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ANALYSIS OF SOLAR ENERGY RESOURCES IN SOUTHERN POLAND FOR PHOTOVOLTAIC APPLICATIONS

ANALIZA STRUKTURY ZASOBÓW ENERGII SŁONECZNEJ OBSZARU POLSKI POŁUDNIOWEJ DO ZASTOSOWAŃ FOTOWOLTAICZNYCH

Abstract: The article presents an analysis of the resources and the structure of the solar energy in the area of Southern Poland on the basis of complete meteorological data from the AGH University of Science and Technology in Krakow in 2009. An analysis attempt of its use for photovoltaic conversion using different modules with different spectral characteristics of absorbers was made. These latest methods for characterizing the structure of solar energy resources such as: distributions throughout the year: sky clearness or cloudiness indexes, the average values of photon energy (APE) and the contents of the useful fraction (UF) of the solar spectrum, are not yet widely known and used as in Poland and in other EU countries, despite the fact that most accurately determine the spectral matching factor for the chosen photovoltaic module. Due to the need for a very expensive measuring equipment, are used only by a few laboratories in the European Union, such as CREST (***C****entre for* ***R****enewable* ***E****nergy* ***S****ystems* ***T****echnology*) in the UK. The article presents - developed and used in the Opole University - a new low-cost method for determining of the spectrum with the use of above-mentioned indexes, including APE and UF, without buying an expensive spectroradiometer, which gives comparable results.

Keywords: solar radiation spectrum, insolation, sky clearness index, diffused component content index, average photon energy (APE), useful fractions (UF), solar energy, photovoltaics

Introduction

In recent years all over the world there is increasing interest in alternative, environmental clean sources of electricity. The largest of these sources, and at the same time practically unlimited and widely available, is the energy of solar radiation. The development of solar energy is mainly concentrated around the technologies using photothermal and photovoltaic conversion. Photovoltaic conversion is the most perfect way

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to process solar energy into electricity, as it is a direct conversion. This method is highly popularized worldwide. Accurate information about the structure and resources of the solar radiation is essential for the proper design of a photovoltaic system, and the proper estimation of energy yield in specific climatic conditions.

The rest of the paper presents the results of analyses of resources and the structure of solar radiation in southern Polish territory for the purpose of conversion in photovoltaic modules made of different materials and different technologies. The aim of the joint research at the Opole University and AGH University of Science and Technology is developing the so-called, low-cost renewable energy technologies. Technology for which the performance factor of energy produced in photovoltaic systems in relation to the purchase cost of 1 W_p power station is the largest in our geographical and climatic conditions.

Description of measurement system - meteorological station AGH in Krakow

Weather station (Fig. 1) recording weather and lighting parameters located on the roof of the building C-3 (approximately 25 m above ground level), located at the intersection of ul. Czarnowiejska and al. Mickiewicza in Krakow [1]. It is in close proximity to the test photovoltaic systems up and running continuously since the beginning of 2006. It was built largely on the basis of the unit of the German company Theodor Friedrichs & Co.: datalogger COMBILOG 1020, thermohygrometer, barometer and wind speed and direction sensors. For the measurement of solar radiation using two pyranometers CM-21 Kipp & Zonen, and the study of its structure - suntracker STR-22 of Japanese company EKO with an equivalent shading system. Later in its work, it has been retrofitted with Ocean Optics HR4000 photospectometer recording light spectrum of λ = 200÷1100 nm. Due to the nature of the device, however it is not used for continuous measurement.

Fig. 1. Specialized weather station on the roof of Building C-3, AGH Krakow

Station records the following meteorological parameters:

- ambient temperature,
- relative humidity,
- pressure,
- wind speed,
- wind direction,
- the total value of solar radiation in the horizontal plane,
- the value of diffused solar radiation in the horizontal plane.

These parameters are measured every two seconds, and after that averaged and recorded at 5-minute intervals. With an additional SRAM memory card, datalogger is able to store measurements with nearly 3-month work period. Once a month, the data is retrieved from the logger to a PC via a serial RS-485 bus. The results are in ASCII text file in which each line corresponds to one record averaged measurements. These files are further processed into formats that facilitate their analysis, *eg* in the PVSyst. For the study described in this article select the measurement data collected in 2009, because their level of completeness is 99.6%.

Distribution of the irradiation

Table 1 summarizes the average monthly values of the energy of radiation on the horizontal plane in AGH-Krakow area for 2009 originating from: a) a global (the total), and b) a diffused component of solar radiation. However, histogram of the daily values of irradiation, occurring in 2009, AGH Krakow area is shown in Figure 2.

Table 1

Summary of monthly values (in the plane of the horizon) of the solar radiation energy: total (global), diffused and diffused component content index, AGH Krakow area in 2009

Month	**Global irradiation E_0 [kWh/m^2]**	**Diffused irradiation E_S [kWh/m^2]**	$k_{S/0}$
January	22.1	15.4	0.70
February	33.3	27.6	0.83
March	57	40.6	0.71
April	157.8	52.9	0.33
May	163.4	69.6	0.43
June	137.6	72.8	0.53
July	188.7	74.3	0.39
August	146.1	57.3	0.39
September	103.2	47.6	0.46
October	41.9	29.0	0.69
November	29.7	16.3	0.55
December	13.3	10.4	0.78
2009	1094.2	513.7	0.47

The histogram shows that the test area was characterized by the presence of a large number of cloudy days with insolation not exceeding 800 Wh/m^2, which accounted for more than 24.5% of the monitoring period. They are mostly a day MIMT (*Medium Irradiation, High Temperature*) or even LILT (*Low Irradiation, Low Temperature*) [2, 3] for the period of autumn and winter (from October to March). During the six months only 18% of the annual energy radiation (see Table 1), reaches the module. Then they are very difficult conditions for photovoltaic energy conversion, and energy needs increased (the need of heating, lighting for a long time because of the short days and frequent heavy overcast and reheating the water from the lower temperature). In addition, during the monitoring period were 35.9% of cloudy days with irradiation in the range of 800 to 3200 Wh/m^2. These are the days of the typical weather failures occurring in the entire period of spring and autumn. Then median[4] exceeds 1.6 kWh/m^2, in which typical modern PV inverter already operates with an efficiency of up to 98% of its maximum efficiency [4-6], and a typical PV system already exceeds 75% of its nominal performance [7, 8]. To different category can be classified so-called sunny and very sunny days (like HIHT - High Irradiation, High Temperature), which are respectively 18.6 and 21% of the days monitored. They occur during the spring and summer, in which are the ideal conditions for the operation of photovoltaic systems. Since the number of these days largely depends the value of generated energy in the PV system [7].

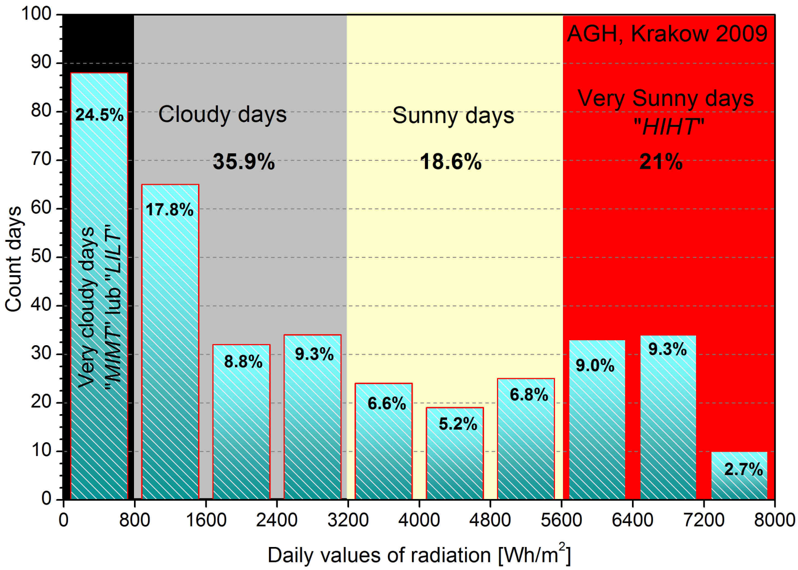

Fig. 2. Histogram of the daily values of irradiation, occurring in 2009, AGH Krakow area

Distribution of temperature and intensity of solar radiation

Figure 3a shows the distribution of average ambient temperatures in 2009 for the area of Krakow. One may notice the lack of symmetry of hourly temperature distribution. In summer days are characteristic cooler mornings and significant warming in the afternoon and evening hours.

