Sun tracking in PV systems aspects

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1. Introduction

Total solar radiation is a hemispherical radiation, achieving the receiver surface of any spatial orientation, from the solid angle in the range 2π [sr], supplemented by the component reflected from the ground and from the objects surrounding the receiver. In particular case of a receiver located in parallel to the ground the reflected component does not exist. Direction of incidence of the direct radiation at an inclined surface is evident – it is identical to the direction of the radiation beam. In case of the receiver that is inclined with respect to the ground proper definition of the diffused radiation is the most difficult. Three components should be specified in this radiation:

- isotropic radiation;
- circumsolar radiation;
- the radiation coming from the bright horizon.

The first of these components is distinguished by the fact that it comes uniformly from the whole hemisphere. On the other hand, the circumsolar component is a result of diffusion of the solar radiation. Nevertheless, it is specifically related to the direct component. The third component is focused near to the horizon and observable in case of clear sky.

Additionally, in case of the receiver inclined at a certain angle $\beta \neq 0$ to the ground the radiation reflected from the ground and surrounding objects should be considered too, apart from the direct and diffused components of radiation, all being the components of the so-called total radiation.

2. Characteristics of mathematical models

The paper characterizes selected mathematical models for calculating power density of solar radiation incident on the plane inclined with regard to the base and directed at proper azimuth angle with regard to southern direction.

Based on the above consideration, in case of an inclined surface the total radiation is given by the equation [10]:

$$G_c = G_b + G_d + G_r \tag{1}$$

where G_b – the direct radiation; G_r – the reflected radiation; G_d – the diffused radiation, being a sum of three components:

$$G_d = \sum_{k=1}^{3} G_{dk} \tag{2}$$

The Authors of early computational models focused chiefly at determining the direct component, devoting considerably less attention to the other ones. The diffused radiation was considered as an isotropic one. Such an approach is appropriate, but only in case of the surfaces located in parallel to the surface of Earth.

One of the first methods, that partially took into account the effect of receiver inclination is the Liu-Jordan method [12]. The authors introduce correction factors into the calculation. Nevertheless, the method does not fully reflect the complex character of the diffused component, as in the proposed model it is considered as an isotropic one.

Since the time of development of the Liu-Jordan method, i.e. about 50 years ago, many mathematical models have been developed, that allowed to determine the total density of the solar radiation incident on the arbitrarily oriented receiver surface. However, they are more complex from the mathematical point of view.

The HDKR model seems to be particularly appropriate. It is a result of the methods developed by several authors, i.e. the models of J.E. Hay, J.A. Davies, T.M. Kluchera, and D.T. Reindl [10].

In the first of them the authors assume isotropic distribution of the diffused radiation, considering the diffused, isotropic, and circumsolar components. The effect of anisotropy was here taken into account only as a function of atmospheric transparency for the direct radiation. D.T. Reindl supplemented the mathematical apparatus by the component resulting from the bright horizon. T.M Klucher inserted the effect of clouding factor to the correction factor of the bright horizon of the equation derived by Reindl. The relationship modified by him explains the considered components with sufficient accuracy, even in case of the receivers inclined at large angles with respect to the ground [10, 14].

Specification of the example results obtained with the isotropic and anisotropic methods is presented in Table 1 [5, 6].

According to the example data of Table 1, maximum of the function of solar radiation power density in yearly scale incident at the plane inclined and directed at appropriate azimuth angle occurs for the angles $\beta = 30^o$, $\gamma = 15^o$ for the isotropic model, or for $\beta = 40^o$ and $\gamma = 15^o$ in case of consideration of anisotropy.

Differences in the calculation results obtained with both methods usually are of the order of several percent, reaching even 1 percent in case of small inclination of the receiver with respect to the ground.

Maximum difference occurs in case of vertical orientation, i.e. for photovoltaic applications existing in case of façade BIPV solutions.

Table 1. Maximum power density in yearly scale falling at an inclined plane directed at appropriate azimuth angle

The angles β and azimuth angle γ / Model	β=20° γ=15°	β=30° γ=15°	β=40° γ=15°	β=45° γ=15°	β=60° γ=20°	β=80° γ=25°	β=90° γ=30°
Isotropic computation model	3870 MJ/m^2	3900 MJ/m^2	3870 MJ/m^2	3850 MJ/m^2	3600 MJ/m^2	3100 MJ/m^2	2740 MJ/m^2
Anisotropic computational model	4000 MJ/m^2	4100 MJ/m^2	4140 MJ/m^2	4120 MJ/m^2	3900 MJ/m^2	3450 MJ/m^2	3100 MJ/m^2

3. The Liu-Jordan method

Authors of the present paper used the Liu-Jordan method. Its advantage lies in rather simple mathematical apparatus [12].

