The effect of spatial orientation of solar energy receiver on the energetic gain

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Abstract. The angle of incidence of solar radiation on the PV panel is a function of many factors: the angle of solar declination, the angle of latitude, the hour angle, the azimuth angle and the angle of receiver inclination to the ground. Optimization of the positioning of a solar energy receiver, considering the possible energetic gain, with the Liu-Jordan isothropic mathematical model has been made. The influence reflectivity coefficient of the ground and transparency coefficient of the atmosphere on the investigated angle has been taken into account. The computer simulation results have been presented and compared with those obtained by other authors.

Key words

solar energy, optimal setting of the receiver, energetic gain, computer simulation.

1. Introduction

The Sun is composed of a mixture of gases with a predominance of hydrogen. Through most of the Sun"s life, energy is produced by nuclear fusion through a series of steps called the proton - proton chain.
These process are sourced with energy of solar radiation. This energy is radiated away from the Sun uniformly in all directions. Sources of solar energy are in practice unlimitted and at the same time, environment friendly. The total power sent by the Sun in cosmic space is equal 3,826 10^{26} W. Taking into account the conversion of solar energy into electric energy, the angle of incidence of solar radiation of the receiver plane is of considerable significance.
The European Union is preparing a new energy strategy for 2011-2020, 3 x 20 Report (20% reduction of emissions, 20% improvement of energy, and 20 % energy consumption from of renewable sources.

2. Density of solar power radiation

A. Basic relationships

The angle $\theta_{\beta,}$ is an angle of incidence of the radiation on a plane inclined at the angle β to the ground being the function of many variables. The variables and interrelations among them are shown in the figure 1 [9].
The angle $\theta_{\beta,}$ is described by the relationship [9, 20]:

$$\cos\Theta_\beta = \sin\delta\sin\varphi\cos\beta - \sin\delta\cos\varphi\sin\beta\cos\gamma + \cos\delta\cos\varphi\cos\beta\cos\omega + \cos\delta\sin\varphi\sin\beta\cos\gamma\cos\omega + \cos\delta\sin\beta\sin\gamma\sin\omega \quad (1)$$

The declination angle δ depends on the day n of the year. It is calculated according to the approximate Cooper rule [9, 20]:

$$\delta = 23{,}45\cdot\sin\left(360\cdot\tfrac{284+n}{365}\right) \quad (2)$$

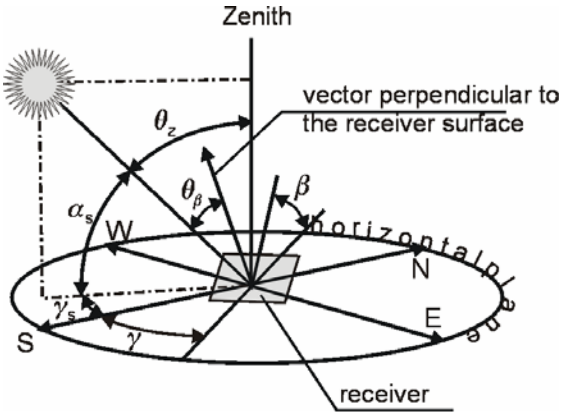

Fig.1. Sun and receiver in a horizontal coordinate system. Explanations: α_s - the solar angle, β - angle of inclination of the receiver vs. of the ground, γ - receiver azimuth, ω - the hour angle, θ_β - the angle of incidence of the radiation on the surface of the receiver inclined at the angle β, to the ground, θ_Z - the zenith angle

ω - is the hour angle, taking the following value in accordance to the time of the day:

$$\omega = 15\left(\tau - 12^{00}\right) \quad (3)$$

where τ is the hour of the day.
The angle of latitude φ depends on the location. The next parameter , that is the azimuth angle of the receiver (Fig. 1), is the deflection accounted from the local meridan to the south direction (-15° - +15°). Taking into account that the surface of the receiver inclined at the angle β to the ground is oriented to the South, it takes a zero value [20]. Where β=0, $\theta_Z = \theta_\beta$, θ_Z - angle of incidence of the radiation on a horizontal surface (the zenith angle), Fig.1:

$$\cos\Theta_Z = \cos\delta\cos\varphi\cos\omega + \sin\varphi\sin\delta \quad (4)$$