However, Figure 3b shows the distribution of intensity of solar radiation on the horizon surface at the testing site. Note the wide range of changes in both the intensity of the radiation, as well as the time of solar radiation. The data are the basis to determine the

[4] The expected value of the distribution of insolation

so-called insolation of area, *ie* determine the average number of hours of daily activity of the Sun in different months of the year, *enough*[5] to operate the PV system.

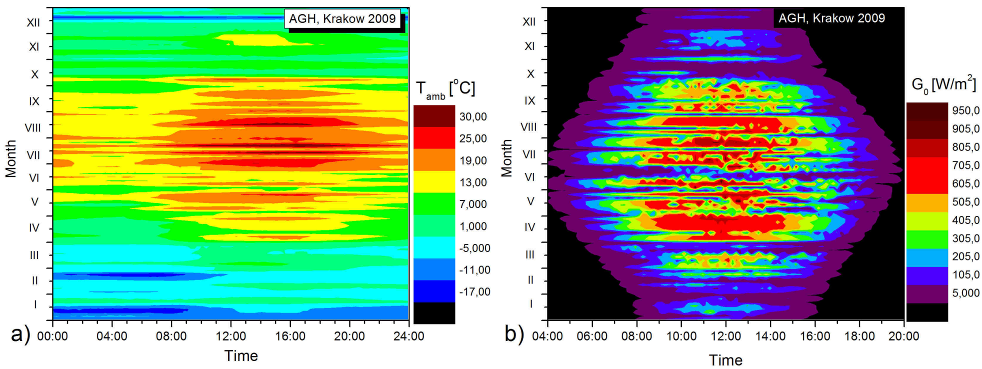

Fig. 3. Distribution of daily values of: a) ambient temperature and b) intensity of solar radiation occurring in the AGH in Krakow in 2009

Distribution of values diffused component content index of solar radiation

The relationship between the intensity of solar radiation incident on the earth's surface, and reaching into the upper atmosphere in the plane of the horizon is a measure of the transparency of the atmosphere and is determined as the clearness index (k_{Tm}). This index translates directly to the contents of a diffused component of the global solar radiation incident on the surface of horizon, known in the literature as diffused component content index $k_{S/0}$ (see Figure 4).

For each day of month one could determine from integral values [9, 10]:

- daily atmosphere clearness index k_{Tm} as:

$$k_{Tm} = \frac{E_0(0)}{E_C(0)} \tag{1}$$

- daily diffuse component content index of solar radiation as:

$$k_{S/0} = \frac{E_S(0)}{E_0(0)} \tag{2}$$

where: $E_C(0)$ - average daily value of insolation energy in specific month in higher layer of atmosphere in horizontal plane, $E_0(0)$ - daily value of insolation energy, $E_S(0)$ - daily value of insolation energy from diffuse component.

Similarly as in the case of daily values of indexes, temporary values of *atmosphere clearness* (*transparency*) and *diffuse component content* indexes could be computed. It is

[5] Typical photovoltaic inverter has a characteristic threshold of DC input power connected to the area of this work at maximum efficiency. For properly designed PV system that threshold inverter DC input power corresponds to value of solar radiation ≈ 200 W/m^2. Then a typical efficiency of the inverter is already above 95% of its maximum efficiency.

made by substitution in equations (1) and (2) daily energy values by temporary values of solar radiation intensity and then the equations take form, respectively:

$$k_{Tm}(t) = \frac{G_0(t)}{G_C(0) / AMp(t)} \tag{3}$$

$$k_{S/0}(t) = \frac{G_S(t)}{G_0(0)} \tag{4}$$

Solar radiation intensity $G_C(0)$ in higher layers of atmosphere in plane of horizon for specified day in year is described [9, 11] by:

$$G_C(0) = E_C^0 \cdot \varepsilon \tag{5}$$

$$\varepsilon = 1 + 0.033 \cdot \cos\left(\frac{360 \cdot dn}{365}\right) \tag{6}$$

where: E_C^0 - solar constant (1367 W/m^2), *dn* - number of day in year, *ie* January the 1st = 1, February the 1st = 32, etc. Parameter *AMp*(*t*) (Air Mass) in equations (3) and (4) is value of real mass of air given by Kaston and Young in 1989 in the form [12]:

$$AMp(t) = \frac{p}{p_0} \cdot \left[\cos(\Theta + 0.50572 \cdot \left(96.079950^o - \Theta\right)^{-1.6364}\right]^{-1} \tag{7}$$

Mutual connections of daily indexes defined according to (1) and (2) were shown in Figure 4a, while in Figure 4b was presented monthly values for Warsaw (Warszawa), Poland.

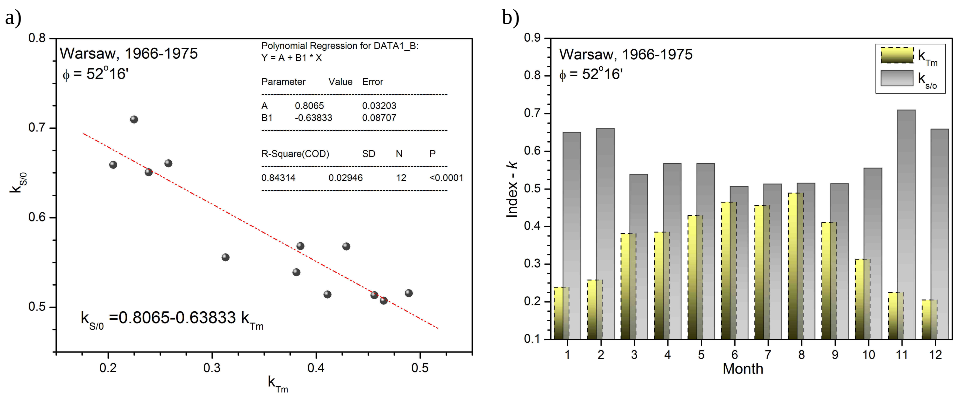

Fig. 4. Graphs of: a) in the daily value of the irradiation as a function of index, b) diffused component content and atmosphere clearness indexes for each month of the year. The graph is made on the basis of averaged data for the years 1966-1975, published in the European Solar Radiation Atlas for Warsaw [13]

Figures 5 a-i are examples of the daily value of the atmosphere clearness and diffused component content in the global solar radiation values occurring in Krakow for a few days with different values of daily irradiation.

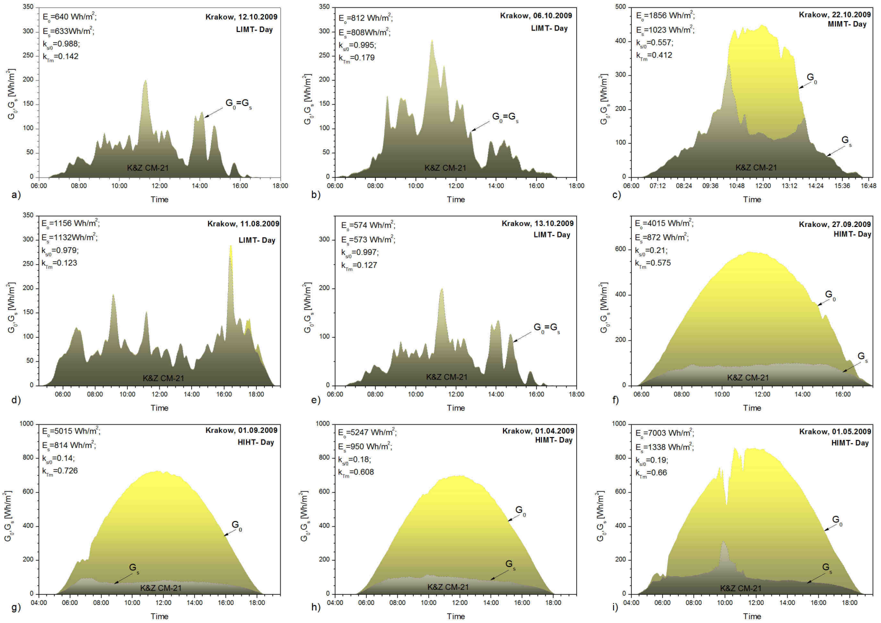

Fig. 5. Global solar radiation intensity and related to it indexes of atmosphere clearness and diffuse component content for days with different values of insolation. Investigations were carried out in Cracow (Krakow), Poland for different days