Moreover, comparison of the results obtained by other authors [6] for the calculation carried out both with the method considering anisotropy of the diffusion radiation and ignoring its effect, has shown that the results of the radiation power density in yearly scale differ only slightly. In case of the Liu-Jordan method the results are a little lower as compared to the ones obtained with consideration of anisotropy.

Under our geographical and weather conditions the Liu-Jordan method is well justified. In summer months, when higher factor of anisotropy may be expected, the optimal inclination angle is not large, due to power gain, reaching the values of 25-35°. On the other hand, in winter conditions the optimal inclination angle amounts to 55-60°. Therefore, the isotropic Liu-Jordan model may be used with sufficient accuracy, particularly in case of lower power systems [7, 12].

Total density G_β of solar radiation flow is a sum of components [7, 9, 12]:

$$G_\beta = G_b R_b + G_d R_d + (G_b + G_d)\rho_0 R_0 \tag{3}$$

where: G_b, G_d – direct and diffusive component of density of solar radiation, and ρ_o – coefficient of the bed reflectivity assumed from 0,07 (for dry asphalt) to 0,095 (for fresh snow), R_b, R_d, R_o – the correction efficients defined below, related to direct, diffusive, and reflected components, respectively. Therefore:

$$R_b = \frac{\cos\theta_\beta}{\cos\theta_z} \tag{4}$$

$$R_d = \frac{1+\cos\beta}{2} \tag{5}$$

$$R_0 = \frac{1-\cos\beta}{2} \tag{6}$$

where: Θ_Z - is an angle of incidence of the radiation on a horizontal surface (the zenith angle) [7, 9, 12]:

$$\cos\theta_z = \cos\varphi\cos\delta\cos\omega + \sin\varphi\sin\delta \tag{7}$$

and Θ_β - is an angle of incidence of the radiation on a plane inclined at the angle β to the ground, being a function of many variables:

$$\begin{aligned}\cos\theta_\beta &= \sin\varphi\sin\cos\beta - \cos\varphi\sin\delta\sin\beta\sin\gamma + \cos\delta\cos\varphi\cos\beta \\ &\cos\delta\sin\varphi\sin\beta\cos\gamma\cos\omega + \cos\delta\sin\beta\sin\omega\sin\gamma\end{aligned} \tag{8}$$

where: φ - the angle of latitude, δ - the declination angle, ω - the hour angle, β - the angle of receiver inclination to the ground.

The G_b and G_d values are assessed on the grounds of many years data obtained from weather stations [4, 17].

4. The sun follow system

Receiver spatial orientation with respect to the direction of solar radiation may be adjusted in stationary or follow-up systems, i.e. Sun follow-up mono- or bi-axis systems, Fig. 1. Much more advantageous result may be achieved with the bi-axis ones, nevertheless, such a solution requires additional financial expense because of its structure and assembly as well as the operation, as the systems requires slightly higher electric power supply [1, 3, 8].

a) b)

Fig. 1. Examples of photovoltaic installations: stationary on Frosta roof in Bydgoszcz (a), [phot. Grażyna Frydrychowicz-Jastrzębska] and provided with Sun follow-up; the tracker with PV modules (b), the Communication Plant of Alarm System PHU, Leżajsk [with approval of Mr. Stanisław Krupa]

Sometimes the additional concentrating systems (HCPV concentrators) are used, particularly in the countries of high insolation [7, 8].

In Poland such an approach is disadvantageous due to large diffusive component of the radiation. Moreover, it should be noticed that in case of the concentration system of high concentration factor, effectiveness of conversion of solar radiation into electric power is reduced in consequence of module temperature growth, Fig. 2.

Fig. 2. The follow-up system with concentration system, ITER Tenerife, [phot. Grażyna Frydrychowicz-Jastrzębska]

In the "Sun follow-up" systems the trackers are assembled, that may be of two types [2, 8, 11, 15]:

- mono-axis and
- bi- axis.

