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Comparison of optimum tilt angles of solar collectors determined at yearly, seasonal and monthly levels

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ABSTRACT

The amount of energy that is transformed in solar collector depends on its tilt angle with respect to horizontal plane and orientation of the collector. In this article the optimum tilt angle of solar collectors for Belgrade, which is located at the latitude of 44°47′N is determined. The optimum tilt angle was found by searching for the values for which the solar radiation on the collector surface is maximum for a particular day or a specific period. In that manner the yearly, biannual, seasonal, monthly, fortnightly, and daily optimum tilt angles are determined. Annually collected energy per square meter of tilted surface is compared for ten different scenarios. In addition, these optimum tilt angles are used to calculate the amount of energy on the surface of PV panels that could be installed at the roof of the building. The results show that for observed case study placing the panels at yearly, seasonal and monthly optimum tilt angles, would yield increasing yearly amount of collected energy by factor of 5.98%, 13.55%, and 15.42% respectively compared to energy that could be collected by putting the panels at current roofs' surface angles.

1. Introduction

The amount of solar energy that is converted in solar collector depends on tilt angle of collector with respect to horizontal surface and orientation of the collector. Although in recent study [1] authors show that the tilt angle is nearly irrelevant that is the difference of plant yield is just 6% for tilt angles between 0° and 70°, these results are counterintuitive and as authors claim themselves the further investigations considering other locations and time periods are needed to clarify this issue. The tilt angle of a solar energy system was investigated for different applications: evacuated tube solar water heaters [2,3], hybrid power system [4], PV generation [5], solar cooker [6], mirror-augmented PV system [7], and many others.

The most efficient solar energy yield can be obtained by using Sun-tracking devices. There are number of studies showing that tracking systems enable significant amount of solar energy compared to fixed systems. Abdal lah [8] found that tracking systems increase total daily energy collection of about 43.87% as compared with fixed system. A very detailed review of energy gain of different trackers is done in Mousazadeh et al. [9]. In that paper authors report boost of collected solar energy by means of tracking system in the range of 10–100% depending on different periods of time and geographical conditions. Tomson [10] reported increasing of seasonal energy yield by 10–20% by using the two-positional tracking system that positions collectors in the morning and in the afternoon. Chang [11] found substantial gains of 51.4%, 28.5% and 18.7% from the extraterrestrial, predicted and observed radiations respectively by using a single-axis tracking system.

However, Sun-tracking systems are quite expensive, energy intensive and are not recommended for using for small solar panels [9,10]. The other approach to increase amount of collected energy is to place collectors at optimum angle. There are number of studies that were carried out in order to find the optimum tilt angle of solar collectors around the world (Carbondale, Illinois [12], Izmir in Turkey [13], Sanliurfa, Turkey [14], Dhaka [15], 30 cities in China [16], Madinah, Saudi Arabia [17], Jordan [18], Helwan, Egypt [19], Brunei Darussalam [20], Syria [21], Cyprus [22], Burgos, Spain [23], Brisbane, Australia [5] and many more).

Many researchers proposed various schemes for optimizing the tilt angle of solar collectors for different latitudes. Some of them gave even set of 12 equations for calculating optimum tilt angle for each month [24,25]. However, although during last two decades, researchers have made efforts for estimation of local optimum tilt angles, no definite value, or method is accepted by all researchers and reported optimum angles for the same latitude differ for more than 15° : $(\phi + 15) \pm 15$ [26], $\phi - 10$ [27], $\phi \pm 10$ [28].

In this paper optimum tilt angles of solar collectors for Belgrade, Serbia are found at yearly, biannual, seasonal, monthly, fortnightly

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Nomenclature

Greek symbols

β	tilt angle of solar collector(rad)
δ	declination (°)
γ	surface azimuth angle (rad)
ω_{ss}	sunset hour angle (rad)
ω	solar hour angle (rad)
ϕ	latitude (rad)
ρ	albedo of the ground
θ	solar incidence angle (rad)
θ_z	zenith angle (rad)

Roman symbols

a_1	coefficient
b_1	coefficient
H	terrestrial daily solar radiation on a horizontal surface (W h/m^2)
H_0	extraterrestrial daily solar radiation on a horizontal surface (W h/m^2)
I	terrestrial hourly solar radiation on a horizontal surface (W h/m^2)
I_0	extraterrestrial hourly solar radiation on a horizontal surface (W h/m^2)
I_{dif}	sky diffuse radiation (W h/m^2)
I_{dir}	direct or beam radiation (W h/m^2)
I_T	hourly total radiation on the inclined surface (W h/m^2)
n	the number of the day corresponding to a given date

and daily level. The optimum tilt angles are found for collectors oriented towards the equator. The recorded meteorological data of daily sums of global radiation were taken from the World Radiation Data Centre (WRDC) [29]. Annually collected energy per square meter of tilted surface is compared for ten different scenarios. Seasonal scenarios are defined in four different ways and biannual scenarios in two different ways. In addition, a case study of buildings that were used in simulation is given.

