbell, & Sandhya, 2017). The aim of the present study is to determine the monthly optimal tilt angle for different months in Čačak. A simple mathematical procedure for the estimation of the hourly solar flux parameters is presented. The solar radiation on a horizontal surface is converted to different tilt angles so that the optimal tilt angle is determined.

MEASUREMENTS OF GLOBAL SOLAR IRRADIANCE

The measurement data of the global solar irradiance used in this research were supplied by the automatic weather station MicroStep which is situated at the Fruit Research Institute in Čačak, during the 2018 (Figure 1). The station operates in real time and it consists of control unit (logger, AMS111 II), with local memory up to 2GB, communication interface (USB, Ethernet 10/100 Mbit and RS485 port) and sensors for air temperature and relative humidity, the solar radiation and sunshine duration, wind speed, wind direction, atmospheric air pressure, rainfalls and the snowfall measurement. Each sensor records measurements at 1-minute intervals. The meteorological data were recorded in the Renewable Energy Laboratory at the Faculty of Technical Sciences in Čačak, with the IMS Lite software for data collection and processing, and at the same time they are transferred to Republic Hydrometeorological Service of Serbia.

Global solar irradiance has been measured by using the CMP3 (KIP&ZONEN) pyranometer. The thermopile sensor construction measures the solar energy that is received from the total solar spectrum and the whole hemisphere (180 degrees field of view). The CMP3 pyranometer (ISO 9060:1990 Second Class) is intended for shortwave global solar radiation measurements in the spectral range from 300 to 2800 nm.

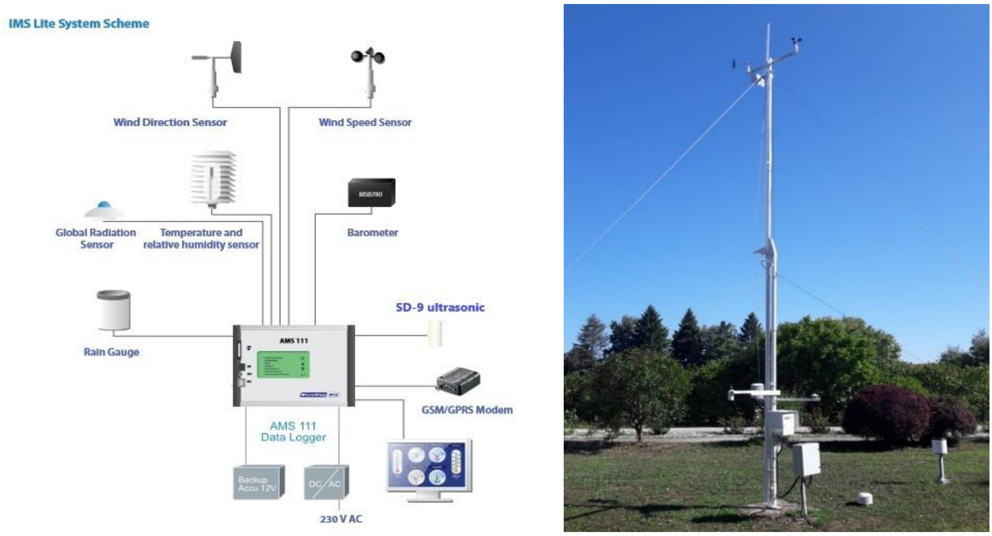


Figure 1. MicroStep-MIS weather station scheme and experimental setup.

HOURLY SOLAR FLUX COMPONENTS

Extraterrestrial radiation and clearness index

Solar radiation outside the earth's atmosphere is called extraterrestrial radiation. The extraterrestrial solar irradiation on a horizontal surface is a function of the distance between the earth and the sun, and independent of other location parameters. Hourly extraterrestrial irradiation on a horizontal surface I_o for a period defined by hour angles ω_1 and ω_2 which define an hour is evaluated as follows (Duffie, & Beckman, 2013):

$$I_0 = \frac{12\times3600}{\pi} G_{SC}\left(+0.033\cos\frac{360n}{365}\right)\left[\cos\varphi\cos\delta(\sin\omega_2 - \sin\omega_1) + \frac{2\pi(\omega_2-\omega_1)}{360}\sin\varphi\sin\delta\right] \quad (1)$$

where G_{sc}=1367 (W/m^2) is the solar constant, n is the day of the year ranging from 1 on January to 365 on 31 Decemeber, φ is the latitude of the site (Abdallah, Juaidi, Abdel-Fattah, & Manzano-Agugliaro, 2020).

