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Numerical procedures and their practical application in PV modules' analyses. Part II: Useful fractions and APE

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ABSTRACT

The article regards aspects of PV modules tested with the use of natural sunlight. The analysis of spectral structure of solar energy resources in southern Poland, carried out on the basis of meteorological data originating from SolarLab PW Wrocław and AGH Kraków, Poland [1] was used in the article. It is a continuation of the article: *Analysis of solar energy resources in southern Poland for photovoltaic applications* [1], describing the method to determine spectral parameters of average photon energy (*APE*) and useful fraction (*UF*) with the use of a solar radiation spectrum simulator. This article, however, includes an experimental presentation of their impact on PV conversion of modules with different absorbers. Theory and practice of the measurements were described with the use of spectral parameters such as: *UF*, *APE*. Their influence on the efficiency of modules' photovoltaic conversion with various spectral characteristics of absorbers was presented. The most recent methods described, which characterise the structure of solar energy resources such as annual distributions of *APE* and *UF*, have not been commonly used yet in Poland and other countries, even though they most precisely define adjustment of the spectral factor to the selected PV module.

Practical application of *UF*, in detection of absorber type used in the tested PV module/cell is demonstrated in the final part of the article.

Introduction

It is quite difficult to estimate the usefulness of modules (i.e., they maintain their standard parameters) made with different absorbers in different technologies, in areas located in higher geographical latitudes. This is due to the fact that such areas are characterised by considerable variability of climactic conditions. There are considerable differences in yearly distributions of: average environmental temperatures, irradiance and the average energy of photons of the solar irradiance spectrum, i.e. they have a different structure of solar energy resources' distribution. Precise information about the structure and resources of solar irradiance is the basis for a photovoltaic system correct design and estimation of the energy yield in a given climate conditions.

Currently, there is an abundance of studies underway that focus on the environmental conditions' impact on the PV modules and systems' operation. These include influence of temperature, irradiance, radiation, atmospheric transparency, wind speed, dust and dust formation on the efficiency of PV modules and systems. The investigations of this type were conducted in many countries and also at high latitude, e.g.: in the Netherlands [2], UK [3] and in Poland [4]. A lot of ongoing studies also concern the influence of the varying solar spectral irradiance on PV performance, e.g. at higher latitude, e.g. in Germany [5] and in Italy [6].

Yearly distributions of environmental temperatures and irradiance may be determined in a simple, unambiguous and cheap way: problems arise during preparation of the annual solar irradiance spectrum distribution. This procedure, together with an analysis of conformity of solar irradiance spectrum distribution with *spectral response* $SR(\lambda)$ of the used PV modules, i.e. Preparing distributions of the useful fractions for individual PV modules requires the use of expensive and complex measuring equipment. Therefore, characteristics of the structure of solar energy resources in the form of annual distributions for a given area of: *APE* and the content of the *UF* of solar irradiance spectrum fractions, have not been frequently prepared and applied either in Poland or other countries, even though they most precisely define adjustment of the spectral factor to the selected photovoltaic module.

This article was prepared using measurement data generated in two research centres - AGH University of Science and Technology in Kraków and Laboratorium SolarLab in Wrocław Technical University. The basic studies were carried out with the use of

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Nomenclature

AM	Air mass [-]
APE	Average photon energy of solar radiation [eV]
Eph(λ)	Photon energy with wave length λ [J]
E0	Daily value of insolation energy [Wh/m^2]
ES	Daily value of insolation energy from diffuse component [Wh/m^2]
EPOA	Daily value of insolation energy in Plane of Array [Wh/m^2]
G0=G0,H	Global solar irradiance in the plane of the horizon [W/m^2]
GS=GS,0	Diffuse component in the plane of the horizon [W/m^2]
GPOA	Global irradiance in plane of array [W/m^2]
GPOA(λ)	Spectral irradiance GPOA [Wm-^{2}λm^{-1}]
kTm	Daily atmosphere clearness index [-]
kS/0	Daily diffuse component content index of solar radiation[-]
Rs	Serial resistance of a cell/module [Ω]
SR (λ)	Spectral Response [A/W]
UF	Useful Fraction [-]
λcut	Limit wave length measured by the equipment
φph	Photon spectral flux density [cm^{-2}s^{-1} μm^{-1}]
POA	Plane of Array, LST - Local Solar Time

measurement data from SolarLab in Wrocław Technical University, whereas the data generated in AGH Kraków were treated as supplementary[1] i.e. comparative. Due to the extensive nature of the material presented, the article focused on the presentation of the influence of solar irradiance spectral parameters on the operation of PV modules made of different absorbers.