2. Governing equations

The instantaneous solar radiation on a fiat-plate collector surface depends on the Sun's position in the sky, which changes continuously (Fig. 1). As designated in Fig. 1 the slope and orientation of collector are defined by tilt angle of collector with respect to horizontal surface (β) and surface azimuth angle (γ), which represents the orientation of the solar collector with respect to due south (westward is designated as positive).

The zenith angle (θ_z) is the angle between the vertical and the line to the Sun, and its value is given by the following equation [30]

$$\cos\theta_z = \sin\alpha = \sin\delta\sin\phi + \cos\delta\cos\omega\cos\phi \tag{1}$$

where ϕ is latitude, δ is declination and ω is the solar hour angle.

The δ is calculated by a simple approximation equation as [30]

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

The solar incidence angle (θ) is the angle between the Sun's rays and the normal on a surface. It is calculated as

$$\begin{aligned}\cos\theta = {} & \sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\gamma \\ & + \cos\delta\cos\phi\cos\beta\cos\omega + \cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega \\ & + \cos\delta\sin\beta\sin\gamma\sin\omega\end{aligned} \tag{3}$$

The relationship between the daily and hourly extraterrestrial and terrestrial irradiations is given as Notton et al. [31]:

$$\frac{I}{H} = (a_1 + b_1\cos\omega)\frac{I_0}{H_0} \tag{4}$$

where a_1 and b_1 are:

$$a_1 = 0.409 + 0.5016\sin(\omega_{ss} - \pi/3) \tag{5}$$

$$b_1 = 0.6609 - 0.4767\sin(\omega_{ss} - \pi/3) \tag{6}$$

where (ω_{ss}) is the sunset hour angle given by the following equation

$$\omega_{ss} = \cos^{-1}(-\tan\delta\tan\phi) \tag{7}$$

The relationship between diffuse and total terrestrial solar radiation is adopted as fourth order polynomial relation according to pioneer work of Liu and Jordan [32]

$$\frac{H_{dif}}{H} = 0.974 + 0.693\frac{H}{H_0} - 6.067\left(\frac{H}{H_0}\right)^2 + 6.416\left(\frac{H}{H_0}\right)^3 - 1.931\left(\frac{H}{H_0}\right)^4 \tag{8}$$

The hourly total radiation on the inclined surface is a sum of direct radiation, sky diffuse radiation and ground reflected radiation

$$I_T = I_{dir}\frac{\cos\theta}{\sin\alpha} + \frac{I_{dif}(1+\cos\beta)}{2} + \frac{\rho I(1-\cos\beta)}{2} \tag{9}$$

where $I_{dir} = I - I_{dif}$, and ρ is albedo of the ground, which is in this work taken to be 0.2.

The optimum angle is calculated by searching for the values β for which the total radiation on the collector surface is a maximum for a particular day or a specific period.

3. Simulation arrangement

The simulation was carried out for Belgrade, which is located at the latitude of 44°47′N. The measured values of daily sums of global radiation were taken from the World Radiation Data Centre (WRDC) [29], which is one of recognised World Data Centres sponsored by the World Meteorological Organization (WMO). The WRDC centrally collects and archives radiometric data from the world to ensure the availability of these data for research by the international scientific community. The daily sums of global radiation serving as the inputs in simulation were obtained as mean values of measured data for period of 28 years (from 1964 to 1991).

Optimum tilt angles of collectors were found by searching for the values for which the solar radiation on the collector surface is a maximum for specific period, which is usually by other authors taken to be a month, a season or a year. However, different authors define seasons in different manner. Some authors mean by winter season the months: December to February Sultan et al. [33] Skeiker [21], Ismail et al. [34], Yadav [35]. Some authors define winter season from November to January Talebizadeh et al. [36]. Others understand by winter the first quarter of the year Talebizadeh et al. [37], and others mention that winter season is the period started from 22 December to 21 March Soulayman and Sabbagh [25].