Astronomical and Meteorological Conditions of a Solar System Operation

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Abstract. Acquisition and processing of as much solar energy for heating and electricity generation in Poland and in the world is a very important objective in the policy of alternative energy sources. The main problem with the reception of solar energy by solar collectors is vary energy supply at different times of day and year and low flux density of radiation. The term of solar radiation one mean transmission or emission of energy in the form of electromagnetic waves. The radiation emitted from the surface of the sun spreads out in all directions in space, reaches the Earth's surface in only partly, especially the solar collectors. The most important parameters characterizing solar radiation are daily, monthly and annual sum of solar radiation. Its express the amount of solar energy which falls on a unit area at a given time. Number of hours of sunshine during the day are dependent on two key factors. The first one is the time from the sunrise to sunset, which strongly depends on the date and latitude. The second factor is the weather (clouds), influences solar radiation, radiation in touch with clouds is absorbed and dissipated. This publication shows the impact on the energy yield of the flat collector installation and astronomical conditions (angle of inclination and declination of solar), and climate. The calculations of determining the astronomical conditions of the place where the installation is located ware analyzed. The solar installation is located in Rzeszów (Poland) and the plate collector placed on the roof of building. Based on specific methodology for selected days the calculation of the elevation angle of the Sun, hourly angle, the sun azimuth and angle of incidence of the radiation on any plane were set. The results are shown in diagrams. The effect of cloud cover on the acquisition of solar energy by the collector is also shown.

1. Introduction
Solar radiation energy constitutes the biggest and unlimited source of energy which is accessible to humans. A participation of solar energy is necessary for many physical, chemical and biochemical processes which take place on the surface of the Earth. A source of energy on the Sun are processes which occur inside the Sun which change hydrogen into helium. Energy created in that process is emitted in a form of radiation into the universe and reaches, inter alia, the surface of the Earth. Such radiation has the range of wavelengths from gamma radiation, through X, ultraviolet, visible and infrared radiation to radio waves.

One half-billionth part of energy emitted by the Sun reaches the limit of the atmosphere. Its stream has the power of approx. 1.39 kW/m²- it is so called solar constant. However, only approx. 45- 50% of such value reaches the Earth, depending on the time of the day and season of the year. It is assumed that on average 31% of solar radiation reaching the Earth is reflected, including 22% reflected by the
atmosphere (clouds, dusts, gases) and 9% reflected by the surface of the Earth. The remaining 69% of radiation is absorbed in the atmosphere and on the surface of the Earth, including: 16% by the atmosphere (most ultraviolet radiation), 3% by clouds and 50% by the surface of the Earth.

Waves which reach the Earth are perceived by humans as visible radiation, i.e. light, and infrared radiation perceived as heat. Additionally, radiation may be processed into electric energy through photovoltaic conversion or converted photochemically into heat by using solar collectors.

This publication includes calculations determining astronomical conditions for the place in which a solar power system has been located. The analyzed solar power system has been installed in Rzeszow and a flat plate collector was fixed on a roof of that building. On the basis of specific methodology for chosen days, the angle of sunrise, hour angle, the azimuth of the Sun and the angle of incidence on a freely adjusted plane were calculated. Achieved results were presented on charts. An influence of cloud cover on the acquisition of solar energy by the above-mentioned collector was presented as well, [1-4, 10].

2. Influence of weather conditions on the operation of a solar power system

A very irregular annual distribution of solar energy is typical to meteorological conditions in Poland. It is estimated that the average amount of energy reaching the upper layer of the atmosphere is 1.39 kW/m². Maximum radiation in Poland is approx. 1200 W/m². Approx. 80% of the total annual insolation falls during six months of the spring and summer seasons.

In Poland there exists a division into climatic zones and depending on a region the usage of collectors may be more or less effective. Residents of the east, central and south parts of Poland will benefit most because average annual insolation there is larger than in other parts of the country. In Rzeszow it is 1.02 kW/m². A climate of Rzeszow is unique because the north part of the Rzeszow District has a climate of foothill lowlands and valleys and the south part has a mountain climate. The average annual temperature for Rzeszow is +7.5 °C. Highest average annual temperatures are in July (+17.6 °C) and lowest ones are in January (–4.6 °C). Rzeszow is a city situated quite high: 197-384 m above sea level, which is significant in the process of absorption of sun rays. The average annual insolation is 1857 h, and daily one is 5.1 h.