The density of solar power radiation flux is a sum of radiation energies in the whole spectrum of wave lengths reaching a surface unit [W/m^2]. Solar radiation is characterized by components:direct component G_{dr}, diffused component G_{df} and secondary reflected radiation G_r [9]. The G_{dr} and G_{di} values are assessed on the grounds of many years data obtained from weather stations [1], G_r is considered as a secondary radiation component. In order to ensure maximal energetic gain most of solar power receivers are arranged at a certain angle to the ground, with consideration of the above mentioned data. For further consideration it is assumed that the diffusive and reflected radiation components are isotropic, that enables to determine the solar energy reaching a surface arranged at the angle β, to the ground and having the azimuth angle γ using the Liu-Jordan method [16]. Hence, the following may be written:

$$G_\beta = G_{dr} \cdot R_{dr} + G_{di} \cdot R_{di} + \left(G_{dr} + G_{di}\right) \cdot \rho_r \cdot R_r \quad (5)$$

with R_{dr}, R_{di}, R_r - the correction coefficients defined below, related to direct, diffusive and reflected components, respectively, assumed from ρ_r=0,07 (for dry asphalt) to ρ_r=0,095 (for fresh snow) [20]. Therefore:

$$R_{dr} = \frac{\cos(\varphi-\beta)\cdot\cos\delta\cdot\cos\omega+\sin(\varphi-\beta)\cdot\sin\delta}{\cos\varphi\cdot\cos\delta\cdot\cos\omega+\sin\varphi\cdot\sin\delta} \quad (6)$$

$$R_{di} = \frac{1+\cos\beta}{2} \quad (7)$$

$$R_r = \frac{1-\cos\beta}{2} \quad (8)$$

B. The influence of variables on density of solar radiation power

As a result of computer simulation the dependence of density of solar radiation flux on different variables has been calculated.

Fig. 2 shows the declination angle δ in function of the days of the year at 12 o'clock.

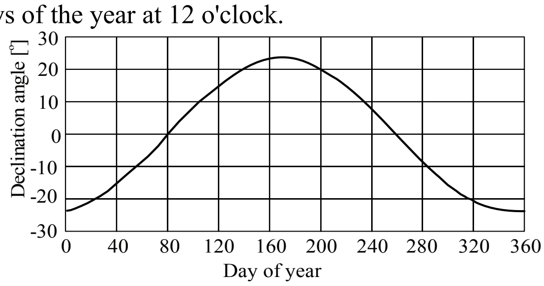

Fig.2. The declination angle δ in function of the days of the year at 12 o'clock

Fig 3. shows the relationship between the changes of total solar radiation power density on a horizontal plane and - hour angle on selected days in Warsaw.

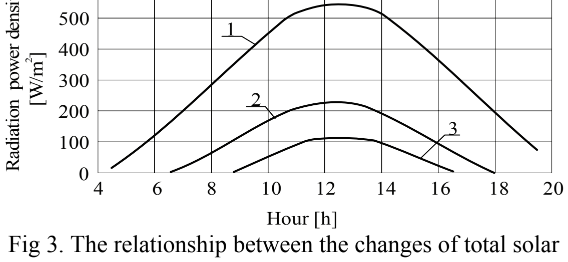

Fig 3. The relationship between the changes of total solar radiation power density on a horizontal plane and - hour angle on selected days in Warsaw, ρ_r=0,35, June 15 (1), October 1 (2), January 15 (3)

Fig. 4 shows changes of total solar radiation power density on a vertical plane in Warsaw on June 15 for selected azimuth angle.

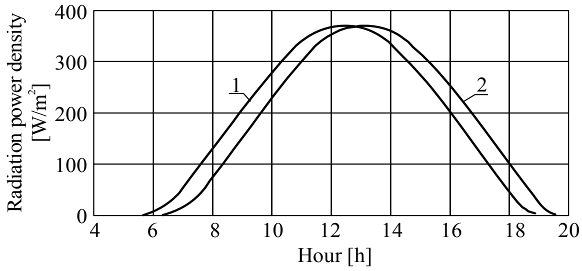

Fig. 4. The relationship between the changes of total solar radiation power density on a horizontal plane and - hour angle on selected days in Warsaw, denotations γ=0° (1), γ=15° (2)

3. Optimization of space orientation of the receiver

Dependence of the energy possible to be obtained from Sun on the above mentioned parameters may be partially reduced by optimal arrangement of the receiver at such an angle to the ground as to achieve maximal energetic gain.

The optimization problem requires defining full relationships between the parameters allowing for finding maximal (minimal) values of the function considered. In this case the priority of the selected variant is a result of aiming at maximal energetic gain.

Many authors dealt with this problem, among others in [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23].