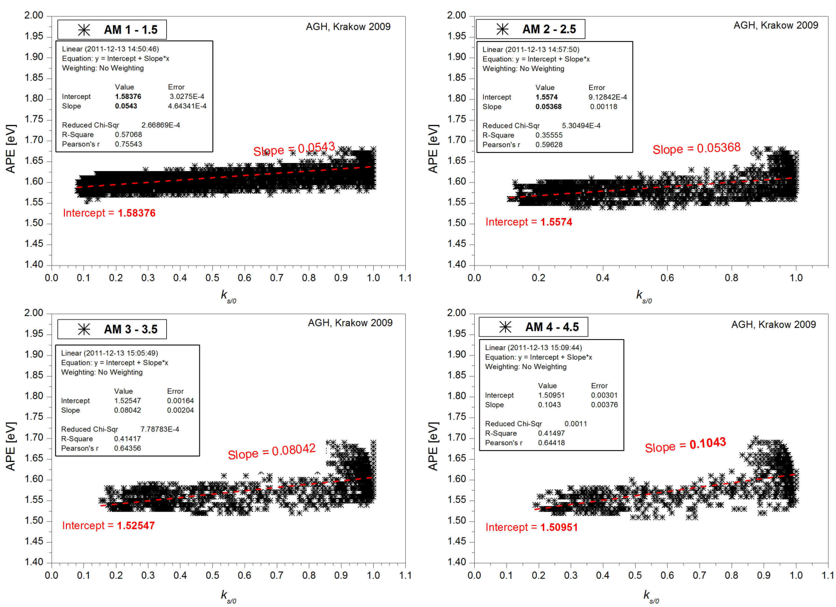

Fig. 6. The average photon energy (APE) of solar radiation (at a surface of horizon) dependence on diffused component content index $k_{S/0}$ for different ranges of air mass values. The study was performed in the AGH Krakow area

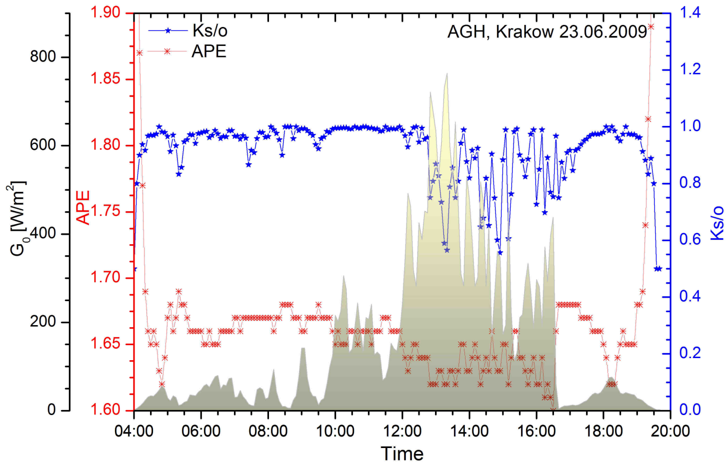

Fig. 7. Diffused component content index, average photon energy and global solar irradiance during cloudy day

Presented diffused component content and atmosphere clearness indexes are physically connected not only with solar radiation way through the Earth's atmosphere, which is dependent on the value of AM, but also on the chemical composition and the clouds.

Liu and Jordan have already shown [14] that, regardless of latitude, the global value of the intensity of solar radiation reaching the Earth's surface is directly dependent on this parameters. For this reason, these indexes can properly characterize the solar conditions for specified locations. It can also provide information about the average photon energy in the spectrum, and the structure of the solar spectrum (see Figures 6 and 7).

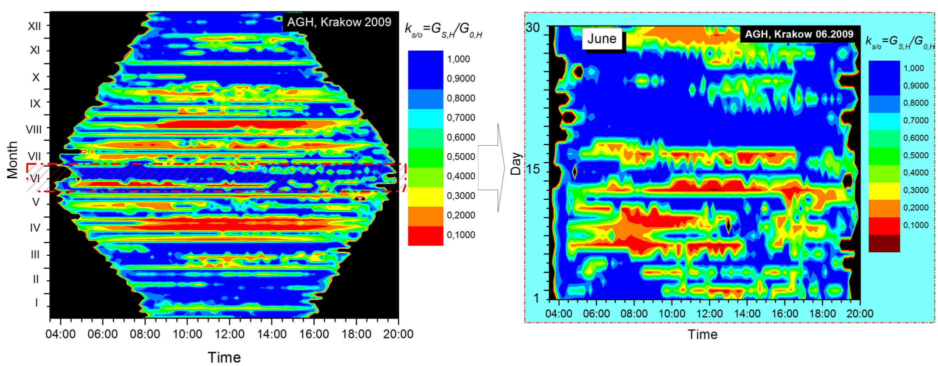

Fig. 8. Diffused component content index $k_{S/0}$ of solar radiation for AGH Krakow area in 2009. In zoomed window (blue field) - temporary values of the index in June 2009

Diffused component content index $k_{S/0}$ directly determines the level of cloud cover. It is very useful for a proper characterization of specified locations in order to select the optimal modules for climatic conditions. For example, in Figure 8 is shown the diffused component content index for the area of AGH Krakow 2009. In the enlarged graph (blue box) - are instantaneous values of index in June 2009.

Distributions the water vapour content and average values of photon energy

To calculate the pressure of saturated water vapour in the air is used equation (8) given by Gueymard and others [15-17]:

$$W = 0.1\left(0.4976 + 1.5265\frac{T_{\mathrm{amb}}}{273.15} + \exp\left[13.6897\frac{T_{\mathrm{amb}}}{273{,}15} - 14.9188\left(\frac{T_{\mathrm{amb}}}{273.15}\right)^3\right]\right)\times$$
$$\left(216.7\frac{RH}{100T_{\mathrm{amb}}}\exp\left[22.33 - 49.14\frac{100}{T_{\mathrm{amb}}} - 10.922\left(\frac{100}{T_{\mathrm{amb}}}\right)^2 - 0.39015\frac{100}{T_{\mathrm{amb}}}\right]\right) \tag{8}$$

where: W - estimated layer thickness of water vapour [cm], T_{amb} - ambient temperature [K], RH - relative humidity [%]. The results are shown in Figure 9.

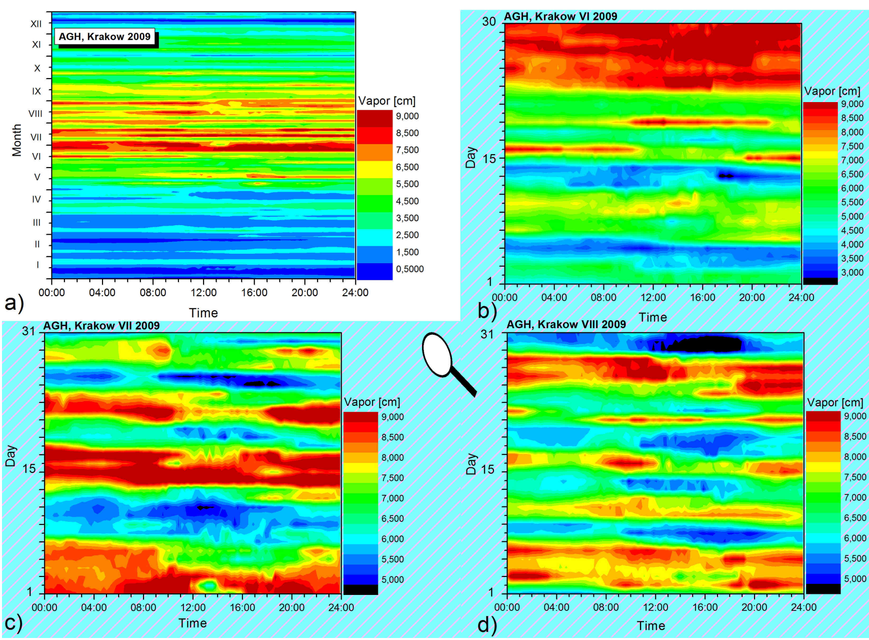

Fig. 9. Water vapour pressure in air for AGH Krakow area in 2009. In zoomed window (blue field) - temporary values for 3 summer months

