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# EXTERNAL CONDITIONS FOR USING SOLAR ENERGY IN PHOTOVOLTAICS

A consideration connected with the possibilities of obtaining solar energy depending on external conditions, such as: the latitude φ, the solar declination δ, the hour angle ω was performed. The operation of photovoltaic modules in very cloudy conditions as well as under clear sky was taken into consideration. The results of the measurements of radiation power density that reaches the surface of the photovoltaic receiver for its different positions, for the geographic location of the cities of Poznań and Playa del Ingles and for different time periods (yearly and daily) are presented in a graphical form.

## 1. INTRODUCTION

The insolation conditions on the territory of Poland (49°-54,5°N) are similar to analogous conditions in most European countries [1, 2, 4, 5, 6]. The yearly illuminance value per unit area for most of the Polish territory can be estimated to amount to over 1000 kWh/m$^2$ (950 -1250 kWh/m$^2$). Coastal areas, including Gdańsk 1117 kWh/m$^2$ and Szczecin 1137 kWh/m,$^2$ are characterized with the most advantageous conditions in that respect. In central Poland and in the south, illuminance values are not much lower.

The annual distribution of solar radiation is characterized with irregularity. Spring and summer constitute over 75% of annual potential.

The number of sunny hours reaches 1 600 hours per year [7]. The number of solar activity hours on different days of the year fluctuates from 8 to 16. The fluctuation in the number of sunny hours applies also to different regions of the country which results from the impact of the latitude angle. For example, the insolation value for Kołobrzeg is 1624 hours per year, whereas for Zakopane the value is only 1467 hours per year.

Unfortunately, the share of the diffuse radiation element in the total radiation value is high, 50% on average, and even over 70% in winter [7].

Thus, the availability of solar resources is influenced by a number of external factors, such as the geographic location, time factors (within the period of a day

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and of a year), cloud cover, the number of sunny hours [3, 4, 8]. To sum up, it is, however, found that the solar energy potential in our country provides a lot of capabilities but requires appropriate utilization as well as neutralization of the disadvantageous external factors.

Determining the angle at which the sun rays fall on the surface of the receiver that guarantees maximal energy gains, but which is a function of many variables, is helpful in this context [1]:

$$\cos\Theta_{\beta} = \sin\delta\sin\varphi\sin\beta - \sin\delta\cos\varphi\sin\beta\cos\gamma +$$
$$+ \cos\delta\cos\varphi\cos\beta\cos\omega + \cos\delta\sin\varphi\sin\beta\cos\gamma\cos\omega +$$
$$+ \cos\delta\sin\beta\sin\gamma\sin\omega$$

where: φ-latitude angle, δ-solar declination angle, γ-receiver azimuth, that is the deflection angle with the local meridian measured in relation to the south, negative to the east, positive to the west, ω-hour angle, β-the inclination angle of the recipient in relation to the horizon.

Through modifying two of those values; β and γ, it is possible to manipulate the receiver so as to optimize the amount of energy obtained from the Sun. This was proved through theoretical considerations complemented with a computer simulation [1].

## 2. THE INFLUENCE OF THE LATITUDE ANGLE ON RADIATION POWER DENSITY

As it was demonstrated in [1, 8], the latitude angle has a considerable influence on the possibility of using solar energy. The awareness of this phenomenon will make it possible to use the positioning of the receiver in order to minimize the negative effects for the energy gain.

Table 1 presents examples of solar energy potential for a receiver positioned horizontally in selected geographic locations.

In order to confirm the theoretical considerations and the results of the computer simulation [1] regarding the influence of the latitude on the availability of solar energy, the authors conducted measurements of the values of radiation power density for two different geographic locations: in Poznań (Poland) 52°24'30"N, 16°56'3"E and for Playa del Ingles (Gran Canaria, Spain), 27°45'24"N and 15°34'43"W, Fig.1 [9].

The measurements were performed in the same time periods, days and hours, and for the same positioning.

Figures 2 and 3 present the radiation power density values obtained from the measurements, for example for the day of 6.08.2012, 18:00, taking into account the spatial optimization of the receiver with respect to the receiver inclination angle in relation to the horizon and the azimuth angle for the geographic locations analyzed, according to Fig. 1.