In case of consideration of only the direct radiation component the optimal angle of receiver inclination to the ground takes the value [20]:

$$\beta = \varphi - \delta \quad (9)$$

As permanent adaptation of receiver arrangement to varying angle δ would be difficult, an average value of the angle is assumed for a given season, for example for summer months, or β=φ. is admitted.

The problem of optimal arrangement of the receiver is of particular significance in our weather conditions, due to important rate of the diffusive component in the total radiation level. It is assessed to be of 50 percent and, in winter season - even 70% [5]. In case of Poland the contributon of the diffuse and reflected components may be approximately taken into account by reduction of the β angle by 5 - 10 ° with respect to the value referred to in (9), [20]. The authors of the work [18] obtained similar results. They suggest arrangement of the receiver at the angle (φ+15°)±10° for American conditions.

The authors of the work [11] calculated optimal angle of panel arrangement with respect to the bed using the program PVSYST V2.0 They considered the location for the town of Lublin with previously defined azimuth values.The results were as follows,; for the full year optimization β=34°, while for summer β=24°, and for winter β=50°.

In the work [7] pertaining to analysis of a hybrid system of the power 4 kW, using the energy of wind and Sun in Lowell (New England, USA) the authors suggest permanent set-up of photovoltais cells at the angle 42° ensuring maximal gain in spring.
The considerations made in [12] show that for the location φ=52°N from October to March density of radiation power falling of a vertical surface is twice as large as on a horizontal one. On the other hand, from April to September the most advantageous inclination angle for the receiver amounts to β=30°.
Authors of the work [5] have come to the similar conclusions. They considered all three radiation components and studied the effect of transparency coefficient of the athmosphere and bed reflectivity factor on the density of radiation power. Computer simulation served for determining optimal receiver inclination angle to the ground. In June the angle amounts to 20-40° (according to the bed reflectivity), while in December 50-60°.
The work [15] informs that in case of such a large photovoltaic investment like the Lehrter Railway Station in Berlin the solar modules are installed at the angles 7-19°, Fig.5.
Photovoltaic modules installed in Älvkarleby in Sweden are inclined at the angle 42° [8].
The work [10] determined intensity of radiation for horizontal and vertical set-up of the receiver as functions of Sun altitude, that were then compared to the density of radiation power for an optimally set-up of the plane.
In the work [22] it is noticed how disadvantageous is horizontal arrangement of a receiver in the locations of higher latitudes (e.g. Iqaluit 64°N).

Fig 5. Lehrter Railway Station in Berlin - the PV modules [foto from author]

For Beer Sheva Station (Israel) angle of the inclination of the receiver β=40°, is the most advisable for August and the least for January [13].
The analysis of an influence of a receiver inclination angle the ground and azimuth angle, on monthly and yearly radiation energy density has been made. Authors considered cities with different angle of latitude. They give plot of the yearly radiation in Agoncillo (Spain).for arbitrary inclination and azimuth angles, expressed in % of maximum [2].
Author of the publication [19] demonstrated considerable dependence of the power gained from solar energy on the latitude and declination angles. The considerations are supported based on many years measurements.

Author of [3] suggests that the arrangement of the receiver in Poland should be at the angle between 10°-65° (for all components) and 29°-75° (for direct component only).
In [4] BIPV- modules position to the ground has been described.
In [17] optimal position of the receiver, taking into account the inclination angle and azimuth angle, declination angle, latitude and hour angle has been analysed.
Author suggested the optimal receiver inclination angle in Poland is between 39° and 75° [23].
Authors [14] has given the optimal receiver inclination angle for Paris (latitude 48,8°N), for May-September equals 0° and for September -May equals 60°.
More energy is collected by the end of the day if the PV receiver is installed on a tracker with an actuator that follows the sun. There are two types of sun trackers: one-axis trackers (from east to west during the day) and two-axis trackers (from east to west during the day and .from the north to south during the seasons of the year) [19]. The PV installation Euclides with parabolic concentrators and one axis trackers. in Institutó Tecnológicó y de Energias Renovables ITER on Teneriffe (Fig. 6), is the example of applications.

Fig. 6. .PV - installation with concentrators and one axis trackers in Instytutó Technologicó Energie Renovable (ITER) on Teneriffe [foto from author]

4. Results of computer simulation

The above considerations and the relationships (1) to (8) served as a basis for a program developed with a view to making the calculation and computer simulation. For purposes of the analysis the angle φ of latitude of the town of Warsaw has been assumed, with G_b and G_d acquired from many years' data, coefficient ρ_o of the bed reflectivity in the range from 0.07 to 0.95 (here ρ_o=0.3), transparency coefficient of the atmosphere k_t from the calculation carried out for Warsaw [20].
Figures 7, 8, and 9 present the plots of solar radiation power density falling on the surface of the power receiver for its varying spatial orientation (the angles β) on June 15 [6]. The horizontal, vertical, and for whole year optimal arrangements and the effect of the angle of azimuth are considered.

