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Studying the Impact of Orientation and Roof Pitch on the Operation of Photovoltaic Roof Tiles

***Abstract**. The work presents the dependencies between the value of power generated by photovoltaic roof tiles and different tile inclination angles in two planes. The power density of solar radiation for different orientations was compared with the values of generated power obtained. The results analyzed indicate the importance of considering the orientation and roof pitch during roof design.*

Streszczenie.** W pracy przedstawiono zależność wartości generowanej mocy przez dachówkę fotowoltaiczną od zmiany kąta nachylenia dachówki w dwóch płaszczyznach. Porównano gęstości promieniowania słonecznego dla danego położenia z wartościami uzyskanej mocy. Opracowane wyniki wskazują na istotność uwzględnienia usytuowania oraz kąta nachylenia dachu podczas jego projektowania.* ***(Badanie wpływu usytuowania oraz kąta nachylenia dachu na pracę dachówek fotowoltaicznych)

Keywords: photovoltaics, roof pitch, power density of solar radiation, photovoltaic cell power
Słowa kluczowe: fotowoltaika, kąt nachylenia dachu, gęstość mocy promieniowania słonecznego, moc fotoogniw.

Introduction

Elements integrated with the building, such as solar roof tiles, become more and more popular among individual investors, which shows an increase in their ecological awareness. Apart from serving as replacement for traditional photovoltaic panels, solar roof tiles can also replace the roofing itself, combining the features of both those elements.

From the perspective of photovoltaic conversion, apart from the efficiency of particular installation elements, the location of the system installation also plays an important role. The contributing factor is not only the geographic location, on which the level of insolation, the number of solar insolation hours per day and the power density of solar radiation that reaches the Earth's surface are directly dependent, but also the roof orientation and pitch. In the case of solar roof tiles that constitute an integral part of the roof, their inclination angle must be defined in advance in order to obtain optimal working conditions for the system [2,3,4].

Solar radiation

From the perspective of energy production from photovoltaic sources, solar radiation is characterized by means of different physical properties, the most important of which are [1,3]:

- solar density of radiation E [W/m^2] – it is the sum of the amount of direct solar radiation reaching the receiver E_b, diffuse solar radiation E_d and reflected solar radiation E_o;
- insolation H [kWh/m^2] – it is the total energy of solar radiation received on a given surface area unit during a given time (an hour, a day, a month, a year);
- Sun hours h [h] – it is the number of hours during which direct sun radiation reaches the surface of the Earth in a given period of time.

The selection of the appropriate technology of transforming the energy of the Sun into electricity requires estimating the potential and actual solar energy amounts in a given region as well as establishing the meteorological conditions in the region.

The position of the Sun in the sky determines the angle at which direct sunlight reaching a precisely specified point on the surface of the Earth that is determined by means of specific angles in the horizontal coordinate system strikes the surface (Fig.1).

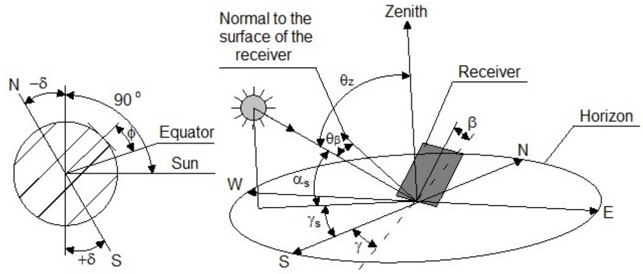

Fig. 1. The geometry of the Sun – receiver system [3]

The angles presented on figure 1 can be interpreted in the following way [1,3]:

ϕ – latitude – positive value is assumed on the Northern Hemisphere and negative value is assumed on the Southern Hemisphere;

δ – solar declination – specifies the position of the Sun in relation to the plane of the equator at the astronomical noon. Its value varies within the range from –23,45° to +23,45°. For the latitude in Poland, the northern declination is a positive value in the summer. Its value can be determined with the use of Cooper's formula in which „n" stands for the day of the year [1,3]:

(1) $$\delta = 23{,}45 \cdot \sin\left(360 \cdot \frac{284+n}{360}\right)\ [°];$$

β – receiver inclination relative to the plane of the horizon;