The average photon energy value is determined by the measurement of the spectrum and is the quotient of the power and flux density in specified band recorded by the wide range receiver according to:

$$\mathrm{APE} = \frac{\int_{0.3\mu m}^{1.7\mu m} [N_{\mathrm{ph}}(\lambda) E_{\mathrm{ph}}(\lambda)] \mathrm{d}\lambda}{q \int_{0.3\mu m}^{1.7\mu m} N_{\mathrm{ph}}(\lambda) \mathrm{d}\lambda} \tag{9}$$

where: APE - average energy of solar radiation photons, q - electron charge, $N_{ph}(\lambda)$ - number of photons in sunlight in the wavelength λ, $E_{ph}(\lambda)$ - the energy of a photon in the wavelength λ.

The method of the solar radiation spectrum analysis using the average photon energy (APE) have several advantages. One of them is occurring very strong correlation between the average photon energy (APE), a range of short-term spectral characteristics of solar radiation, which strongly influences the efficiency of photovoltaic cells. In addition, the assuming as a unit of APE [eV], gives a full picture of the spectral matching of used absorber in PV cell/module to the solar spectrum. It should be noted that the APE value depends on the bandwidth integral of equation (9). This effect is shown in Table 2, which compares the obtained results of average photon energy (APE) of standard spectrum (STC, type of radiation AM1.5G), using a different bandwidth of measurement devices.

Table 2

APE of the standard spectrum evaluated from different spectral integration limits (own calculations)

	Measurement (integration) range [nm]	**APE [eV]**
1	300-4000	1.43
2	300-2500	1.48
3	300-1700	1.62
4	300-1100	1.86

The most appropriate definition of APE would relate to the average photon energy obtained from the measurements using full range of the solar spectrum 300-4000 nm, because the result gives the true value of APE. However, the measurement instruments in this range are very rare and unsuitable for use in long-term test cycles. Taking into account that the spectral range of solar radiation (distribution type AM1.5G) in the range from 300 to 2500 nm contains over 98% of its power so making measurements in this band is a very interesting, although there is also a very small number of units with this range. However, the measurements made in the wavelength range up to 1700 nm can be easily extended to 2500 nm with sufficient precision modelling - for example, method of measuring range extending from 300-1100 nm silicon sensor range spectroradiometer, up to 4000 nm, has been recently developed by NREL (***N****ational* ***R****enewable* ***E****nergy* ***L****aboratory* - Golden, Colorado, USA) [18]. Unchallenged rule is that the most reliable measurement values are based purely on the measurements. Therefore, the measurement system used in the CREST (***C****entre for* ***R****enewable* ***E****nergy* ***S****ystems* ***T****echnology*) measures the spectrum of radiation in the spectral range 300-1700 nm, without the use of additional procedures, and the result is given indicating the width of the band.

Figure 10 a,b shows the correlation between the APE and AM factor for cloudless day. A comparison of Figure 10a and b very clearly shows the impact of the measurement range of the instrument (*ie*, the range of integration) on the obtained APE values.

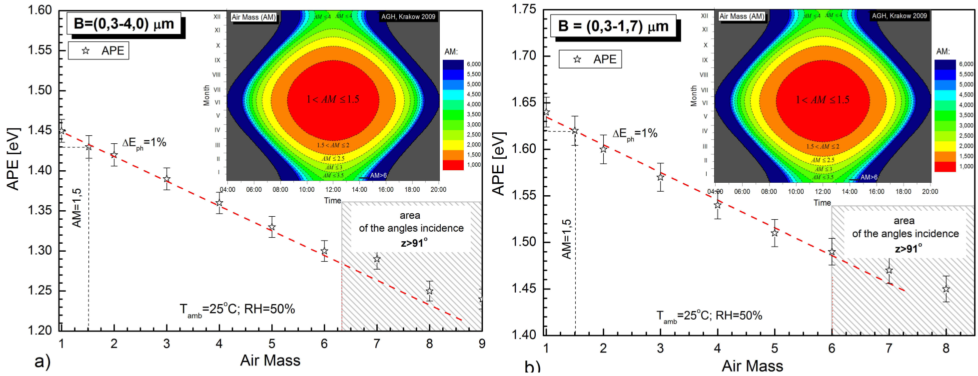

Fig. 10. Dependence between the APE and AM factor for cloudless day, after integration: a) in range (0.3÷4) µm, and b) in range (0.3÷1.7) µm

In this article, the average photon energy of solar radiation in horizontal plane and plane of array (POA) is determined by using the program developed at the University of Opole SolarSpectrum [19] used to determine the spectral distribution of solar radiation on the basis of instantaneous measurement data from a local weather station. Corresponding to this program *ddl* library made it possible to perform automated research/calculations. To allow verification of the correctness of the APE values (*ie* validation of results), it is assumed the same as in the CREST range of integration/apparatus (300÷1700 nm). Used in the Solar Spectrum model to creation of the spectrum, uses of codes SEDES2 by Nann and Bakenfelder [20], which are modified version of the SPECTRAL2 by Bird and Riordan (1986) [21], using the Perez model to determine the value of the diffused component on plane of array of modules (POA) [22, 23] and with the addition of an empirical model for modifying the spectrum of clouded day. Used modifier for overcast day is a function of wavelength, air mass, and proportion of broadband global irradiance: measured in the horizontal plane and the estimated (designated) spectral distribution for clear sky. So made the simulator calculates the spectrum of solar radiation in the range 300 to 2500 nm with an acceptable accuracy. In addition, application allows to specify the value of APE and *useful fraction* (UF) for radiation well below 200 W/m^2. Utilized in this way, measuring procedure is cost-effective measurement method for determining the value of APE and UF for general use.

In this study assumed a typical spectroradiometer range B = 0.3-1.7 µm. The studies were used measurement data from the local meteorological station of the AGH University of Science and Technology in Krakow and the Opole University.

Obtained in this way, the values of average photon energy on the surface of the horizon and the other inclined exposure of PV modules surfaces are shown in Figure 11. One can observe a large hourly variability during the day, which is causing large changes in the instantaneous energy efficiency of PV modules. The high value of the average photon energy (APE) corresponds to the spectrum of solar radiation rich in short-wave components

(UV), while a low value indicates a high content of long-wave components (IR) in the spectrum. For comparison, the standard spectrum AM1.5G (STC) has an average value of photon energy (APE) equal to 1.62 eV. The disadvantage of the method using of APE for the analysis of efficiency of solar cells and modules is that it does not provide direct information about the contents of so-called *useful fractions* (UF) of solar radiation.