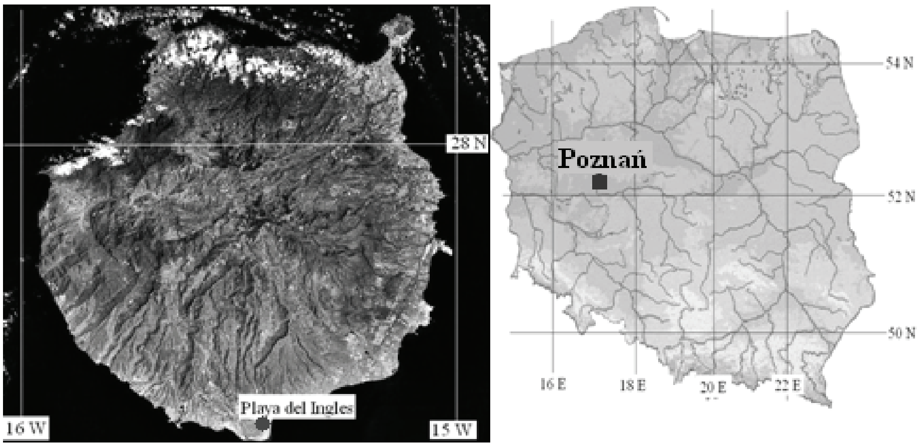


Fig. 1. Geographic location of the cities analyzed, included in the measurements of illuminance values

Table 1. Comparison of solar conditions for different locations [3]

| City | Geographic location | | | Total radiation [MJ/m$^2$/rok] | Number of sunny hours [h] |
|---|---|---|---|---|---|
| | Latitude | Longitude | AMSL height | | |
| Helsinki | 60° 19’ N | 24° 58’ E | 48 | 3495 | 1740 |
| St. Petersburg | 59° 18’ N | 30° 18’ E | 72 | 3369 | 1700 |
| Stockholm | 59° 21’ N | 18° 04’ E | 30 | 3479 | 1700 |
| Kaunas | 54° 53’ N | 23° 53’ E | 73 | 3744 | 1700 |
| Gdynia | 54° 31’ N | 18° 33’ E | 22 | 3667 | 1624 |
| Kołobrzeg | 54° 11’ N | 15° 35’ E | 16 | 3830 | 1618 |
| Suwałki | 54° 06’ N | 22° 57’ E | 193 | 3525 | 1577 |
| Mikołajki | 53° 47’ N | 21° 35’ E | 127 | 3636 | 1598 |
| Hamburg | 53° 39’ N | 10° 07’ E | 49 | 3421 | 1533 |
| Potsdam | 52° 23’ N | 13° 06’ E | 110 | 3643 | 1677 |
| Warsaw | 52° 16’ N | 20° 59’ E | 130 | 3477 | 1600 |
| London | 51° 31’ N | 0° 07’ W | 77 | 3402 | 1530 |
| Kiev | 50° 24’ N | 30° 27’ E | 121 | 4230 | 1877 |
| Zakopane | 49° 18’ N | 19° 57’ E | 857 | 3556 | 1464 |
| Paris | 48° 49’ N | 2° 30’ E | 50 | 4068 | 1658 |
| Vienna | 48° 15’ N | 16° 22’ E | 202 | 3881 | 1716 |
| Budapest | 47° 26’ N | 19° 11’ E | 130 | 4320 | 1830 |
| Rome | 41° 48’ N | 12° 35’ E | 131 | 4968 | 2445 |

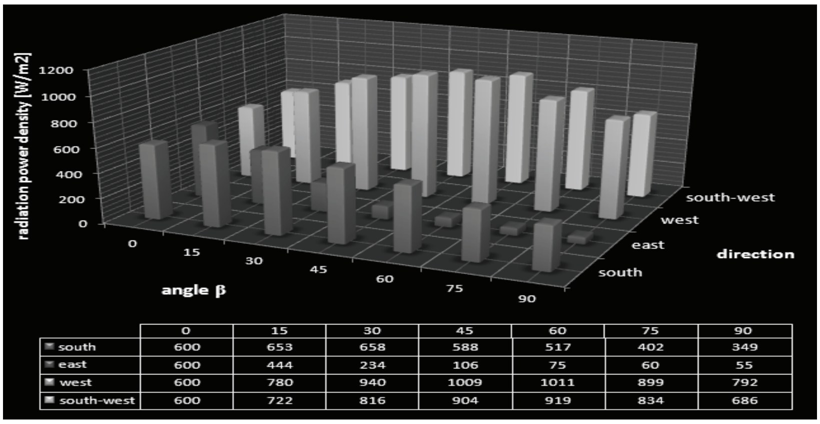


Fig. 2. Radiation power density as a function of the positioning angles for Playa del Ingles on 6.08.2012 at 18.00, on the basis of own measurements