The follow-up systems are classified according to [8]:

1. the method of spatial orientation control of the PV receiver;
2. the type of feeding;
3. the type of the drive;
4. the control manner.

Figure 1 a show the example of the stationary systems in case of the Polish conditions and 1 b - of photovoltaic installations provided with Sun follow-up.

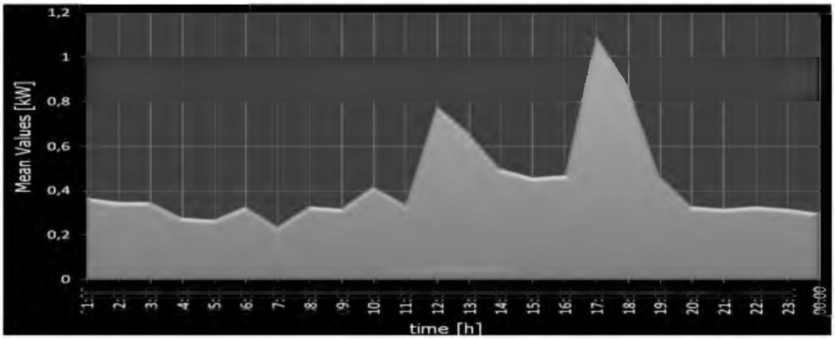
The photovoltaic investment shown in Figure 1a, installed on the roof of frozen food manufacture Frosta in Bydgoszcz, operates already from more than three years ago. It achieves peak power of 80.5 kWp and is composed of 366 polycrystalline modules PP 220P from Conergy, of unit power equal to 220 Wp. The whole system includes 9 subsystems provided with separate inverters. The photovoltaic modules are located on a stationary structure, ensuring the inclination angle with respect to the ground that guarantees maximum energetic gain in yearly scale. The other system includes photovoltaic panels of IBC 215 TA type, the Sunny Boy 1100 inverter, and the battery of accumulators 48V 600 Ah and Sunny Island 4248.

The system has been installed in May 2009 and two years later supplemented by WebBox that ensured direct monitoring of energy production. During next years additional assemblies of the panels Trina Solar 235W and IBC 235 MS, and the Sunny Boy 1200 inverters have been added.

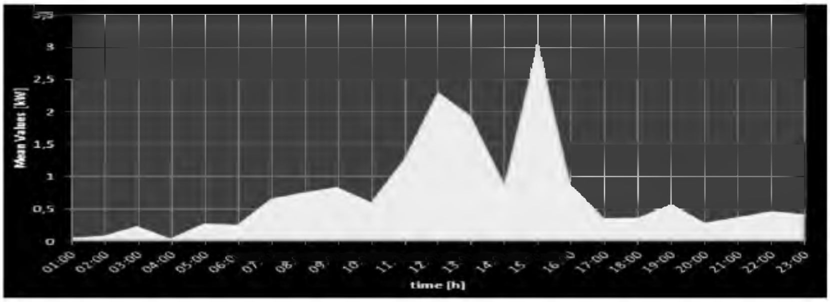
At present the system delivers total power of 4.11 kWp.

5. Exemplary monitoring results

Figure 3 presents the plot of the power production recorded on May 15, 2012 (a) and May 17, 2012 (b), from 1:00 a.m. to 11:00 p.m. and , based on the data collected from the Alarm System PHU, Leżajsk.



a)



b)

Fig. 3. Read-out from the solar radiation power monitoring obtained by Communication Plant of Alarm System PHU, Leżajsk, power production recorded on May 15, 2012 (a), on May 17, 2012 own elaboration based on [16]

As shown above, on May 15, 2012 the follow-up system enables the use of favourable values of solar radiation, particularly from 11:00 a.m. to 2:00 p.m. and from 4:00 p.m. to 7:00 p.m. Between the hours 2:00 p.m. to 4:00 p.m. cloudiness appears that is characteristic for the Polish territory. Such advantage is unavailable in case of stationary photovoltaic installation, particularly when it is horizontally positioned [8].

As it is shown, on May 17, 2012 the follow-up system allows to obtain advantageous values of the solar radiation power, reaching at 3:00 p.m. even 78 per cent, while in the time from 11:00 a.m. to 1:00 p.m. 61 percent of the installed power. Such efficiency is unavailable in case of stationary photovoltaic installations, particularly when horizontally aligned.