γ – receiver azimuth – the angle measured relatively to the north-south direction (negative eastward and positive westward), calculated with the use of the following equation:

(2) $$\sin\gamma = \frac{\cos\delta \cdot \cos\omega}{\cos\alpha};$$

γ_s – solar azimuth – the angle specifying the deviation of the projection of the direction of direct sun rays onto the surface of the Earth due south (eastward – negative, westward – positive);

θ_β – the angle at which sun rays strike the surface of the receiver contained between the normal to the receiver and the angle of direct sun rays, calculated with the use of the following equation:

(3) $$\cos\theta_\beta = \cos(\phi - \beta) \cdot \cos\delta \cdot \cos\omega + \sin(\phi - \beta) \cdot \sin\delta$$

α_s – Sun height relative to the plane of the horizon;

θ_z – zenith angle, which can be calculated with the use of the following equations:

(4a) $$\theta_z = 90° - \alpha_s$$ or

(4b) $$\cos\theta_z = \sin\alpha = \cos\phi \cdot \cos\delta \cdot \cos\omega + \sin\phi \cdot \sin\delta;$$

ω – hour angle (recalculated for the surface of the receiver) whose value is positive after noon and negative till noon and is calculated with the use of the following equation:

(5) $$\cos\omega = -\tan(\phi - \beta) \cdot \tan\delta.$$

The trajectory of the Sun presented on figure 2 in the coordinates α_s=f(γ_s), reflects the path of the Sun on the sky during the day.

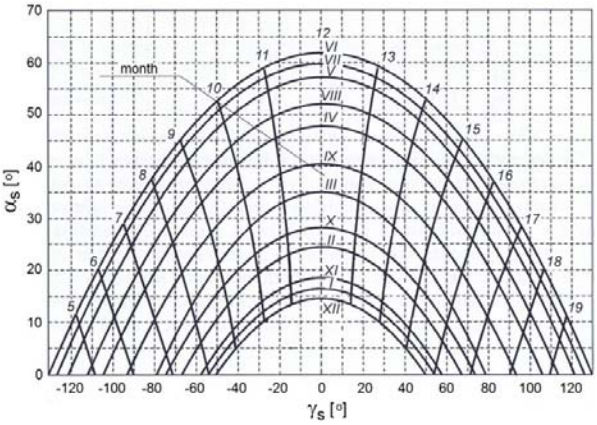

Fig. 2. The trajectory of the Sun for Warsaw (ϕ=52°) [3]

The value of solar density of radiation reaching the surface of the Earth can be provided by weather stations but they are usually sums of energy values in a given period or average values. That is why a few methods of recalculating the radiation values from a flat plane to an inclined plane have been developed. In practice, the Liu-Jordan method assuming the isotropic nature of diffuse and reflected radiation is frequently used [1,3]. The value of solar density of radiation E_β [W/m^2] striking a surface inclined at the angle β relative to level ground due south can be calculated by means of the following equation:

(6) $$E_\beta = E_b \cdot R_b + E_d \cdot R_d + (E_b + E_d) \cdot \rho_o \cdot R_o$$

where:

- E_b, E_d – the density of the direct and diffuse luminous flux striking a flat plane;
- R_b, R_d, R_o – correction coefficients for direct, diffuse, and reflected radiation;
- ρ_o – reflection coefficient (surface reflectivity) e.g. 0,8 for water; 0,4 for ground; from 0,46 to 0,86 for snow.

The correction coefficients used in the equation can be determined by means of the following equations:

(7) $$R_b = \frac{\cos\theta_\beta}{\cos\theta_z}\ ,\ R_d = \frac{1+\cos\beta}{2}\ ,\ R_o = \frac{1-\cos\beta}{2}.$$

Information on local illuminance levels provided by weather stations or statistical reports can be used during the design of photovoltaic installations. Poland lies in the temperate climate zone and its area is geographically closed between the latitude of 49 and 54,5 degrees north. Thanks to that, the climate conditions for big cities, such as Poznań and Warsaw, are very similar and can be treated as valid for the whole country [7]. Another important factor is the dependency between the energy density of solar radiation within a given twenty-four hour period and the weather conditions during the day. A diagram prepared for the city of Poznań on a specific day for a receiver inclined at the angle of 30° relative to level ground towards the south is presented on figure 3. It confirms, however, that cloudiness and the proportional share of diffuse radiation are extremely important when it comes to obtaining energy from photovoltaic sources.