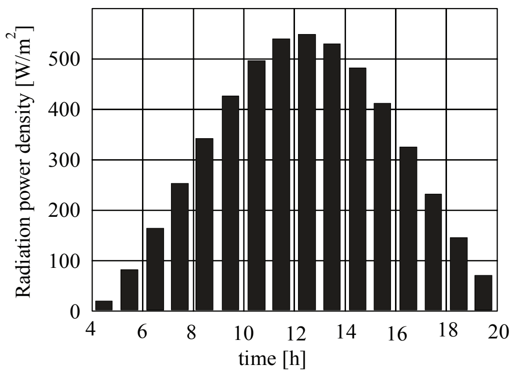

Fig. 7. Hourly distribution of radiation power density falling on a horizontal plane, for γ=0º, on June 15

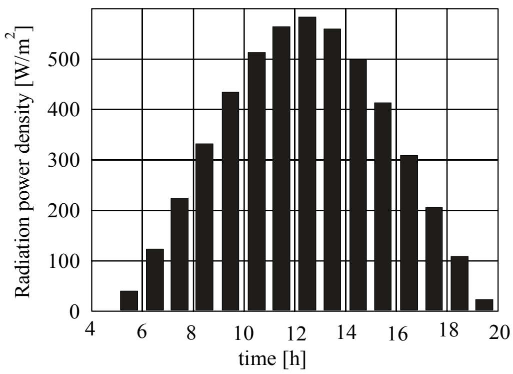

Fig. 8. Hourly distribution of radiation power density falling on a plane inclined at the angle β=32º, for γ=0º, June 15

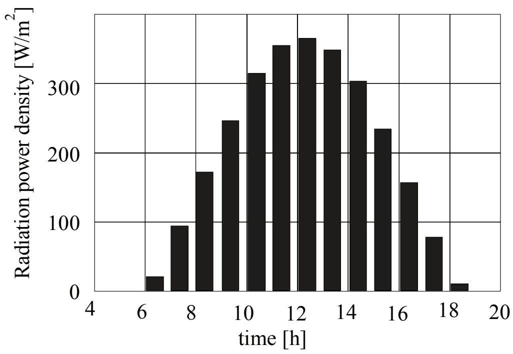

Fig. 9. Hourly distribution of radiation power density falling on a vertical plane, for γ=0º, on June 15

Figures 10, 11, 12 and 13 show selected results of the daily sum of density of the energy for particular days, and particular angle of receiver inclination and azimuth angle.

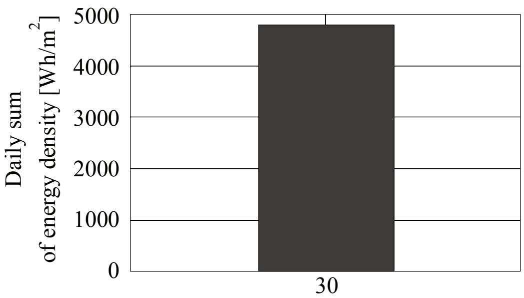

Fig.10. The daily sum of density of the solar energy falling on a plane inclined at the angle β=32º, for γ=15º, on June 15 in in the hours from 4 a.m. to 8 p.m.

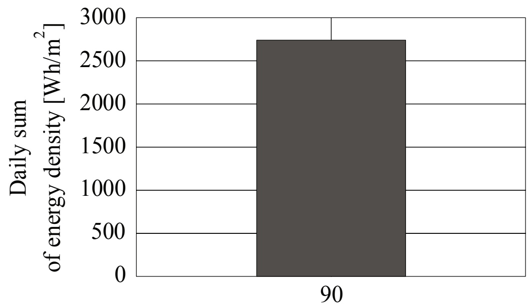

Fig. 11. The daily sum of density of the solar energy falling on a plane inclined at the angle β=90º, for γ=15º, on June 15 in in the hours from 4 a.m. to 8 p.m.