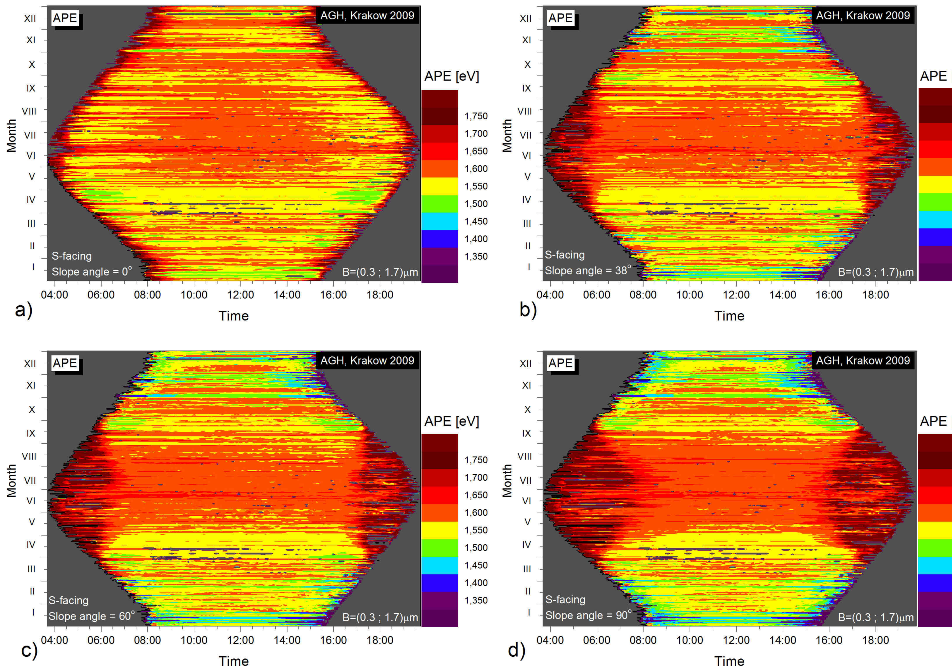

Fig. 11. The distribution of the average photon energy for: a) horizontal position, b) the optimum angle for the Krakow area (38°) and c) typical for PV facades angle 60°, d) vertical position (90°). All planes have southern setting

Distributions of the useful fractions of solar radiation

Useful fraction (UF) is called a power contained in the frequency band of the spectrum of solar radiation, limited by spectral sensitivity of the semiconductor absorber (*eg*: c-Si, mc-Si, CIS, and Si_SJ-and-Si_TJ)[6] to the power of solar radiation recorded by broadband meter with bandwidth (0.3 µm, λ_{cut}) according to:

$$UF = \frac{\int_{\lambda 1}^{\lambda 2} P(\lambda)d\lambda}{\int_{0.3\mu m}^{\lambda cut} P(\lambda)d\lambda} \tag{10}$$

[6] c-Si - monocrystalline silicon; mc-Si - multicrystalline silicon; CIS - cell with $CuInSe_2$ absorber; a-Si SJ - single junction cell made of amorphous silicon; a-Si TJ - triple junction cell made of amorphous silicon.

where: λ_{cut} - limit wavelength measured by the instrument (adopted by default, as the 1700 nm), (λ_1; λ_2) - spectral sensitivity range of cell, known as the wavelength range for which the normalized value of the cell spectral response is $SR_{norm} \geq 0.5$ (see Figure 12), $P(\lambda)$ - spectral power density of the radiation for the wavelength λ.

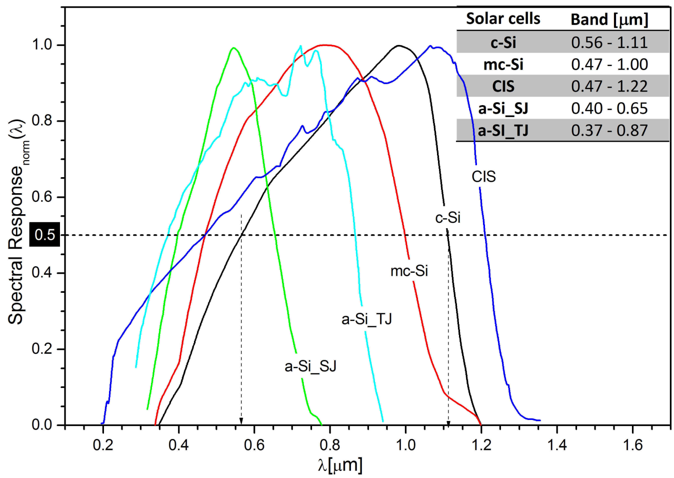

Fig. 12. Determination of conversion band for each cell absorber based on SR characteristics

By substituting in the expression (10) the instantaneous values of power by the daily values of the solar radiation energy recorded at the same intervals, receives the value of *the daily value of useful fractions* (11):

$$UF_{Day} = \frac{\int_{\lambda 1}^{\lambda 2} E(\lambda)d\lambda}{\int_{0.3\mu m}^{\lambda cut} E(\lambda)d\lambda} \tag{11}$$

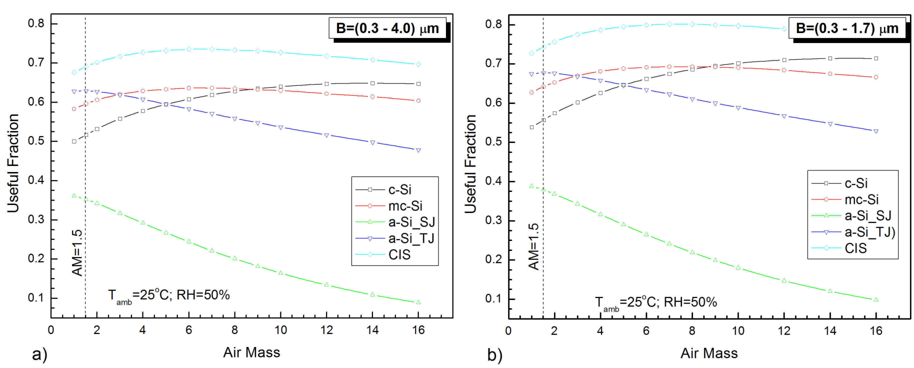

Fig. 13. Dependence between the UF and AM factor for cloudless day, after integration: a) in range (0.3-4) μm, and b) in range (0.3-1.7) μm

As with the determination of APE, UF value (useful fraction) is dependent on the bandwidth of the measuring instrument integration.

Figure 13 shows dependence between the UF and AM factor (for a cloudless day and the same meteorological conditions), obtained for different values of the integration bandwidth of the measuring instrument.

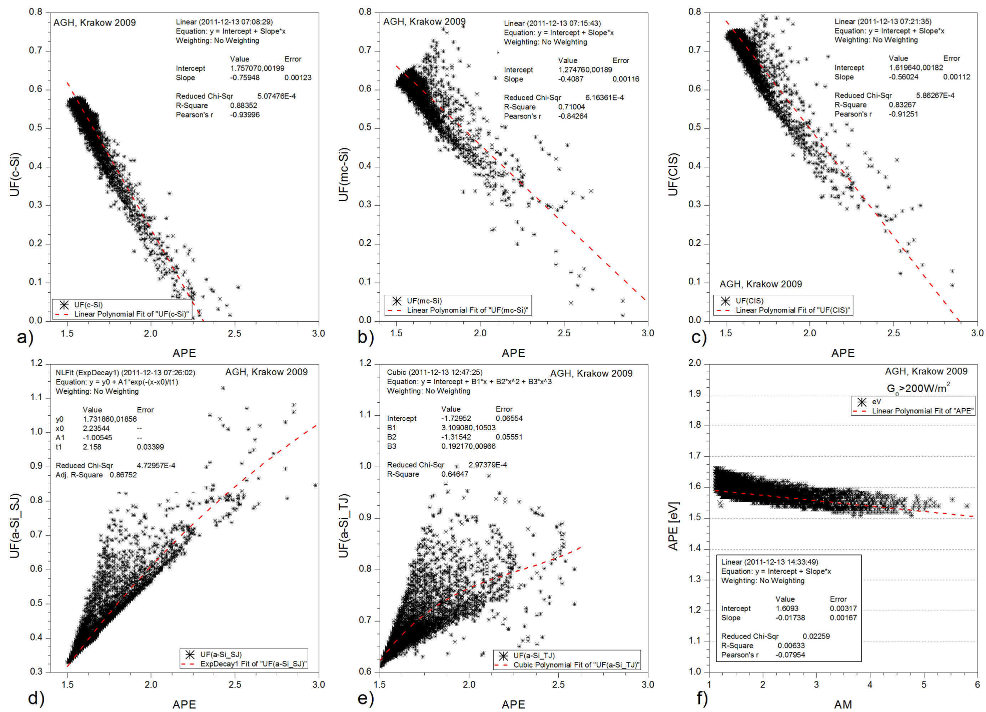

Fig. 14. Dependence between the UF and APE for: a) c-Si cells; b) mc-Si cells; c) CIS cells; d) a-Si_SJ cells; e) a-Si_TJ cells; f) dependence between the APE and AM factor for day with irradiation (G_0) greater than 200 W/m^2

Useful fractions (UF) are parameter dedicated for the type of PV cell/module. It is characterizing the spectrum of solar radiation, providing a direct information about the content of useful part in the spectrum involved in the conversion in that type of photovoltaic cell/module. It does not contain information about the impact of spectrum to other cells with different spectral sensitivity range, and does not indicate a present (in the measurement) solar radiation intensity or the daily value of radiation energy. The strong correlation between the average photon energy (APE) and the useful fraction content (UF) for each type of PV cell/module is shown in Figure 14 a-e.