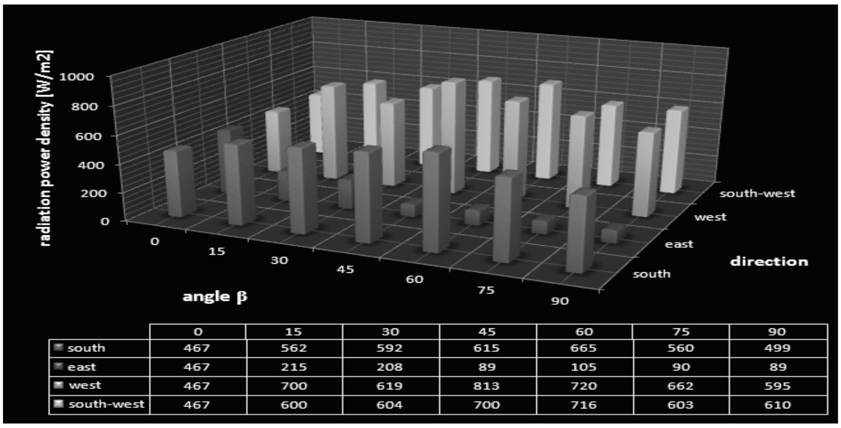


Fig. 3. Radiation power density as a function of the positioning angles in Poznań (Poland) on 6.08.2012 at 18.00, on the basis of own measurements

## 3. THE INFLUENCE OF THE SOLAR DECLINATION ANGLE ON RADIATION POWER DENSITY

The solar declination angle specifies the angular position of the Sun at astronomical noon time in relation to the plane of the equator. It is determined by the consecutive number of the day of the year. Thus, it is a variable value [4, 8].

Table 2 presents a summary of sample values of momentary power registered by the insolation sensor in one of the Silesian cities [12].

The authors conducted radiation power density measurements for locations that are equivalent to the geographic location of the city of Poznań in different seasons of the year (the declination angle) and at different hours of the day (the hour angle). The measurements were started in the period in which it is possible to obtain high illuminance values, that is – in May; they were continued in summer months as well as in autumn and winter months. This made it possible to perform a comparative analysis of the available solar energy potential in the analyzed periods of time.

Table 2. Radiation power density values of the solar radiation falling on the horizontal plane in the cities of the Silesian Voivodeship in particular days and moments in time [12]

| date/hour | 3.07.2009 | 12.07.2009 | 17.08.2009 | 20.09.2009 |
|---|---|---|---|---|
| 10:00 | 907 W | 323 W | 587 W | 522 W |
| 12:00 | 1209 W | 1256 W | 1005 W | 1063 W |
| 18:00 | 136 W | 147 W | 140 W | 62 W |

Sample results from the measurements performed on the horizontal plane for the selected days of 25.05., 9.07., 11.09., 1.10., 2012 and for 30.01.2013 and hours are presented on Figure 4.