The stationary photovoltaic system from Gemeindesaal Kella of 20.65 kWp is distinguished by very good spatial orientation (inclination angle with respect to the ground amounting to 40° and azimuth angle 53°). It gave 82 per cent of the installed power at 1:00 p.m., nevertheless, before 6:00 a.m. its output equals zero [16].

6. The comparison of the solar energy density from stationary and sun-follow UP systems use

Figures 4 and 5 present comparison of the energy density reaching the PV receiver, with regard to particular months and during the whole year, for selected geographical locations. The plots are made based on the monitoring data [13].

Various solution variants are assumed: bi-axis tracker (1), mono-axis tracker operating in vertical axis for three various inclination angles: equal to the angle of latitude (2), the angle reduced by 15° (3), and enlarged by 15° (4), respectively.

Similar orientations of the devices have been analyzed in case of stationary solutions Figures 4, 5.

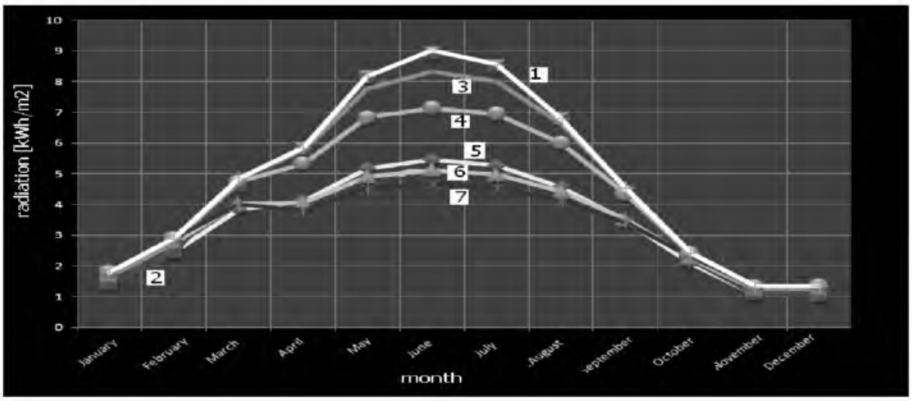


Fig. 4. Density of the power reaching the PV receiver, for consecutive months, in Stockholm (latitude 59°21'N, longitude 17°57'E) Denotations: bi - axis system +(1) and □ (2) mono - axis system for angle of inclination β = φ - 15°, x(3) - angle of inclination is angle of latitude β = φ, o(4) –angle of inclination β = φ + 15°, stationary solution: ◊(5) - angle of inclination β = φ - 15°, Δ(6) – the angle of the inclination is angle of the latitude β = φ , ⚹ (7) - the angle of the inclination β = φ + 15°

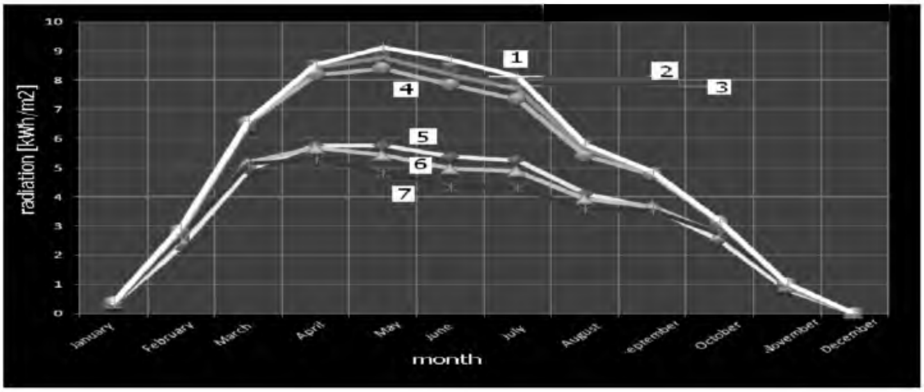


Fig. 5. Density of the power reaching the PV receiver, for consecutive months for Fairbanks, Alaska (latitude : 64°49 'N, longitude147°52' W). Denotations: bi - axis system +**(1)** and □ (2) mono - axis system for angle of inclination β = φ - 15°, x(3) - angle of inclination is angle of latitude β = φ, o(4) –angle of inclination β = φ + 15°, stationary solution: ◊(5) - angle of inclination β = φ - 15°, Δ(6) – the angle of the inclination is angle of the latitude β = φ , ✳ (7) - the angle of the inclination β = φ + 15°

7. Results of computer simulation

The above considerations and the relationship (1) to (8) served as a basis for a program developed with a view to making the calculation and computer simulation. The hourly distribution of radiation power density for recommended months, days and day hours 3 - 20 in Warsaw was determined.