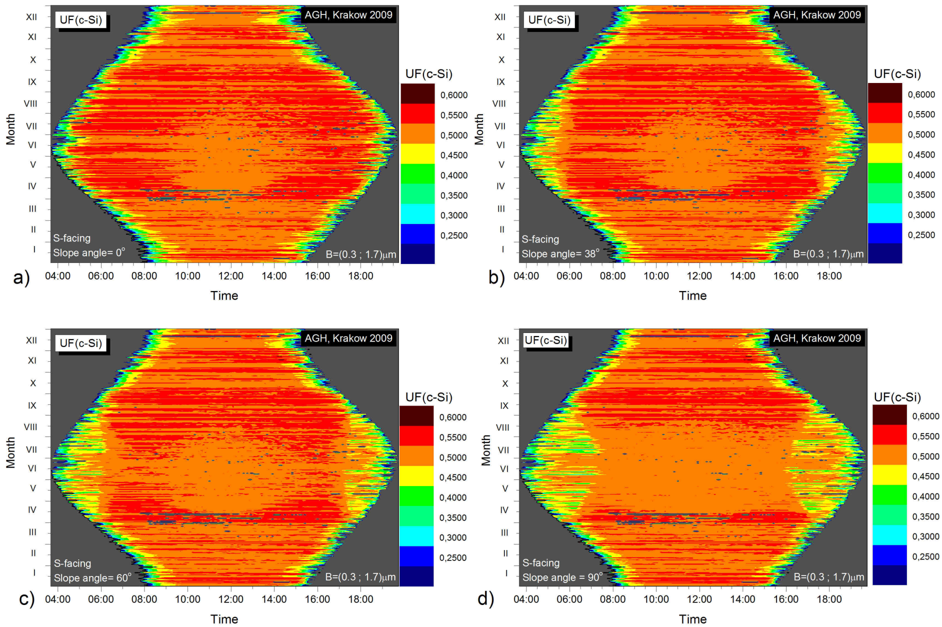

Fig. 15. The distribution of the useful fraction for solar cells/modules made of c-Si for: a) horizontal position, b) the optimum angle for the Krakow area (38°), c) angle 60°, d) vertical position. The meteorological data are from AGH Krakow area collected in 2009

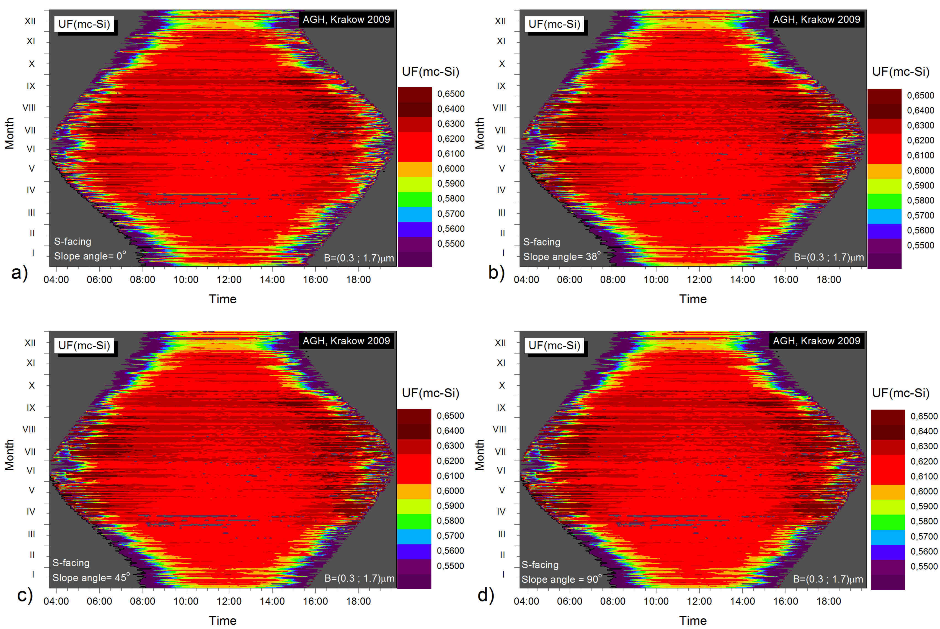

Fig. 16. The distribution of the useful fraction for solar cells/modules made of mc-Si for: a) horizontal position, b) the optimum angle for the Krakow area (38°), c) angle 60°, d) vertical position. The meteorological data are from AGH Krakow area collected in 2009

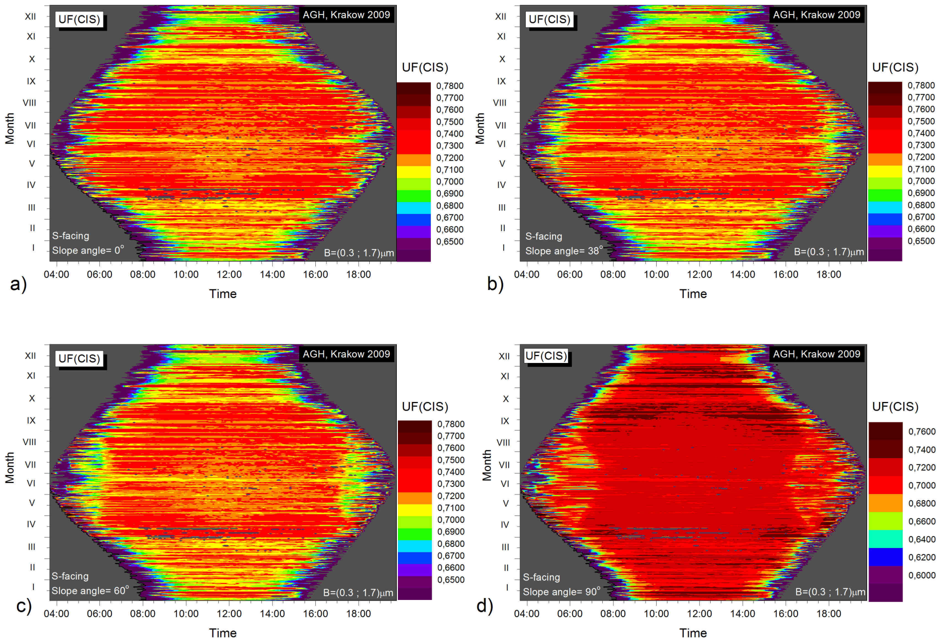

Fig. 17. The distribution of the useful fraction for solar cells/modules made of CIS for: a) horizontal position, b) the optimum angle for the Krakow area (38°), c) angle 60°, d) vertical position. The meteorological data are from AGH Krakow area collected in 2009