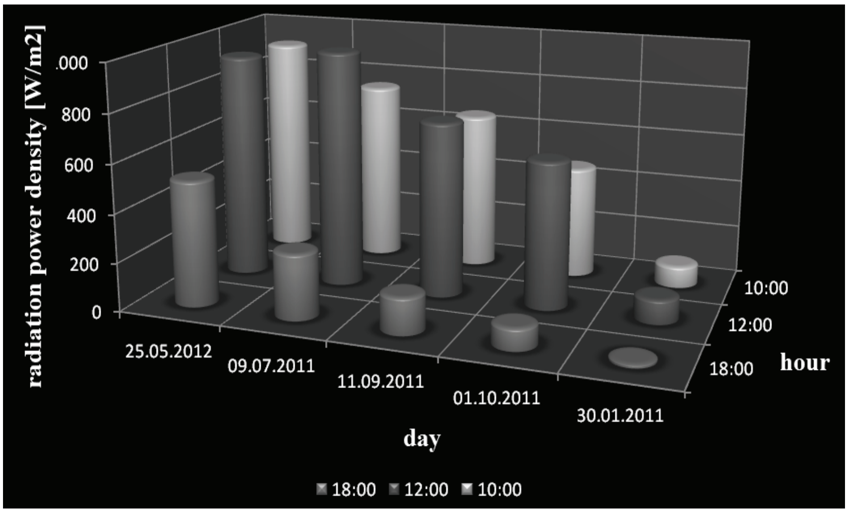


Fig. 4. Radiation power density values for the city of Poznań on the horizontal plane on specific days and at specific moments in time on the basis of own measurements

Figures 5 and 6 present the distribution of radiation power density per one second for different positions of the PV receiver for two selected days: 25 May and 25 July 2012 measured at 13:00.

Modifications with respect to the receiver inclination angle β to the horizontal and the azimuth angle γ were included.

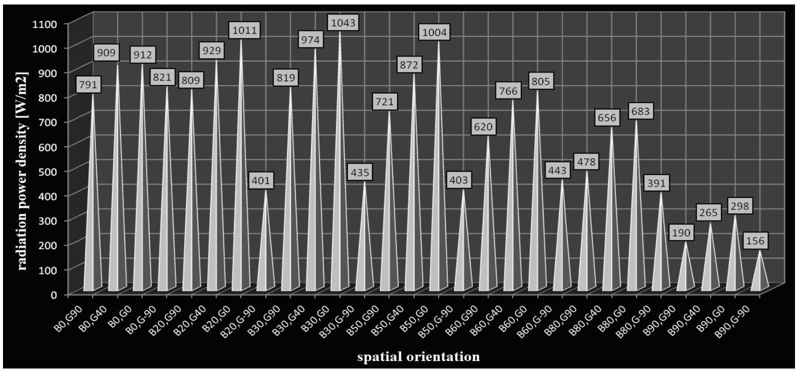


Fig. 5. The distribution of radiation power density per one second for different positions of the PV receiver with respect to the receiver inclination angle β to the horizontal and the azimuth angle γ, for 25 May 2012 (13.00), on the basis of own measurements

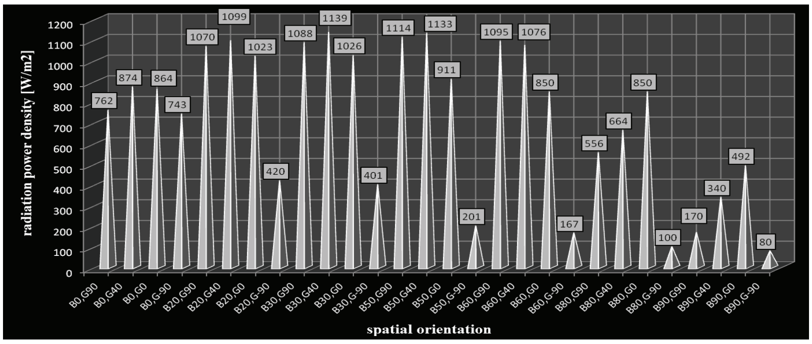


Fig. 6. The distribution of radiation power density per one second for different positions of the PV receiver with respect to the receiver inclination angle β to the horizontal and the azimuth angle γ, for 25 July 2012 (13.00), on the basis of own measurements

## 4. THE INFLUENCE OF THE HOUR ANGLE ON RADIATION POWER DENSITY

The hour angle is an astronomical coordinate in the equatorial system and it specifies the angular declination of the sunrise or sunset in relation to the local meridian [8]. It is calculated from the south to the west and 1 hour corresponds with 15 degrees. It equals zero for 12.00. In the morning, the time change of an hour in relation to 12.00 corresponds with a change of the angle by -15°. In the afternoon, on the other hand, the time change of an hour corresponds with a change of the angle ω by +15°.

Table 3 presents a comparison of the values of momentary power in specific hours of the day for the territory of Silesia on 3.07.2009 [12].