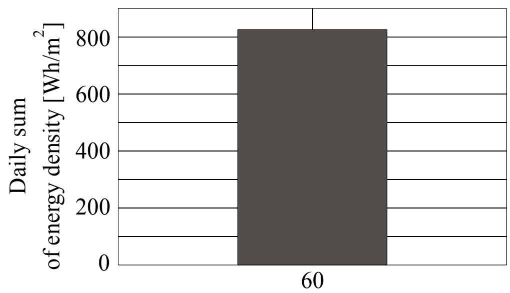

Fig.12 The daily sum of density of the solar energy falling on a plane inclined at the angle β=57º, for γ=15º, on January 15 in in the hours from 4 a.m. to 8 p.m.

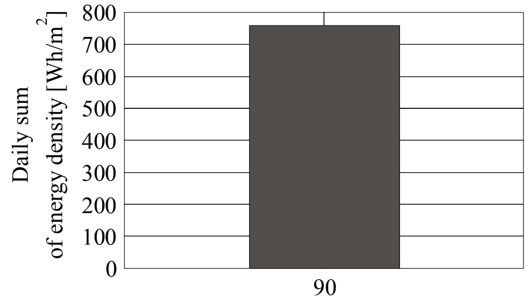

Fig.13. The daily sum of density of the solar energy falling on a plane inclined at the angle β=90º, for γ=15º, on January 15 in in the hours from 4 a.m. to 8 p.m.

Figures 14, 15, and 16 present the plots of monthly sum of energy density, on a horizontal and vertical plane and at the angle β=30º.

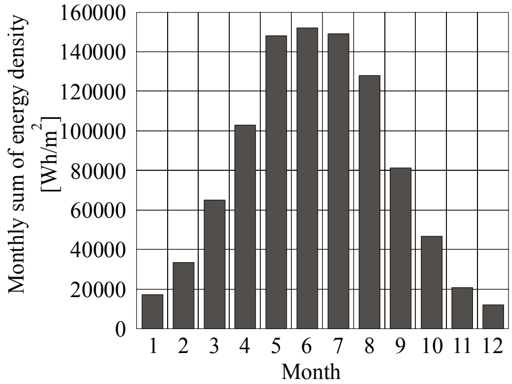

Fig. 14. The monthly sum of density of the solar energy falling on a horizontal plane, for γ=0º, Wh/m^2

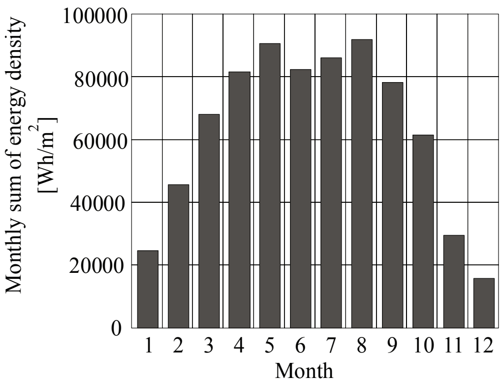

Fig.15. The monthly sum of density of the solar energy falling falling on a vertical plane, for γ=0º, Wh/m^2

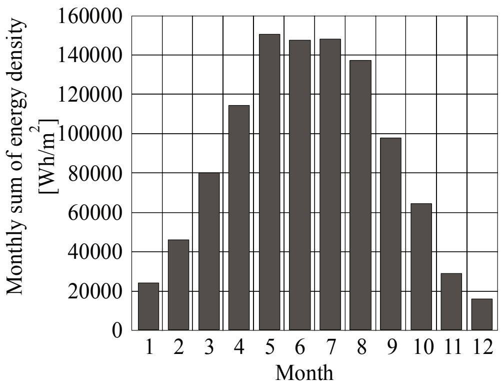

Fig. 16. The monthly sum of density of the solar energy falling on a plane inclined at the angle β=30º, for γ=0º, Wh/m^2

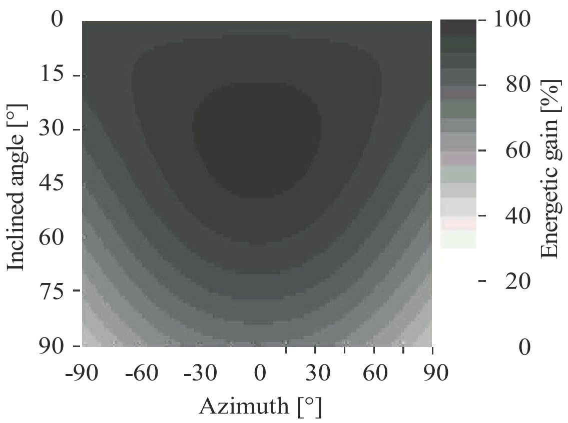

Fig. 17. Yearly energetic gain In the hours from 4 a.m. to 8 p.m., β_{opt}=32°, γ=0°

The program developed for the simulation purposes enables to determine energetic gain possible to be achieved in a given time range, i.e. on a given day, or several days, for a selected receiver location, set-up, and azimuth. This allows to find optimal receiver set-up which is depicted by the isolines of Figs. 17, 18, and 19.