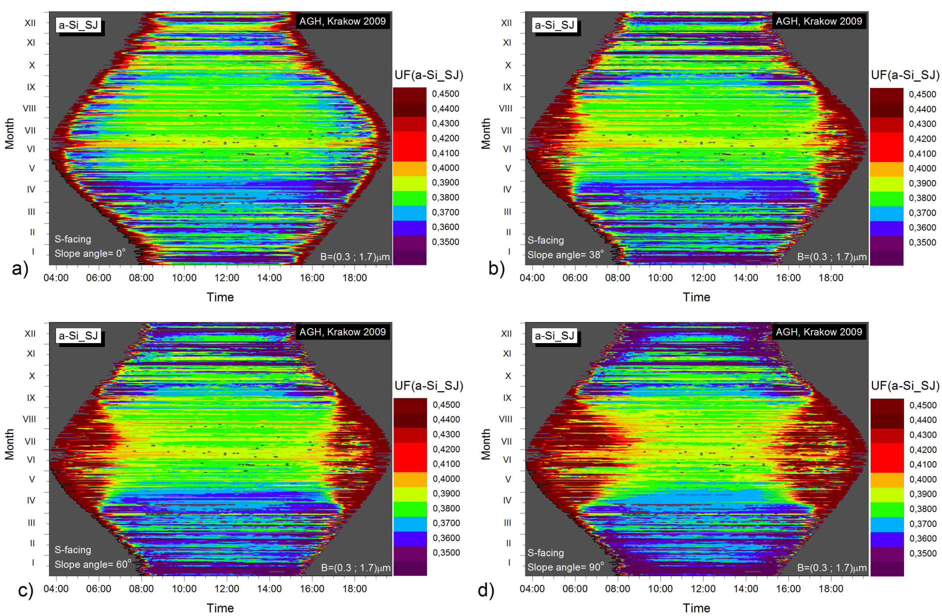

Fig. 18. The distribution of the useful fraction for solar cells/modules made of a-Si_SJ for: a) horizontal position, b) the optimum angle for the Krakow area (38°), c) angle 60°, d) vertical position. The meteorological data are from AGH Krakow area collected in 2009

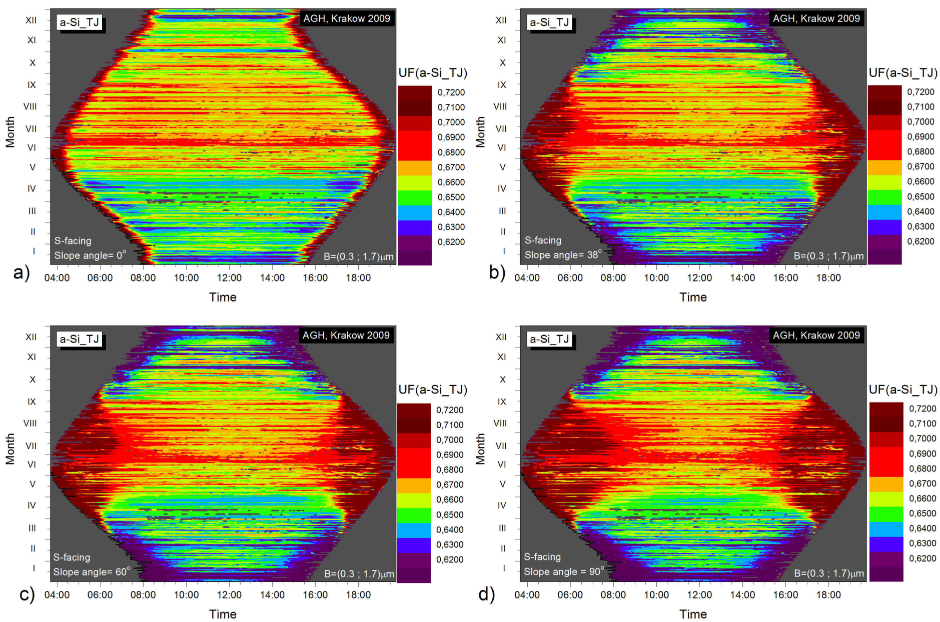

Fig. 19. The distribution of the useful fraction for solar cells/modules made of a-Si_TJ for: a) horizontal position, b) the optimum angle for the Krakow area (38°), c) angle 60°, d) vertical position. The meteorological data are from AGH Krakow area collected in 2009

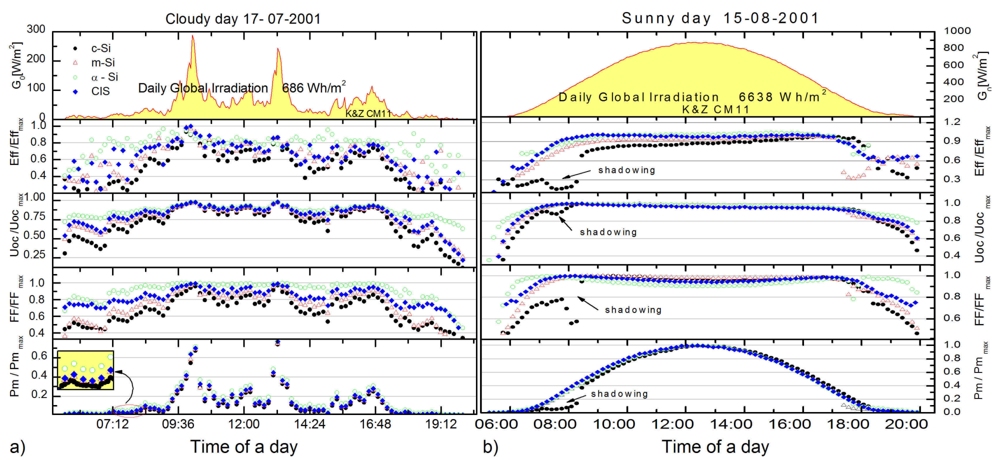

Fig. 20. Normalized parameters values of the tested modules for two typical days differ significantly in daily insolation value: a) cloudy day (17.07.2001), and b) sunny day (15.08.2001). The zoom window shows a much better behaviour of thin-film modules at low irradiation in hours of sunrise and sunset [24, 25]. Modules were tested in the southern direction and constant 40° inclination. The measurement of the intensity of solar radiation in the plane of tested modules was made with pyranometer CM-11 mounted in the plane of tested modules. Tests were performed in Opole in 2001

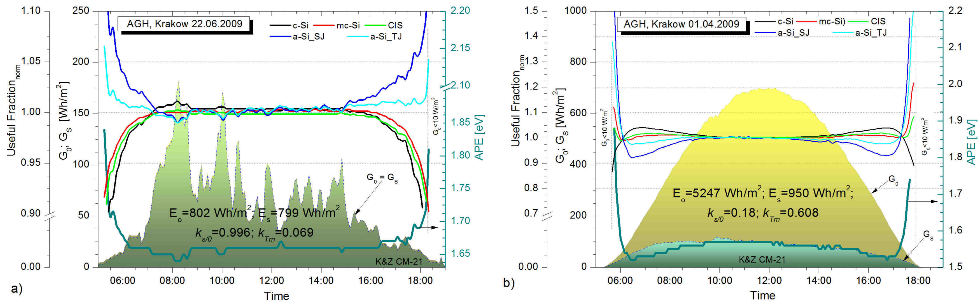

Fig. 21. Changes in the average photon energy of the solar radiation spectrum and the normalized values of the useful fraction for basic types of solar cells / PV modules, during: a) a cloudy summer day, and b) sunny spring day. Thick green line shows the course of APE during the day. The study was performed in the AGH Krakow area in 2009

Figures 15-19 shows the distribution of the useful fraction for different types of solar cells/modules for: a) horizontal position, b) the optimum angle for the Krakow area (38°), c) angle 60°, d) vertical position. The meteorological data are from AGH Krakow area collected in 2009. Particular attention should be paid to:

- range of fraction values obtained for each cell;
- embodied phenomenon of seasonal distribution of UF - emphasizing with the angle of the modules exposure;
- occurring phenomenon a very good spectral fit for amorphous silicon single- and multi-junction during sunrise and sunset.

It should be noted that the same parameter UF did not inform you of occurring irradiance or intensity of solar radiation in any given time. This means that it does not indicate how much energy produce the module for a certain period of time. It only present fitting of distribution of the solar radiation spectrum to spectral sensitivity of the cells, which directly translates into the derived values of efficiency, open circuit voltage and the *Fill Factor* (FF). On the other hand, the impact of UF on parameters such as short-circuit current I_{SC} and the maximum power P_m can be observed only in reference to the value of solar radiation.

This is due to the presence of a very strong correlation between the forcing (ie, solar radiation) and the answer, that is current and output power of PV cells. Figure 20 a,b gives an example of standard module parameters during the day for two very different weather conditions. The zoom window shows a much better behaviour of thin-film amorphous silicon modules working at high cloud cover and low irradiation, which are the hours of sunrise and sunset. However, Figure 21, gives an example the average photon energy in the spectrum of solar radiation and the normalized useful fraction for similar weather conditions as in Figure 20, the strongly cloudy and warm day (LIMT) and cool sunny spring day (HIMT). In Figure 22 a-h are examples of daily changes of APE and UF for days characterized by different meteorological conditions, from different periods of the year.