Figure 6 shows results of hourly distribution in all months of year for direct and diffused components of solar radiation in Warsaw.

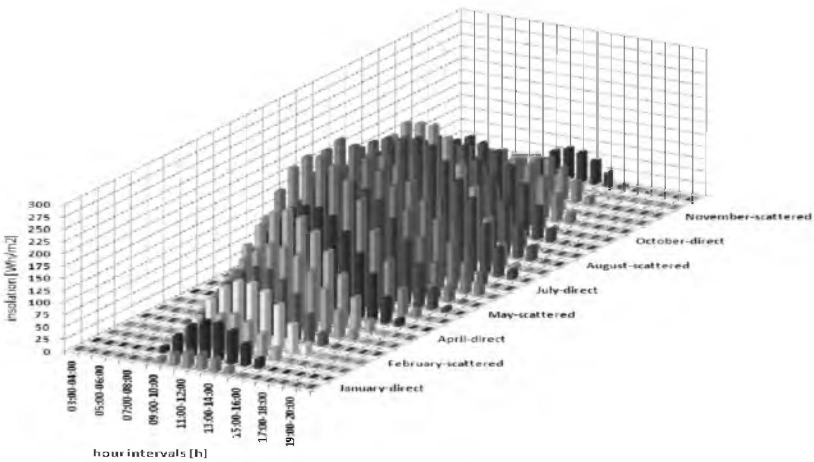


Fig. 6. Results of computer simulation of hourly distribution in all months of year for direct and diffused components of solar radiation in Warsaw

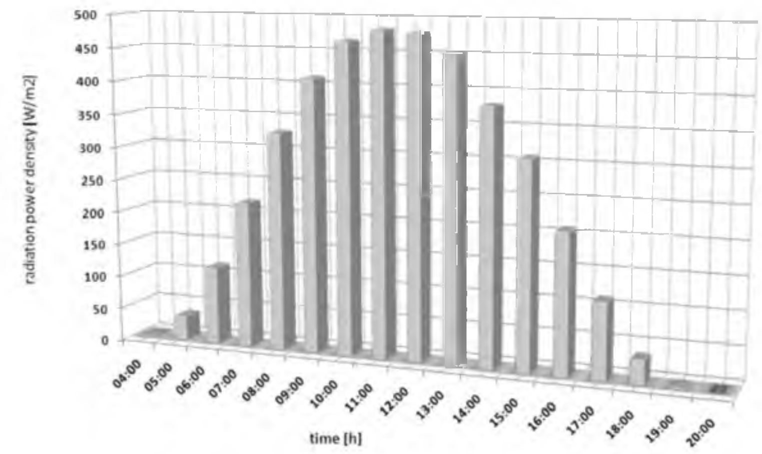


Fig.7. Hourly distribution of radiation power density falling on a horizontal plane, for $\gamma = 0°$, on August 8

Figures 7, 8 show example results for particular months, considerably differing with regard to possible solar power gain, provided the receiver is set-up horizontally.

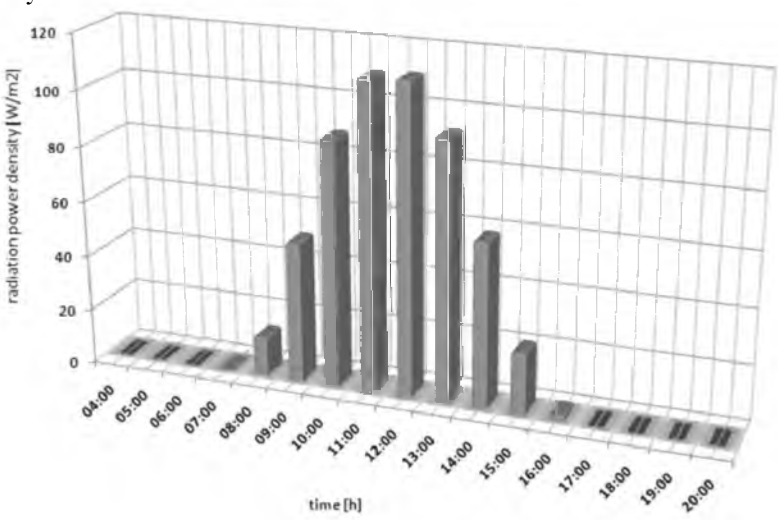


Fig. 8. Hourly distribution of radiation power density falling on a horizontal plane, for $\gamma = 0°$, on January 15