Energy which may be acquired in solar collectors depends on the amount of solar radiation which going through the earthly atmosphere reaches the surface of the Earth. It should be remembered that the amount of such energy is smaller from the amount of energy reaching the orbit. Such reduction is called radiation attenuation and it is an effect of the processes of reflection, absorption and scattering which take place in the atmosphere. The attenuation of radiation intensity depends on the distance radiation covers in the atmosphere.

Solar radiation which reaches the Earth may be described using many different parameters. Three of them are most important: radiant flux density, insolation and sunshine duration.

**Sunshine duration** is a number of hours with directly visible solar radiation. It is a parameter describing main weather conditions, not solar energy resources. However, it is used in solar energetics to estimate conditions of system operation, e.g. to calculate operating hours of a circulating pump in the solar collector system. The average number of sunny hours in Rzeszow on the basis of measurements made in the years 2000-2015 is 1776.7 h; for comparison, a number of sunny hours in 2015 was 1998.8h. The greatest number of hours of sunshine is in summer months. The below chart presents averages for specific months in the last 15 years and an average of sunshine duration in specific months in 2015 (table 1).

**Radiant flux density expresses** a sum of radiation energy flux reaching a unit of surface depending on the time of the day and the season of the year. A unit of that quantity is W/m². In Poland, depending on the geographical situation, potential sums of total radiation fluctuate between 2999 MJ/m² (833 kWh/m²) and 4316 MJ/m² (1199 kWh/m²).
Solar radiation intensity is an instantaneous value of power density of solar radiation falling during 1 second on an area of one m², perpendicular to the direction of radiation. Such value is usually expressed in [W/m²], [3].

The amount of energy reaching collectors in December when the sky is cloudless and when the Sun is at the lowest position above the horizon (16.2° – upper culmination for the latitude of Rzeszów) is the littlest. However, in June when the Sun is at the highest point above the horizon (62.88° – upper culmination for the latitude of Rzeszów), it is the greatest. A difference in the amount of solar energy which reaches the surface of the Earth between the two periods is just contrasting. For the analyzed latitude, approx. 6 times less energy reaches the upper limit of the atmosphere in December than in June. Near the surface of the Earth such contrasts are even larger. It results not only from seasonal changes in the angle of incidence of sun rays but also cloud cover, the length of the day, humidity and air haze (presence of aerosols and water vapour which affect the absorptive properties and transparency of the air). Also, cloud cover and precipitation have an influence on the amount of energy reaching the surface of solar collectors.

Changing weather conditions cause a change in the solar radiation spectrum. Highest values of intensity of approx. 1000W/m² of radiation are when the sky is cloudless, and they fall down to approx. 100 W/m² when it is overcast, [7-9].

### Table 1. Number of sunny hours in Rzeszow

| month     | January | February | March | April | May       | June | July | August | September | October | November | December |
|-----------|---------|----------|-------|-------|----------|------|------|--------|-----------|---------|----------|----------|
| year      | 2000/2015 | 45  | 66   | 127   | 192   | 236  | 235.4 | 235    | 250.9  | 172.3  | 125.6    | 53.2     |
| 2015      | 66  | 74   | 153   | 201   | 188  | 268.6 | 295.8  | 310.9  | 163.9  | 122.9  | 68.8     | 76.1     |

3. **Methodology of calculation**

When analysing solar power systems, an important aspect is to determine a flux of energy which reaches the surface of a collector. It is connected with the position of the collector surface relative to the Sun. The position of a specific surface relative to the Sun may be determined by using basic notions.

When describing mutual relations between the positions of the Earth and the Sun, an essential parameter is an hour angle (ω). It is an angle between a plane of incidence of sun rays at a given moment and a plane of incidence of sun rays at noon. It takes negative values in the morning and positive value in the afternoon. At 12:00 of the astronomical time such value is 0°. A change of the hour angle by 15° is equal to a change of time by one hour.

The solar declination varies from -23.44° at the (northern hemisphere) winter solstice, through 0° at the vernal equinox, to +23.44° at the summer solstice. The variation in solar declination is the astronomical description of the Sun going south (in the northern hemisphere) for the winter.

An amount of radiant flux which reaches surfaces exposed to radiation depends on declination.