Table 3. Momentary power of insolation for the territory of Silesia on the horizontal plane as a function of the hours of the day on 03.07.2009

| hour | momentary power [W] |
|---|---|
| 8:00 | 132 |
| 9:00 | 291 |
| 10:00 | 907 |
| 11:00 | 875 |
| 12:00 | 1209 |
| 13:00 | 1301 |
| 14:00 | 1141 |
| 15:00 | 840 |
| 16:00 | 590 |
| 17:00 | 330 |
| 18:00 | 136 |
| 19:00 | 100 |
| 20:00 | 45 |
| 21:00 | 3 |

## 5. THE NUMBER OF SUNNY HOURS

A parameter that characterizes the possibility of using solar energy is the period of time for which it is available during the day, that is the number of sunny hours with the luminous energy density ≥120 W/m$^2$ [5, 7]. In our climate, this is not synonymous with the number of day hours (from the sunrise to the sunset). The countries that are located in low latitude areas are characterized with a shorter day but with a dominant number of sunny hours and that is why the ratio of sunny hours to the number of day hours is higher in those areas than in Central European climate with relatively infrequent periods of cloudy weather. In connection with the clear dominance of the direct radiation element in solar radiation, the insolation in those areas is much higher than in Poland. Table 4 presents a summary of the average number of sunny hours in the winter period (January), and Table 5, respectively, in the summer period (August), measured in the Ławica airport-Poznań [14].

Table 4. The number of sunny hours during the day (insolation) in January in the years 2000-2011

| year | 2000 | 2001 | 2002 | 2003 |
|---|---|---|---|---|
| [hours] | 4.3 | 2.5 | 3.5 | 2.4 |
| Availability [%] | 32 | 54 | 51 | 45 |
| year | 2004 | 2005 | 2006 | 2007 |
| [hours] | 2.2 | 2.7 | 3.4 | 1.9 |
| Availability [%] | 51 | 61 | 48 | 67 |
| year | 2008 | 2009 | 2010 | 2011 |
| [hours] | 2.9 | 3.4 | 3.4 | 2.0 |
| Availability [%] | 58 | 41 | 32 | 32 |

The averaged value for January ( 2000 - 2012) is 2.9 hours.

Table 5. The number of sunny hours during the day (insolation) in August in the years 2000-2011

| | | | | |
|---|---|---|---|---|
| year | 2000 | 2001 | 2002 | 2003 |
| [hours] | 8.6 | 8,2 | 8,2 | 9,0 |
| Availability [%] | 100 | 96 | 96 | 93 |
| year | 2004 | 2005 | 2006 | 2007 |
| [hours] | 8,1 | 9,4 | 6,8 | 8,2 |
| Availability [%] | 96 | 87 | 80 | 100 |
| year | 2008 | 2009 | 2010 | 2011 |
| [hours] | 7,4 | 10,7 | 7,3 | 8,4 |
| Availability [%] | 90 | 93 | 93 | 100 |

The averaged value for August ( 2000 - 2012) is 8.4 hours.

The number of sunny hours during the day (insolation) in January and in August in the years 2000-2011 with polynomial approximation are presented (Fig. 7).

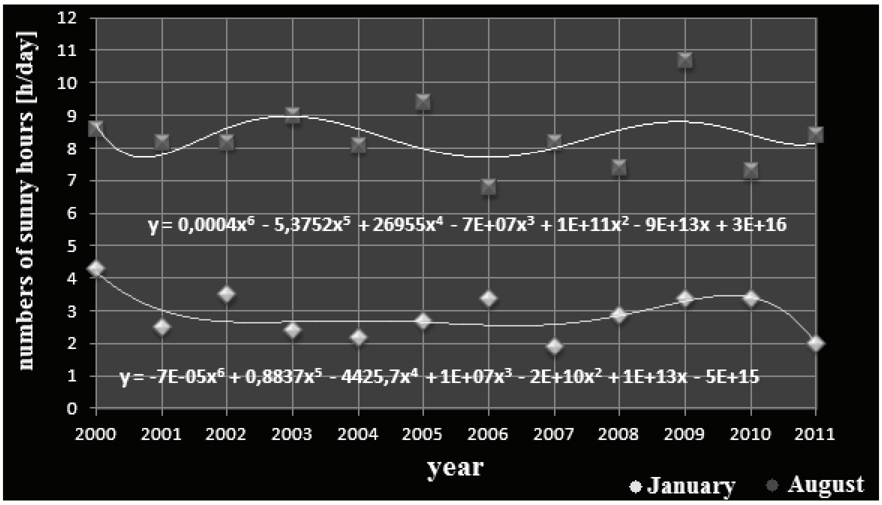


Fig.7. The number of sunny hours during the day (insolation) in January and in August in the years 2000-2011 with polynomial approximation

Table 6 presents the number of sunny hours during the day for particular months in Gran Canaria [13].