The next Figures 9, 10 present the plots of solar radiation power density falling of the surface of the power receiver for its varying spatial orientation (the angles β and γ) on August 8, and the Figures 11, 12 - on January 15.

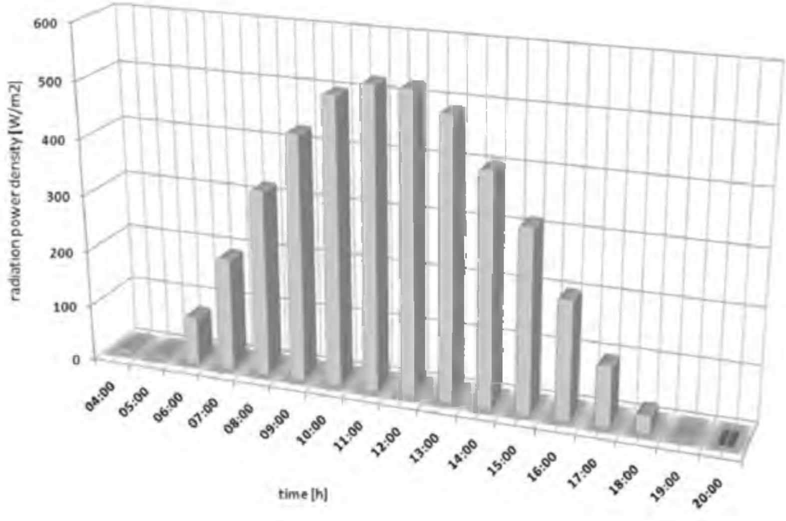


Fig. 9. Hourly distribution of radiation power density falling on a plane inclined at the angle β = 30°, for γ = 0°, on August 8

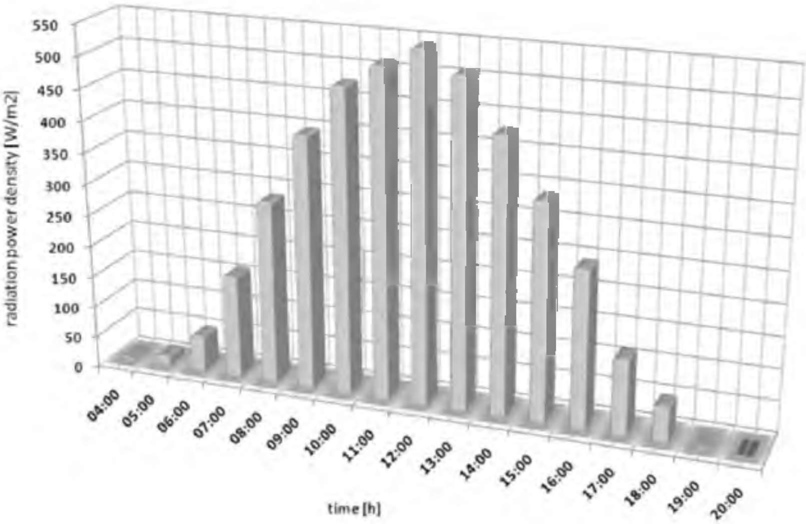


Fig. 10. Hourly distribution of radiation power density falling on a plane inclined at the angle β = 30°, for γ = 15°, on August 8