Another parameter are azimuth and elevation. Azimuth and elevation is an angular coordinate system for locating positions in the sky. Azimuth is measured clockwise from true north to the point on the horizon directly below the object. Elevation (angle α) is measured vertically from that point on the horizon up to the object. Because our planet rotates, azimuth and elevation numbers for stars and planets are constantly changing with time and with the observer's location on earth.

Angle α describes the relation:

\[ \sin \alpha = \cos \varphi \cdot \cos \delta \cdot \cos \omega + \sin \varphi \cdot \sin \delta \]  

(1)
where:

\( \phi \) - latitude; (for Poland it is \( \phi = 50^\circ \)),

\( \omega \) - hour angle (the angle between the plane on which sun rays fall at a given moment and the plane on which sun rays fall at noon),

\( \delta \) - declination (the angle at which sun rays fall on the surface of the Earth).

Declination is determined by the following formula:

\[
\delta = 23,45^\circ \cdot \sin[(n + 284) \cdot \frac{360}{365}]
\]

(2)

where:

\( n \) - subsequent day of the year.

Hour angle \( \omega \) is determined as:

\[
\omega = (12 - t_s) \cdot \frac{360}{24}
\]

(3)

where:

\( t_s \) - actual solar time

During one hour of solar time the Sun moves angularly by 15\(^\circ\). So the actual solar time may be calculating using the following formula:

\[
t_s = t_m + (t_s - \frac{L}{15}) + \frac{E}{60}
\]

(4)

where:

\( t_m \) - actual time in Poland [h],

\( t_s \) - difference between the local time zone and the Greenwich meridian; \( t_s = 2h \),

\( L \) - longitude where the measurements were carried out; \( L = 22^\circ \),

\( E \) - adjustment which considers irregularity of earth's rotation in a year; it is assumed that it may be disregarded. \( E = \pm 15\text{min.} \)

A dihedral angle between the north part of the meridian of reference and a given horizontal direction is called the azimuth of the Sun (\( \alpha_s \)). The azimuth of the Sun is determined using the following formula:

\[
\cos \alpha_s = \frac{\sin \alpha \cdot \sin \phi - \sin \delta}{\cos \alpha \cdot \cos \phi}
\]

(5)

The azimuth of sunrise and sunset may be calculated as follows:

\[
\omega_s = \arccos(-\tan \delta \cdot \tan \phi)
\]

(6)

For a surface inclined in any way, an angle of sunrise and sunset is determined as:

\[
\omega_s = \arccos(-\tan \delta \cdot \tan(\phi - \beta))
\]

(7)

where:

\( \beta \) - angle of inclination of collectors. \( \beta = 45^\circ \).

An angle of incidence of sun rays on a surface with any inclination is determined by the following formula:

\[
\cos \theta_i = \sin \delta \cdot (\sin \phi \cdot \sin \beta - \cos \phi \cdot \sin \beta \cdot \cos \alpha_s) + \cos \delta \cdot \sin \beta \cdot \sin \alpha_s \cdot \sin \omega +
\]
\[
+ \left( \cos \varphi \cdot \cos \beta + \sin \varphi \cdot \sin \beta \cdot \cos A_p \right) \cdot \cos \delta \cdot \cos \omega
\]  

(8)

where:

- \( A_p \) - angle between the meridian and the line perpendicular to collectors' limits; \( A_p = 23^\circ \).

A number of sunny days is determined by the following formula:

\[
n_s = 2 \cdot \frac{\omega_s}{15}
\]

(9)

Additionally, the following formula for collector efficiency was used in calculations:

\[
\eta = \eta_0 - \frac{a_1 \cdot (T_m - T_a)}{G} - \frac{a_2 \cdot (T_m - T_a)^2}{G}
\]

(10)

where:

- \( \eta_0 \) - collector optical efficiency in relation to the aperture area,
- \( a_1 \) [W/(m\(^2\)-K)] - collector loss factor in relation to the aperture area,
- \( a_2 \) [W/(m\(^2\)-K\(^2\))] - collector loss factor in relation to the aperture area,
- \( T_m \) [K] - collector temperature,
- \( T_a \) [K] - ambient temperature outside the collector,
- \( G \) [W/m\(^2\)] - assumed value of solar radiation intensity in Poland under conditions of averagely sunny weather with mist and light cloud cover.