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 (Benghanem, 2011):

$$\delta = 23.45 \sin\left(360 \frac{284+n}{365}\right) \quad (2)$$

The hour angle of the sun ω (in degrees) is given by:

$$\omega = \frac{360}{24}(h - 12) \quad (3)$$

where h is the time of the day (in hours).

Before reaching the surface of the earth, radiation from the sun is attenuated by the atmosphere and the clouds. The ratio of solar irradiation at the surface of the earth to hourly extraterrestrial irradiation on a horizonatl surface is called the clearness index. Thus the hourly clearness index K is defined as:

$$K = \frac{I}{I_0} \quad (4)$$

Determination of hourly solar irradiance on a tilted surface

The solar radiation received by a tilted surface consists of beam I_b, diffuse I_d and reflected radiation. The beam radiation coming of the sun, the diffuse radiation derived from the sky vault, and the reflected radiation coming from the ground in the surrounding area. Adopting the isotropic diffuse model, the solar radiation on a tilted surface can be calculated on an hourly basis based on the following equations (Calabrò, 2013):

$$I_T = \frac{\cos\theta}{\cos\theta_z} I_b + \frac{1+\cos\beta}{2} I_d + \rho_g \frac{1-\cos\beta}{2} I \quad (5)$$

$$\cos\theta_z = \sin\delta \sin\varphi + \cos\delta \cos\varphi \cos\omega \quad (6)$$

$$\cos\theta = \cos(\varphi - \beta)\cos\delta\cos\omega + \sin(\varphi - \beta)\sin\delta \quad (7)$$

where θ is the angle between the beam radiation on a surface and the normal to the surface, θ_z the solar zenith angle, β is the tilt angle, and ρ_g is the ground reflectance factor. The reflectance is usually taken 0.2, but when the surrounding area is covered with snow its value can be 0.87.

Diffuse radiation received by the tilted surface does not depend on the orientation of the surface and does not come from the entirety of the sky vault or the ground nearby. 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. Depending on the value of the hourly clearness index K, the ratio I_d/I is given by the following relations (Duffie, & Beckman, 2013):

$$\frac{I_d}{I} = \begin{cases} 1 - 0.009K & K \leq 0.22 \\ 0.9511 - 0.1604K + 4.388K^2 - 16.638K^3 + 12.336K^4 & 0.22 < K < 0.8 \\ 0.165 & K > 0.8 \end{cases} \quad (8)$$

The beam component of the solar irradiation on a horizontal surface is obtained from:

$$I_b = I - I_d \tag{9}$$

Hourly solar irradiance on an tilted surface has been calculated for Čačak using the measured data of global solar irradiance on horizontal surface and the previous equations.

RESULTS AND DISCUSSION

A computer program has been built based on the preceding formulations to calculate the hourly solar radiation parameters on horizontal and inclined surfaces. As input data, the hourly solar global radiation data for a typical day in the given months were used.

Figure 2 shows the hourly extraterrestrial, global, diffuse, and beam radiation on a horizontal surface on April 15th, July 17th and September 15th. Extraterrestrial radiation increases by 24 % from April to July, then decreases by 30 % from July to September.