Due to the extensiveness of the presented material, the article only demonstrates the impact of spectral parameters of solar radiation on the operation of PV modules made of different absorbers. It is a continuation of the article: *"Analysis of solar energy resources in southern Poland for photovoltaic applications"* [1], describing the method to determine spectral parameters of *APE* and *UF* with the use of a solar radiation spectrum simulator.

A precise description of the lab measuring stations used in the studies: AGH Kraków and SolarLab in Wrocław Technical University was included in, respectively: [1,7]and [8,9]. The procedures for determining average photon energy, useful fraction content in the solar irradiance and an extensive presentation of instantaneous, daily and monthly distribution maps are in Ref. 1.

Analysis and modelling

APE of the solar irradiance spectrum

The average photon value of solar irradiance spectrum is determined from the measurement of the irradiance spectrum and is a quotient of the power registered by a broadband receiver and the density of the detected photon stream in this range, i.e. according to the Eq. (1) [10–12]:

Table 1
APE of the standard spectrum evaluated from different spectral integration limits (own calculations).

No.	Measuring range (integration) [μm]	*APE* [eV]
1	0.3 - 4.0	1.43
2	0.3 - 2.5	1.48
3	0.3 - 1.7	1.62
4	0.3 - 1.1	1.86

$$APE = \frac{\int_{\lambda_1}^{\lambda_2} [\varphi_{ph}(\lambda) \cdot Eph(\lambda)] d\lambda}{q \int_{\lambda_1}^{\lambda_2} \varphi_{ph}(\lambda) d\lambda} = \frac{\int_{\lambda_1}^{\lambda_2} G_{POA}(\lambda) d\lambda}{q \int_{\lambda_1}^{\lambda_2} \varphi_{ph}(\lambda) d\lambda}, \tag{1}$$

where: *APE* of solar irradiance in [eV], q – electron charge, $\varphi_{ph}(\lambda)$ – spectral photon flux density in solar light with wavelength λ, $E_{ph}(\lambda)$ – photon energy with wave length λ in [J], $G_{POA}(\lambda)$ - is the spectral irradiance G_{POA} in [Wm^{-2} μm^{-1}]; (λ_1; λ_2) – the integration limits, φ_{ph} – is the photon spectral flux density [cm^{-2}s^{-1} μm^{-1}].

The analysis method of solar irradiance spectrum with the use of *APE* has many advantages. One of them is a very strong correlation between *APE* and the short-wave range of solar irradiance spectral characteristics which considerably influences efficiency of photovoltaic cells. Moreover, the setting as a unit of [*APE*] = eV, allows fully for illustration of the spectral match of the absorber used in a PV cell/module with the occurring solar irradiance spectrum. However, it should be emphasised, that the APE value depends on the integral range of the Eq. (1). The effect is presented in Table 1, where the obtained results of *APE* of the standard irradiance spectrum (STC) [13], i.e. irradiance type AM1.5 G [13,14] are compared, using different widths of the measuring equipment operating band.

The most appropriate definition for *APE* would refer to the average value of photon energy obtained from the measurement with the use of the full earth range of solar irradiance spectrum (0.3–4.0) μm, as the obtained result gives the actual value of *APE*. However, the measuring instruments in that range are very rare and not adjusted to operate in long-time measuring cycles. Taking into consideration that the spectral range of solar irradiance with the distribution type AM1.5 G in the range from 0.3 to 2.5 μm includes over 98% of its power, taking measurements in this range becomes very interesting. However, the access to the equipment operating in such a wide range is quite difficult. Nevertheless, a measurement taken in the range to 1.7 μm can be easily extended to 2.5 μm with sufficient modelling precision - e.g. the measurement range extension method 0.3–1.1 μm of the silicon sensor, to the measurement range of a spectroradiometer, i.e. to 4.0 μm, was already prepared at NREL (National Renewable Energy Laboratory – Golden Colorado – USA) [15].

Content of UF in solar irradiance spectrum

UF is the proportion of the power included in the range of solar irradiance spectrum, limited by the spectral sensitivity range of semiconductor absorber of a PV cell/module (e.g., c-Si, mc-Si, CIS, a-Si_SJ, a-Si_TJ)[2] to the power of solar irradiance recorded with a wide-range measuring device with the operational range (μm; λ_{cut}) [16,17], i.e. determined according to Eq. (2):

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[1] Taking into consideration that the measuring systems at the SolarLab laboratory are in shadow during early morning hours (i.e., for very low angles of the Sun setting and rising in the sky), it was necessary to supplement the data from an independent measuring system at AGH Kraków, which was free from such problems. This regards, in particular, the presentation of the relations of instantaneous values of *UF* and *APE* coefficients with the value of *AM* coefficient.

[2] c-Si - monocrystalline silicon, mc-Si - multicrystalline silicon, CIS - modules with CuInSe$_2$ absorber, a-Si_SJ - modules from amorphous silicon one and a-Si_SJ - and three-junction.