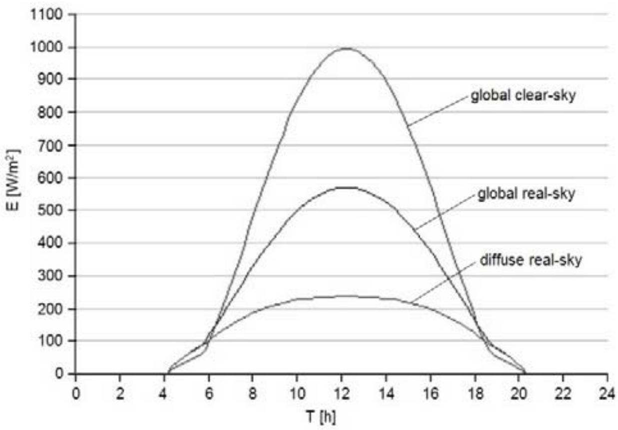

Fig. 3. Sample distribution of energy density of solar radiation during the day in Poznań in relation to cloudiness levels [7]

Luminance values in Poland range between 970 – 1074 kWh/m^2, and the average value of sun hours is 1580 h/year. Diffuse radiation constitutes as much as up to 50 % of total solar radiation [1,3]. Taking into consideration the information presented above, the territory of the country can be divided into 11 helioenergetic regions, in accordance with the report of the Committee of Thermodynamics and Combustion of the Polish Academy of Sciences, as presented on figure 4.

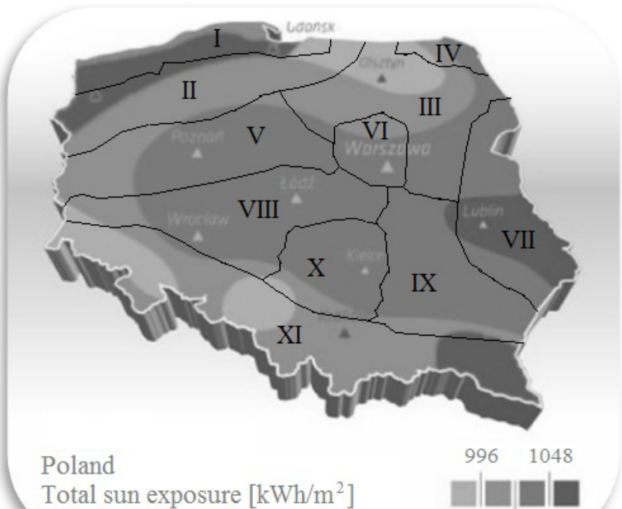

Fig. 4. Reference helioenergetic regions of Poland [1,3,6]

The most advantageous helioenergetic conditions exist in northern and south-eastern Poland (I, VII, VIII, IX), and the worst conditions exist in Upper Silesia (X). Region V where Poznań lies ranks 6th with respect to solar energy production aptitude.

The pieces of information presented above point towards the conclusion that the conditions in Poland are advantageous for energy production from photovoltaic sources. It should be remembered, however, that the amount of solar radiation absorbed by the absorber depends on the angle at which the sun rays strike its surface. That is why obtaining the most advantageous absorber inclination angle is important in order to maximize the energy gain in the primary months of exploitation. Including only the direct radiation component, the optimal receiver inclination angle in relation to level ground will be

$$\beta_{opt} = \phi - \delta, \tag{8}$$

which is solar declination value (usually average for a given exploitation period) subtracted from the latitude value.

In the case of photovoltaic installations which are operational throughout the whole year and absorb only direct radiation, the receiver should be positioned at an angle equal to the latitude value ϕ. For the diffuse radiation component, maximal gains can be obtained by positioning the receiver in a flat plane (angle $\beta=0^o$) and for the reflected radiation component – in a vertical plane (angle $\beta=90^o$). Taking the information provided above into consideration, it appears that the optimal receiver inclination angle maximizing energy gains is an angle that is about 5-10^o smaller than the angle obtained when only direct radiation is analyzed [1,3].