To calculate power obtained from a set of collectors with determined solar energy intensity, the following formula was used:

\[
P = A \cdot \left[ \eta_0 \cdot G - a_1 \cdot (T_m - T_a) - a_2 \cdot (T_m - T_a)^2 \right]
\]

(11)

where: \( A \) - collector surface area [6,8].

4. Methodology and scope of research

In year 2015 at the Rzeszów University of Technology, a series of measurements was taken to calculate parameters of a solar system with a flat collector (figure 1). The solar collector is installed on the roof of building over the room, it is pointed to the south-west and situated at an angle of 45\(^\circ\) to the surface of the Earth. Measurements of total solar radiation was performed using solarimeter Pyra LP 02. Pyranometer measures the radiance on a plane surface (W/m\(^2\)). Measured irradiance is the result of the sum of direct solar irradiance and of diffuse irradiance. LP PYRA 02 is a First Class pyranometer in Accordance with ISO 9060 standard Pyranometers. LP PYRA 02 are well suited for the measurement of incoming global solar radiation (0.3\(\mu\)m ÷ 3 micrometer spectral range).

For the analysis, measurements made on 21 March (spring solstice), 21 June, 21 September and 21 December (winter solstice) 2015 were taken into account. A value of direct solar radiation intensity for measurements made between 9:00 and 15:00 fluctuated between 66.71 W/m\(^2\) in September when the sky was overcast and 999 W/m\(^2\) in June when the sky was cloudless.

5. Results and discussions

The table below presents results of measured values of solar radiation intensity on 21 September 2015 (between 11:10 and 12:34) for extreme values of radiation intensity. Measurements were red every 4 minutes with changing cloud cover. The highest recorded value of solar radiation intensity was 855 W/m\(^2\) when the sky was cloudless at noon. Single clouds decreased such value by approx. 200 W/m\(^2\). Whereas when the sky was overcast, the value fluctuated between 149 W/m\(^2\) at 11:10 and 318 W/m\(^2\) at 11:40. After that time the sky was partly cloudy or cloudless. The measurements made served for calculating the value of the angle of sunrise (7), the azimuth (5), the declination of the Sun (2) and the angle of incidence on a freely adjusted plane. Moreover, collector efficiency [10] and power obtained from the collector were calculated (11).
Figure 1. Schema of the solar system: 1 – vent; 2 – temperature sensor; 3 – solar collector panel; 4 – solar water tank 100 l; 5 – expansion vessel 35 l; 6 – working station; 7 – drain valve; 8 – expansion vessel 8 l. 9 – display.

Table 2. Results of measurements and calculations made on 21 September.

| Time  | $I^a$ [W/m²] | $T_m^b$ [°C] | $T_a^c$ [°C] | $\eta^d$ [-] | $P^e$ [W] | $\delta^f$ [°] | $\omega_s^g$ | $\alpha^h$ | $\cos \theta_t^i$ |
|-------|--------------|--------------|--------------|--------------|------------|--------------|-------------|-----------|----------------|
| 11:10 | 149          | 32.1         | 19.4         | 0.625        | 463.04     | 0.74         | 175.20      | 40.61     | 0.651         |
| 11:18 | 158          | 31.5         | 19.9         | 0.626        | 463.82     | 0.74         | 177.83      | 40.71     | 0.652         |
| 11:22 | 455          | 32.9         | 18.4         | 0.606        | 448.88     | 0.74         | 180.47      | 40.71     | 0.652         |
| 11:26 | 246          | 35.2         | 20.4         | 0.603        | 446.5      | 0.74         | 183.11      | 40.66     | 0.652         |
| 11:34 | 272          | 35.0         | 22.2         | 0.624        | 462.26     | 0.74         | 187.05      | 40.49     | 0.649         |
| 11:46 | 327          | 35.6         | 22.4         | 0.620        | 459.12     | 0.74         | 190.97      | 40.19     | 0.645         |
| 11:54 | 420          | 38.4         | 26.4         | 0.632        | 468.49     | 0.73         | 193.26      | 40.05     | 0.644         |
| 11:58 | 372          | 37.7         | 27.1         | 0.647        | 479.3      | 0.73         | 196.55      | 39.91     | 0.642         |
| 12:02 | 525          | 38.8         | 26.9         | 0.633        | 469.26     | 0.73         | 199.84      | 39.75     | 0.639         |
| 12:10 | 533          | 37.0         | 26.9         | 0.652        | 483.13     | 0.73         | 196.12      | 39.58     | 0.637         |
| 12:14 | 855          | 42.9         | 37.0         | 0.695        | 514.67     | 0.73         | 197.39      | 39.39     | 0.635         |
| 12:18 | 709          | 42.2         | 36.2         | 0.694        | 513.93     | 0.73         | 198.66      | 39.19     | 0.632         |
| 12:22 | 879          | 44.3         | 39.2         | 0.703        | 520.55     | 0.73         | 199.92      | 38.98     | 0.629         |
| 12:26 | 302          | 47.0         | 34.2         | 0.624        | 462.26     | 0.73         | 201.17      | 38.75     | 0.626         |
| 12:30 | 203          | 38.7         | 28.0         | 0.646        | 478.53     | 0.72         | 202.41      | 38.51     | 0.623         |
| 12:34 | 610          | 42.0         | 30.5         | 0.638        | 472.36     | 0.72         | 203.64      | 38.26     | 0.619         |
| 12:38 | 176          | 40.2         | 31.8         | 0.670        | 496.03     | 0.72         |            |           |               |