Table 6. The average number of sunny hours per day for particular months in Gran Canaria

| Month | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gran Canaria | 6 | 6 | 7 | 9 | 9 | 8 | 10 | 8 | 9 | No data | No data | No data |

## 6. CLOUD COVER

The characteristic features of the cloud cover in Poland include its variability in time throughout the year and relative stability for a given location. It is estimated that the cloudiest conditions exist in the north-east part of the country and the lowest level of averaged cloud cover per year can be observed in the south-west part of Poland. The remaining territory of the country demonstrates a certain level of monotony with that respect. On the basis of meteorological data it can be stated that the period characterized by the highest amount of cloud cover are winter months, from November to January. During this period, the amount of cloud cover in Poland is higher than in Austria or Hungary; however, it is considerably lower than in Russia. On the basis of many years of analysis of the data available, it was found [11], that the minimal cloud cover can be observed in May, July, and August.

The lower the latitude towards the equator, the lower the cloud cover level. On average, about 140 days a year can be described as cloudy and 40 days can be described as "bright". The remaining days are periods of average, temporarily variable cloud cover [10]. On the basis of own measurements of illuminance distribution, it was found that the highest level of cloud cover occurs round noon. The phenomenon occurred cyclically throughout the whole multi-day measurement task.

Figures 8 presents the results of measurements of PV module characteristics for horizontal positioning on selected days in May 2012 for a cloudless sky and for considerably cloudy conditions.

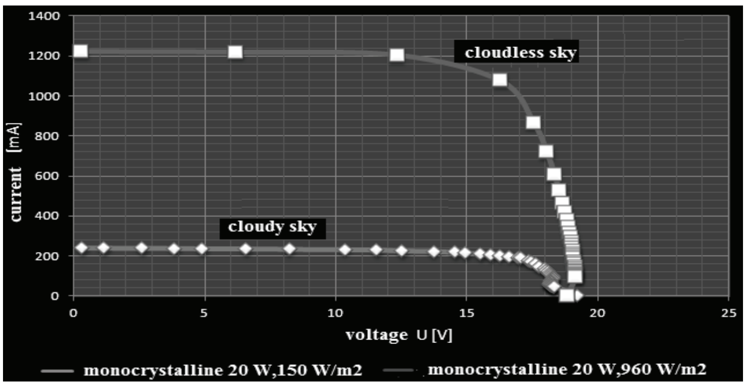


Fig. 8. The current and tensive characteristics of a monocrystalline USL 20 W module for cloudless and cloudy conditions

## 7. SUMMARY

On the basis of the measurements of radiation power density for a photovoltaic receiver as well as the comparative analyses performed as a function of its spatial positioning for different hours of the day, days of the year and locations, it was found that:

– the latitude angle has a considerable influence on the possibility of using solar energy which was determined on the basis of the results of measurements of radiation power density per second for two locations with different geographic location characteristics: Poznań (Poland) and Playa del Ingles (Spain), Fig. 2 and Fig. 3,
– the distribution of radiation power density depends considerably on the solar declination angle (the influence of the day of the year) and on the value of the hour angle (time of the day), which was demonstrated on Fig. 4, as well as Fig. 5 and Fig.6,
– the value of short circuit current for photovoltaic modules depends on the illuminance value of the sunrays falling on the module. The measurements showed that six-fold decrease in the solar energy density value results in almost six-fold decrease in the current value. Thus, the value of the power generated by the system changes,
– the maximum momentary power for geographic locations similar to the latitude of Poland is observed between 12:00-13:00, and the minimum values are observed at sunrise and sunset.,
– the number of sunny hours per year for Playa del Ingles located at the latitude that is twice lower than the latitude of Poznań, is over 40% higher. As it is presented in tables 4, 5 and 6 as well as on Fig. 7, the differences occur mainly during winter months,
– the lower the latitude, the higher the number of sunny hours, which can exceed 2500 h per year.

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