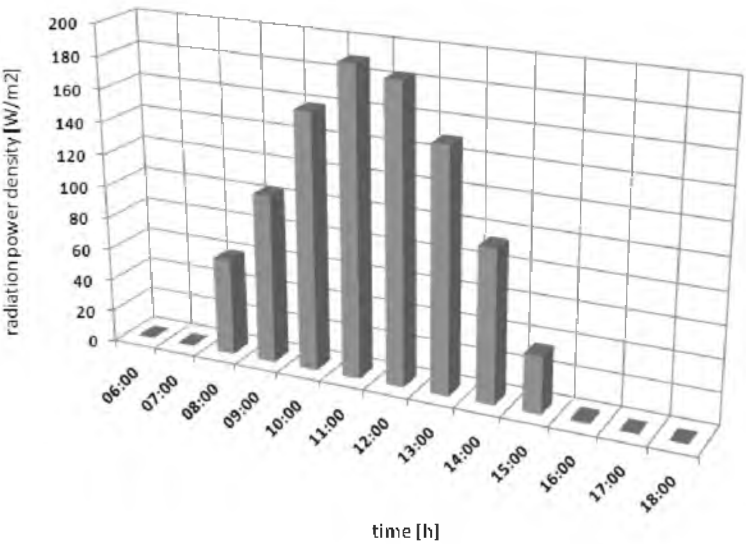


Fig. 11. Hourly distribution of radiation power density falling on a plane inclined at the angle $\beta = 65°$, for $\gamma = 0°$, on January 15

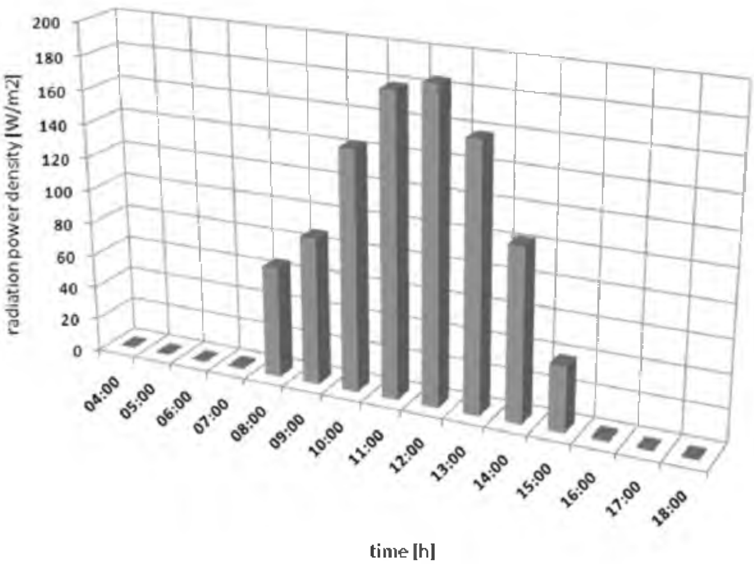


Fig. 12. Hourly distribution of radiation power density falling on a plane inclined at the angle $\beta = 65°$, for $\gamma = 15°$, on January 15

Power gain at different spatial settings (the angles β and γ) of the receiver was determined. The Figure 13 presents the power gain on August 8 and Figure 14 - on January 15.