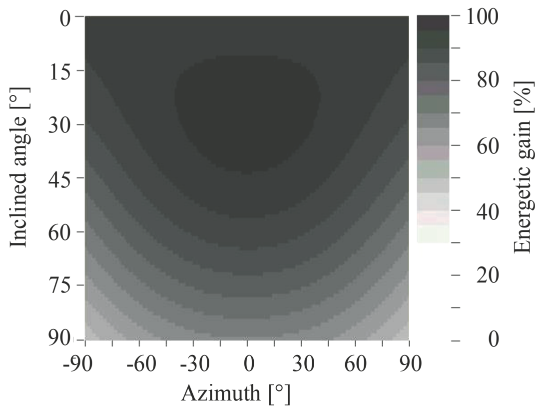

Fig. 18. Energetic gain for the period April-October in the hours from 4 a.m. to 8 p.m., β=27°, γ=0°

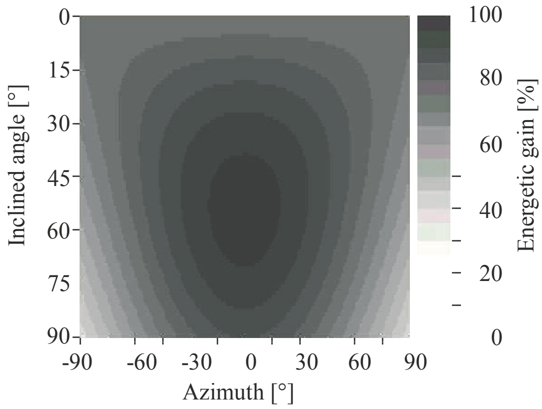

Fig. 19. Energetic gain for the period from January to March, in the hours from 4 a.m. to 8 p.m., β=54º, γ=0º

5. Summary

The above consideration and computer simulations allow to state the following:

1. Weather conditions affect all the radiation components, (5) - (8).
2. Solar declination takes different values on each day of the year, Fig.2
3. The hourly distribution of solar radiation power density is significantly influenced by the declination angles, Fig.3.
4. On different days the number of hour of sunshine and power density is different, Fig.3.
5. The daily sum of density of the solar energy depends on the declination angle, that is clearly visible by comparing, Figs.11 and 13.
6. Analysis of the results of computer simulation (Fig. 10, Fig.11, Fig.12 and Fig.13) shows that daily sum of radiation energy density (between 4 a.m. and 8 p.m.) in June in Warsaw are several times higher than in January (influence of the declination angle). The receiver inclination angle is also significant.
7. Deviation from the south direction defined by the change in azimuth angle γ=15° induces insignificant changes in the power density reaching the receiver, Fig.4. The effect of the azimuth angle is of particular meaning in morning and evening hours. Nevertheless,

the azimuth angle should not be disregarded during the calculation.
The receiver should be oriented to the South at any time.

8. Figures 7, 8 and 9 enable comparing values of power density of solar radiation reaching the receiver arranged horizontally, vertically, and at an optimal angle with regard to energetic gain. In this case the vertical set-up appears to be worst. Power density possible to be gained for optimal panel angle $\beta=32^o$ is nearly 1.6 times bigger than for its vertical set-up.
9. Taking into account interrelations between the considered conditions optimal value (with regard to maximal power yield) of the inclination angle of the receiver of solar radiation power with respect to the ground has been determined.
10. The computer simulation enables optimization of space arrangement of the receiver in chosen time interval with regard to the power gain. The results obtained this way allow comparing values of the solar radiation power density reaching the receiver at its various arrangements, Figs. 17, 18, 19.
11. Low value of power density feasible to be obtained in January (when the rate of reflected radiation component is important) is due to the fact that the energy emitted from the Sun is lower than in other months. Improper panel set-up may still worsen the condition. Finally, taking into account the simulation results obtained for selected receiver arrangements it is clear that vertical panel set-up is more advantageous, as the energetic gain is only by 10 percent lower as compared to the optimal one (the optimal angle $\beta=57^o$), Figs.12 and 13.

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