$^a$I - intensity of radiation,
$^b$T<sub>m</sub> - temperature of the collector,
$^c$T<sub>a</sub> - temperature of the tank,
$^d$η - the efficiency of the solar collector,
$^e$P - power solar collector,
$^f$δ - declination of the Sun,
$^g$ω<sub>s</sub> - solar azimuth,
$^h$α - solar elevation,
$^i$cosθ<sub>t</sub> - cosine of solar zenith angle.
On the basis of the results obtained, charts were prepared. Chart 1 shows values of the azimuth of the Sun on 21.03, 21.06, 21.09, 21.12 between 10:00 and 15:00 (figure 2). Chart 2 presents a value of the angle of incidence of the Sun on 21.03, 21.06, 21.09, 21.12 between 10:00 and 15:00 (figure 3). Chart 3 shows a value of the height of the Sun on 21.03, 21.06, 21.09, 21.12 between 10:00 and 15:00 (figure 4).

**Figure 2.** Values of the azimuth of the Sun on 21.09, 21.03, 21.06, 21.12 between 10:00 and 15:00

**Figure 3.** Value of the angle of incidence of the Sun on 21.09, 21.03, 21.06, 21.12 between 10:00 and 15:00

**Figure 4.** Value of the solar elevation on 21.09, 21.03, 21.06, 21.12 between 10:00 and 15:00
For comparison, Table 3 presents results of astronomical parameters of the Sun at 12 on 21 June, January, October and March. Four months representing different seasons of the year were chosen.

Table 3. Results of astronomical parameters of the Sun at 12 on 21 June, January, October and March.

| Date   | Declination of the Sun [°] | Solar Azimuth | Solar elevation | Cosine of solar zenith angle |
|--------|---------------------------|---------------|-----------------|----------------------------|
| 21.03  | 0.2                       | 186.90        | 39.98           | 0.642                      |
| 21.06  | 23.43                     | 193.52        | 62.88           | 0.890                      |
| 21.09  | 0.73                      | 191.53        | 40.13           | 0.645                      |
| 21.12  | -23.44                    | 187.27        | 16.26           | 0.280                      |

6. Conclusions

On the basis of the measurements conducted on 4 chosen days in different seasons of the year and calculations made, it was found that the collector acquired the largest amount of energy on 21.06. Moreover, it was found that the height of the Sun in December is the smallest. It is a result of the season of the year in which the distance the Sun covers on the sky is shorter, so the angle of sunrise is smaller. Such value was the highest between 11:00 and 12:00 and then it became smaller. The angle of incidence of solar radiation on a freely adjusted plane was the smallest in December, the largest in June. It increased each day between 11 and 12, then decreased.

Comparing solar radiation intensity on 21.03 and 21.09, the values were similar due to similar atmospheric conditions.

The highest instantaneous value of solar radiation was recorded on 21.06 when the sky was cloudless - 990 W/m². It was connected with the largest angle of sunrise. The lowest value of radiation was recorded on 21.09.2015. It was 66.71 kW/m². On that day the temperature of water in the tank was the lowest. It was 27.20°C and remained more or less the same.

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