Tests of photovoltaic roof tiles

The tests were conducted in Poznań (with the graphical coordinates 52,25^{o}N and 16,51^{o}E) for FTDS50 photovoltaic tiles produced by the Fotton company made on the basis of monocrystalline silicon and characterized with the following parameters [5]: maximum power P_{max}=52 W, nominal voltage U_n=9,8 V, open circuit voltage U_{oc}=12 V, short-circuit current I_{sc}=5,55 A, voltage in PMM (maximum power point) U_m=9,8 V, current in PMM I_m=5,3 A.

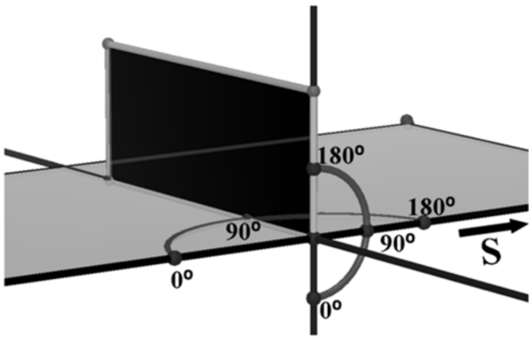

Fig. 5. Schematic positioning of photovoltaic tiles in relation to the horizontal and vertical axes

Measures were conducted for modifications of the tile inclination angle for the rotation axis parallel to the surface of the earth (horizontal axis) in the range from 0° to 160° and for the rotation axis orthogonal to the surface of the earth (vertical axis) in the range from 10° to 140°. The positioning modification range was presented on figure 5. The measurements were conducted during one day in July between 11:30-14:30 under a cloudless sky. Almost constant illuminance amounting to values between 1036 lux and 1050 lux for the plane parallel to the surface of the earth was obtained. Maximum power adjustment as well as electric current, voltage and solar radiation density measurements were performed for every roof tile orientation. On the basis of measurements, the characteristics of the dependency between the power obtained (Fig.6) and the solar density of radiation (Fig.7) and the positioning of the tiles was determined.

Conclusions

On the basis of the characteristics obtained, it can be observed that the most advantageous roof tile orientation is when the inclination angle is 40° of the horizontal axis and above 90° of the vertical axis. The wide range of the vertical axis angle results mainly from three-hour measurements during which the Sun changed its location in relation to the initial position by 30°. The results make it possible to confirm the validity of mounting a photovoltaics installation facing south with the inclination angle between 30° and 45°.

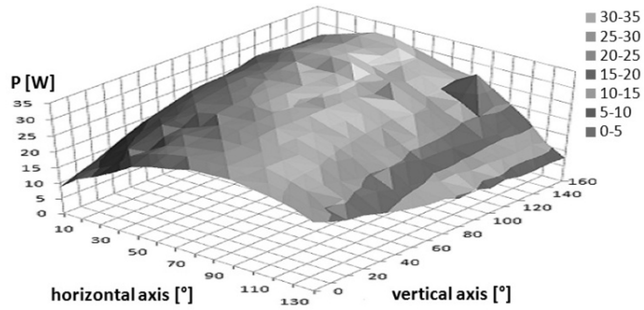

Fig.6. The characteristics of the photovoltaic tile power obtained in proportion to tile orientation along two rotation axes

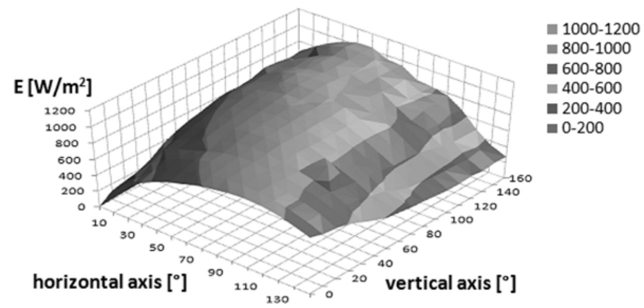

Fig.7. The characteristics of solar radiation density E in proportion to orientation along two rotation axes

The results are subject to random errors (of a few-dozen percent) resulting from the use of resistors with varying levels of accuracy dependent on the current values measured.

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