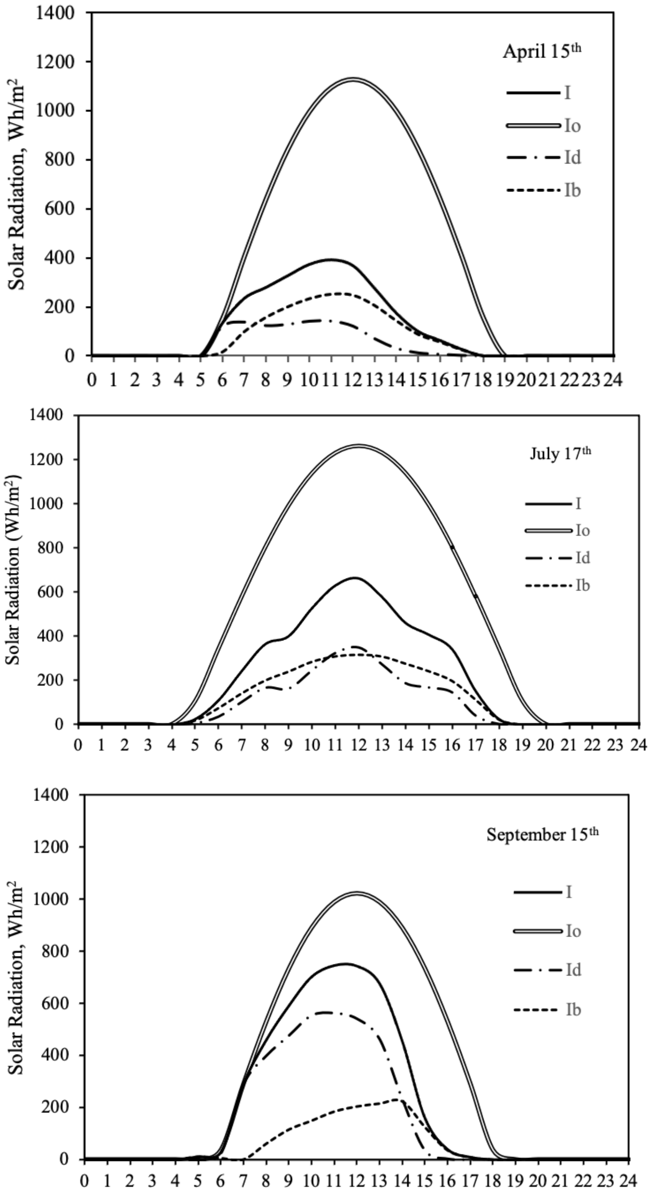


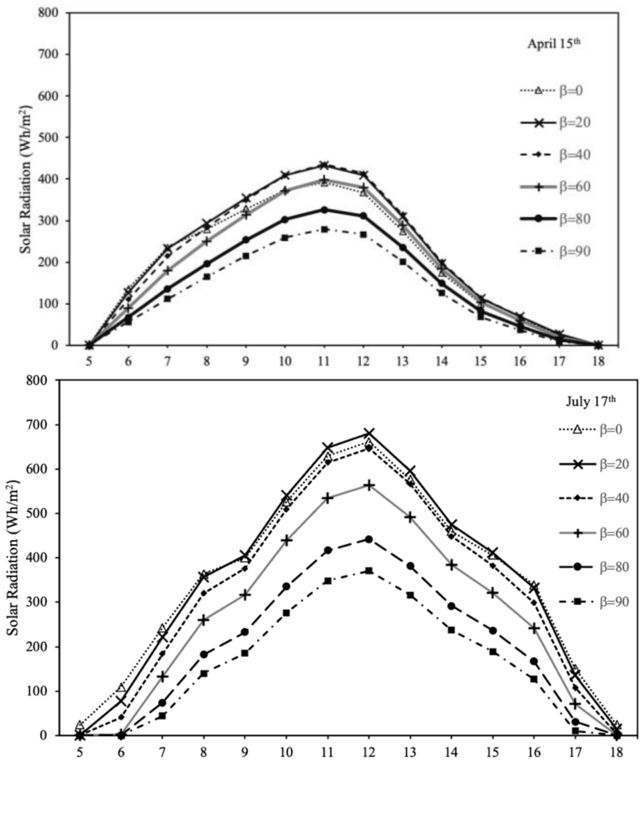
Figure 2. Terrestrial and extraterrestrial solar radiation on a horizontal surface in Čačak area for April 15th, June 11th and September 15th

I – Measured global solar radiation, I_o – Extraterrestrial radiation
I_d – Diffuse solar radiation, I_b – Beam radiation

The global radiation has a different trend of change based on the measurement data, because it increases from April to July by about 79 % and in July and September, has a similar value. The reason for this is that clouds were present during the day when the measurements were taken, as seen by the low value of 0.38 for the clearness index on July 17th. The average daily value clearness index on September 15th was 0.52, indicating that the day was a little brighter.

The increase in diffuse solar radiation is significant, especially from April to September. Obtained results of the increase in the global and diffuse solar radiation indicate the matching between the availability of solar energy and the need for cooling during hot summer months.

A number of simulations were carried out to investigate the effect of the tilt angle on the south-facing surfaces for the current location. By changing the tilt angle from 0° to 90°, the optimal tilt angle is defined by the corresponding value of maximum solar radiation for a given period. Figures 3 shows the hourly solar radiation in Čačak area for a flat surface at different tilt angles towards south.