In the aim of characterizing each day, charts contain daily values of radiation energy: global E_0 and from diffusion component E_S of solar radiation, daily values of diffuse component content index $k_{S/0}$ and atmosphere clearness index k_{Tm}. Due to the fact that at very low irradiance, in some cases began to emerge errors in process determination of the

UF, so was made in such cases filtration of data and the results are shown for the values of the radiation exceeding 6÷10 W/m^2 (this fact was shown on the charts, respectively).

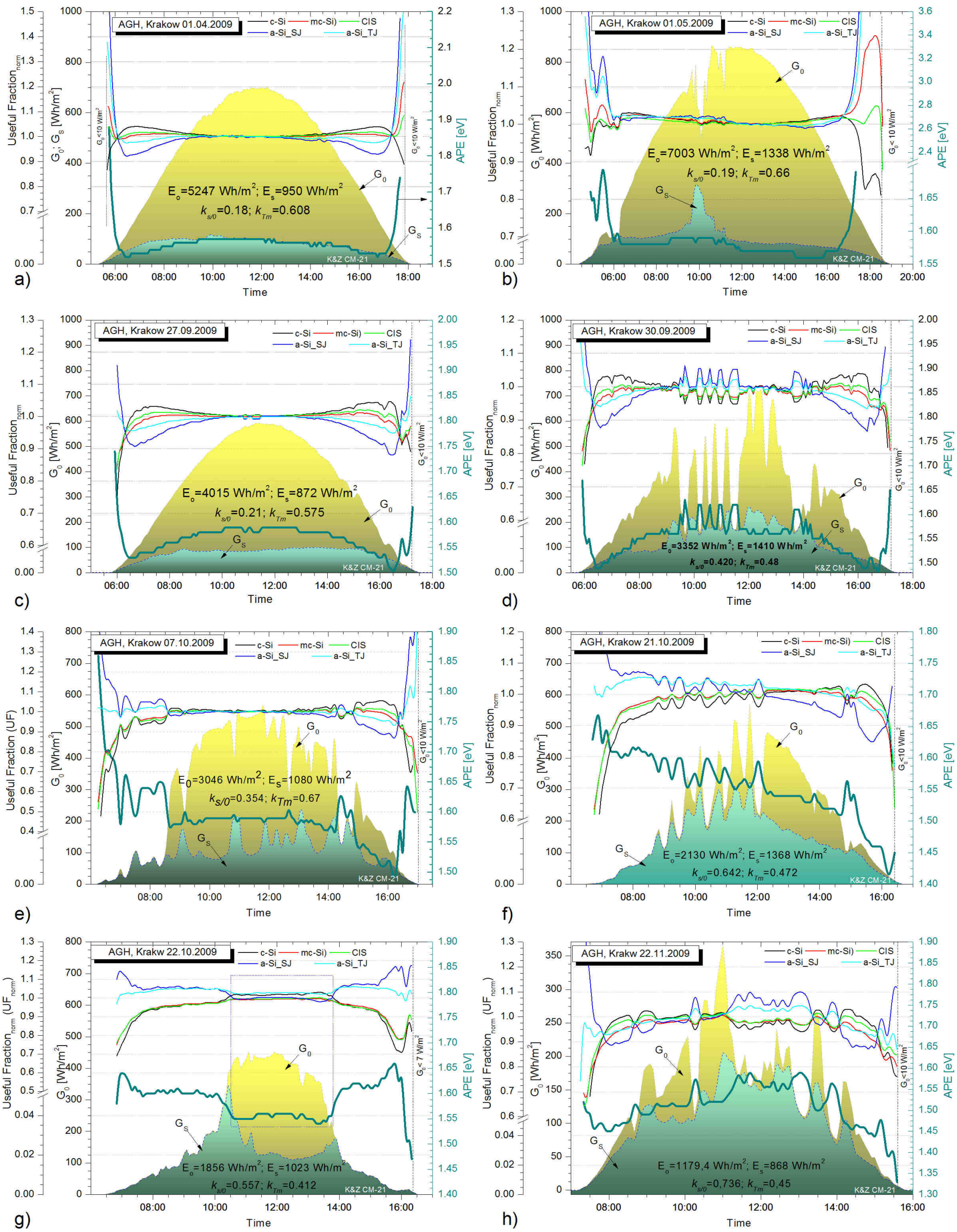

Fig. 22. Examples of daily changes of APE and UF for days characterized by different meteorological conditions, from different periods of the year. Thick green lines - in the lower areas of the drawings show the course of the APE during day. The study was conducted for the AGH Krakow area in 2009

In summary, to make complete analysis of the different types of photovoltaic modules suitability to conversion in various climatic conditions, should be made simultaneous analysis of UF graphs and irradiation in the area. Then it is possible to objectively estimate the potential profit from the configuration used during given period and climatic conditions.

Conclusions

Solar cell is a semiconductor element which direct converts solar energy into electricity. The amount of electricity generated by the PV cell/module depends largely on climate conditions of its work. Decisive influence on the amount of energy produced has a distribution (within a year) daily and monthly values of temperature and radiation, and the structure of the spectrum of radiation reaching the PV module. This structure is determined by the average photon energy value of solar radiation reaching the Earth's surface or through the distribution of daily and monthly atmosphere clearness and diffuse component content indexes. For this reason, we make the comparison of the distribution of these values over the year, the daily and seasonal variations, and the relationships between these parameters - characterizing *solar energy resources for photovoltaic conversion* - with obtained by the cells and photovoltaic modules operating parameters. This comparison is the basis for the selection of the correct modules type, the method of installation and the proper design of the photovoltaic system. A system that will meet future user needs, not only in summer but also in the other seasons of work, and the system for which the *performance factor* (energy produced compared to the cost of PV systems purchase per 1 Wp) will be the best for our geographical and climatic conditions. Methods of measurement data analysis presented in this paper, combined with reliable information on the long-term solar radiation values recorded in Polish territory, and the energy performance of photovoltaic installations already operating will be a valuable source of information for potential investors interested in this, how little known in our country power industry branch [26-28].

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ANALIZA STRUKTURY ZASOBÓW ENENRGII SŁONECZNEJ OBSZARU POLSKI POŁUDNIOWEJ DO ZASTOSOWAŃ FOTOWOLTAICZNYCH

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Abstrakt: W artykule przedstawiono analizę zasobów oraz struktury energii słonecznej obszaru Polski Południowej na podstawie pełnych danych meteorologicznych pochodzących z Akademii Górniczo-Hutniczej z Krakowa z 2009 r. Podjęto próbę dokonania analizy jego wykorzystania do celów konwersji fotowoltaicznej z wykorzystaniem różnych modułów o różnych charakterystykach spektralnych absorberów. Opisane najnowsze metody charakteryzujące strukturę zasobów energii słonecznej, takie jak rozkłady na przestrzeni całego roku: indeksów czystości nieba lub indeksów zachmurzenia, średnich wartości energii fotonów (APE) oraz zawartość użytecznych frakcji widma promieniowania słonecznego (UF), nie są jeszcze powszechnie znane i stosowane tak w Polsce, jak i w innych krajach UE, mimo że najtrafniej określają dopasowanie czynnika spektralnego do wybranego modułu fotowoltaicznego. Ze względu na konieczność posiadania bardzo drogiej aparatury pomiarowej są stosowane tylko przez nieliczne laboratoria w Unii Europejskiej, takie jak np. CREST (***C****entre for* ***R****enewable* ***E****nergy* ***S****ystems* ***T****echnology*) w Wielkiej Brytanii. W artykule zaprezentowano opracowaną i stosowaną w Uniwersytecie Opolskim nową i tanią metodę określania dopasowania widma z użyciem wskaźników, m.in. APE oraz UF, bez konieczności posiadania drogiego spektroradiometru, która daje porównywalne wyniki pomiarowe.

Słowa kluczowe: widmo promieniowania słonecznego, napromieniowanie, indeks czystości nieba, indeks zachmurzenia, średnia energia fotonów (APE), frakcje użyteczne (UF), energia słoneczna, fotowoltaika