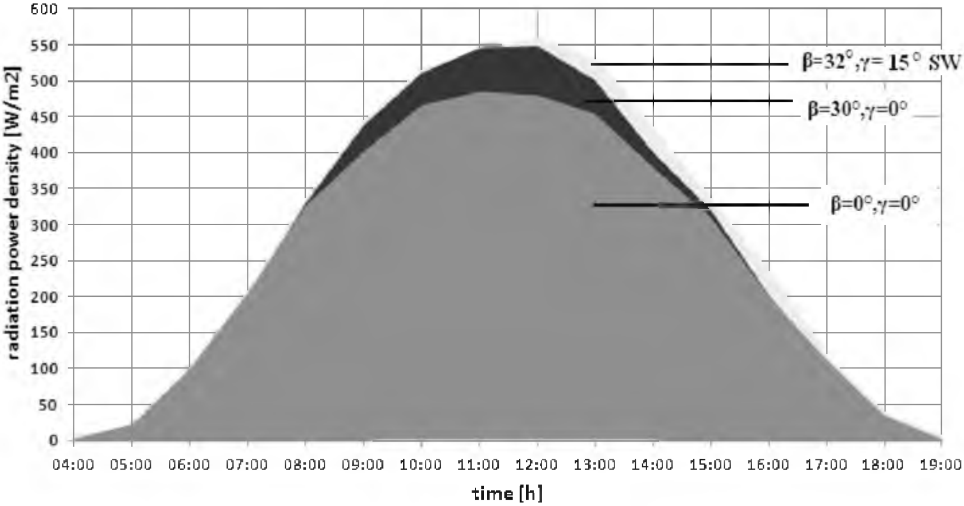


Fig. 13. Power gain at different spatial settings of the receiver on August 8

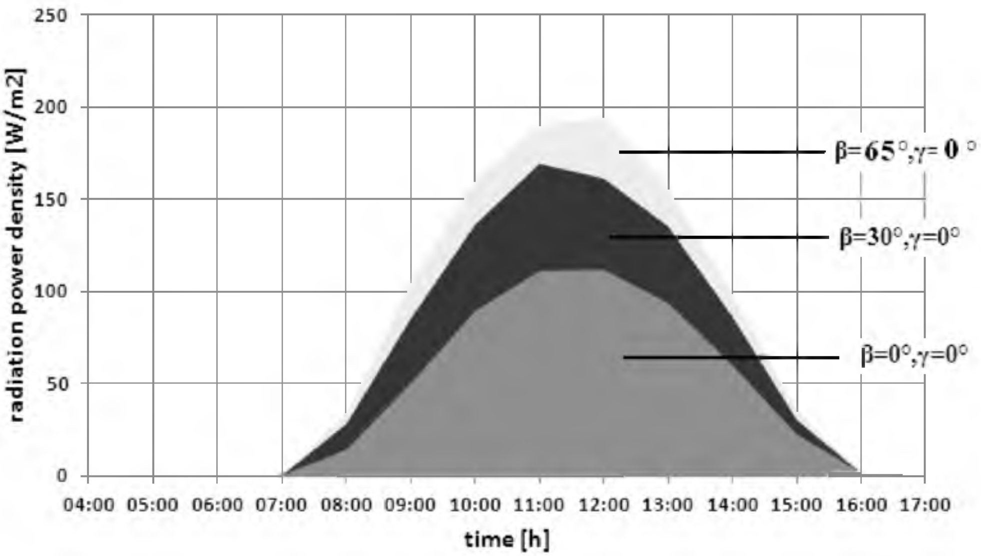


Fig. 14. Power gain at different spatial settings of the receiver on January 15

8. Summary

The above consideration and computer simulations allow to state the following:
- The hourly distribution of radiation power density is significantly affected by the declination and hour angles that is clearly visible by comparing Figs. 8 and 9.

- Figures 8 and 10 enable comparing values of power density of solar radiation reaching the receiver arranged horizontally and at an angle optimal with regard to energetic gain. Radiation power density possible to be gained for optimal panel angle $\beta = 30°$ is 1,13 (12 a.m.) times bigger than for its horizontal set-up.

- For January, power density possible to be gained for optimal angle $\beta = 65°$ is nearly 1,7 (12 a.m.) times bigger than for its horizontal set-up, Figs. 9 and 11.

- Based on the measurement data [13] the effect of azimuth angle on radiation power density has been analyzed. For equal inclination angles chosen from among three azimuth positions, the best results are obtained for the angle γ equal to φ diminished by 15°. On the other hand, the least effective orientation is characterized by the angle enlarged with regard to its initial value – Figures 5, 6.
- Comparison of Figures 8 and 11 as well as 9 and 12 shows the effect of the receiver azimuth angle on possible energetic gain. Influence of this angle is smaller than the one of the angle of inclination, nevertheless, it should not be ignored in calculation.
- The use of the trackers operating in two axes (Sun follow-up) improves effectiveness of the PV system as compared to stationary arrangement, even by 32 percent in yearly scale. In Summer the improvement may reach even 50 percent [13].
- Energetic gain approximating the one obtained in case of the bi-axial arrangement may be achieved with the use of uni-axial tracker operating in vertical axis, with the inclination angle with respect to the ground equal to φ-15°, where φ is for latitude, Figs. 4 and 5.
- Comparison made for the system adjusting its position only in horizontal axis to the results obtained for the receiver inclined to the ground at the angle φ has shown the energetic gain higher by 15 percent in case of the first option, Figs. 4 and 5.
- The results obtained based on measurement data and from computer simulation justify the use of follow-up arrangement in the photovoltaic systems.
- In case of a bi-axial tracker the installation and assembling increase the investment cost by 20 percent as compared to the usual solution. The operational cost resulting from additional power required for the tracker supply is negligible, not exceeding 1-3 per cent of the energetic gain.
- Big PV installations provided with trackers require larger surface, taking into account possible spatial orientation changes of large group of the receivers. Statistically, higher failure frequency is then expected.

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