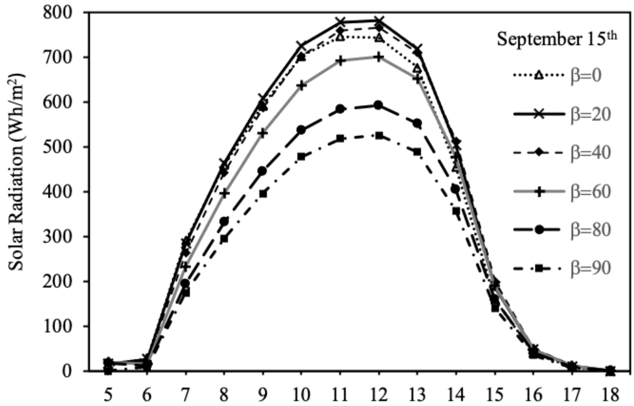


Figure 3. Solar radiation in Čačak area for surfaces with different tilting angles.

Sample results that show the effect of tilt angle on the incident solar radiation are presented. In addition, the optimum surface tilt angles for maximum solar radiation collection in Čačak area is deduced. The general trend of the incident solar radiation is almost the same for presented days, i.e. the solar radiation increases until it reaches a maximum at noon time then it decreases. It is apparent from the Figure 3 that the solar radiation is an intensive function of tilt angle.

The solar radiation on the tilted surface on July 17th is greater than that during April 15th, while the solar radiation on the tilted surface on September 15th is greater on July 17th due to the presence of clouds that was expressed during the measurement. Compared with July 17th, the solar radiation during April 15th is less sensitive to changes in the tilt angle. The maximum radiation is reached at a tilt angle of 30^0 at which the received solar radiation increases 15% above that received by a horizontal surface. On July 17th, the received solar radiation decreases as the tilt angle increases, and the maximum radiation is reached at a tilt angle of 20^0. A similar trend occurs in September when the maximum received solar radiation is achieved with a tilt angle of 24^0 towards the south.

Figure 4 shows the total solar radiation versus tilt angle for the selected months. The calculated solar energy radiation incident on the flat surface is increased, with the increasing of horizontal position from 0° to an angle of inclination, but a further increase of the tilt angle of the flat surface will result in the decreasing of solar radiation received.

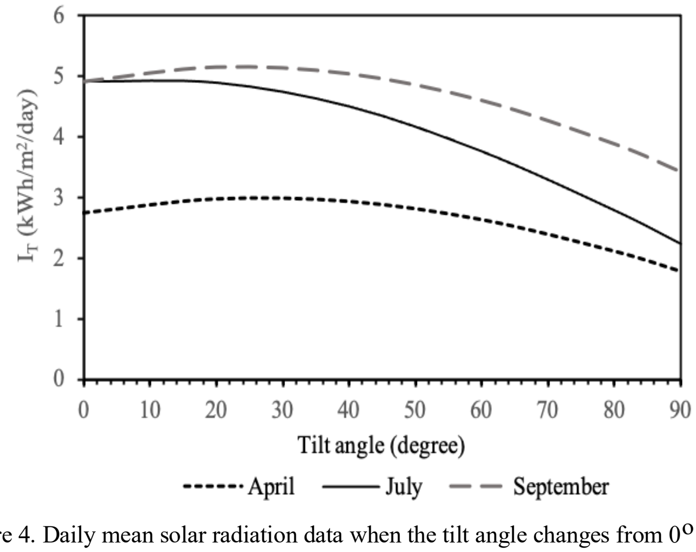


Figure 4. Daily mean solar radiation data when the tilt angle changes from 0^{O} to 90^{O}

Presented analysis indicated that the optimum angle varies with the months of the year. The maximum solar radiation is achieved for every month with a unique optimum tilt angle. The optimum tilt angle increases in the winter months and decreases to the minimum value in the summer and autumn months.

CONCLUSIONS

Using measured data of global solar radiation and the methods described in this study, hourly averages of the extraterrestrial solar irradiance, beam, diffuse and solar radiation on the tilted surface at different tilt angles for Čačak was determined. The effect of tilt angle on the incident solar radiation fluxes are presented along with optimum surface tilt angles for maximum solar radiation collection in Čačak area. This information is useful when a solar collector is to be installed without a tracking system. Using the tilt angle that yields the maximum irradiation for the selected months increases of the PV energy production could be achieved. The results obtained could be used to estimate the power generation of solar systems at any site of interest within the study area.

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