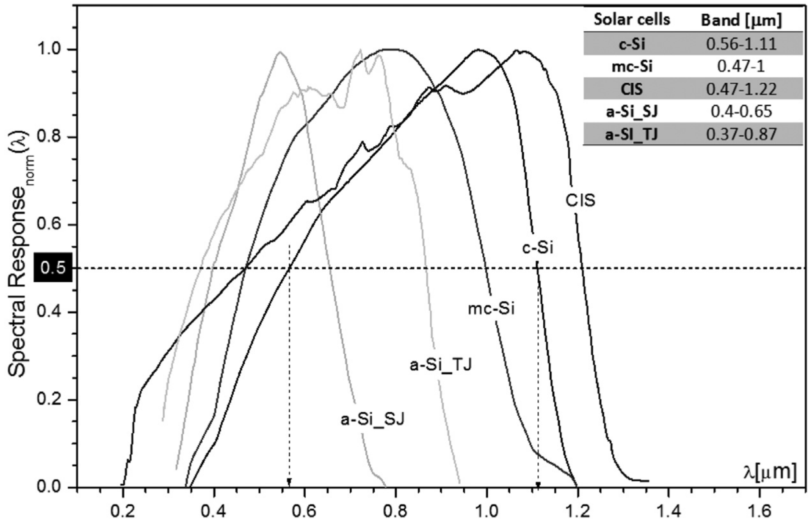

Fig. 1. Determination of the conversion band for individual absorbers of PV cells based on SR characteristics [16].

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

where, λ_{cut} – limit wavelength measured by a device (default 1.7 µm), (λ_1; λ_2) – spectral sensitivity band defined as wavelength range, for which the standardised value of a cell spectral response $SR_{norm}\geq$0,5 (see Fig. 1), P(λ) – spectral density of irradiance power with wavelength λ in plane of array, $G_{POA}(\lambda)$ - spectral irradiance G_{POA}.

By replacing in Eq. (2) instantaneous power values with daily/monthly values of solar irradiance energy recorded in the same ranges, one obtains daily/monthly values of useful fractions (3/4):

$$UF_{day}=\frac{\int_0^{day}\int_{\lambda 1}^{\lambda 2}P(\lambda)d\lambda\cdot dt}{\int_0^{day}\int_{0.3\mu m}^{\lambda cut}P(\lambda)d\lambda\cdot dt} \tag{3}$$

$$UF_{month}=\frac{\int_{\lambda 1}^{\lambda 2}E_{month}(\lambda)d\lambda}{\int_{0.3\mu m}^{\lambda cut}E_{month}(\lambda)d\lambda}. \tag{4}$$

As in the case of determining the *APE* value, the value of *UF* depends on the measuring device integration band.

Modification of the *UF* coefficient involves using characteristics of *SR* instead of conversion band of PV cells/modules [18]. Then, the expressions: instantaneous/daily/monthly value of *UF* coefficient take the following forms, respectively (5 / 6 / 7):

$$UF_{SR}(t)=\frac{\int_{0.3.\mu m}^{\lambda cut}[SR(\lambda)\cdot P(\lambda)]d\lambda}{\int_{0.3\mu m}^{\lambda cut}P(\lambda)d\lambda} \tag{5}$$

$$UF_{SR\_day}=\frac{\int_0^{day}\int_{0.3\mu m}^{\lambda cut}[SR(\lambda)\cdot P(\lambda)]d\lambda\cdot dt}{\int_0^{day}\int_{0.3\mu m}^{\lambda cut}P(\lambda)d\lambda\cdot dt} \tag{6}$$

$$UF_{SR\_month}=\frac{\int_0^{month}[UF_{SR\_day}(t)\cdot E_{day}(t)]dt}{\int_0^{montht}E_{day}(t)dt}. \tag{7}$$

Certainly, modification of these coefficients causes a considerable increase of their precision and reflecting the influence on the parameters achieved by typical PV modules. However, it also causes narrowing of the usefulness range. Reasons: 1) the obtained results shall be dedicated only to a given module, with defined spectral characteristics, 2) due to the unit *SR*(λ) [A/W] - the obtained result from an expression modified in this way for *UF* has another physical interpretation. It does not directly represent the influence of solar irradiance spectrum useful fractions on the power conversion ability of the selected modules, but the ability to generate current I_{SC} of a PV module.

The *UF* parameter is dedicated to a given type of a PV cell/module. It characterises solar irradiance spectrum, directly providing information on the content of the useful spectrum range, which participates in photovoltaic conversion, for a given type of a PV cell/module. It does not contain information on the influence of the irradiance spectrum on other cells/structures, with different

Table 2
Technical parameters of the analysed modules in standard test conditions (STC) [35].

Type[a]	I_m(STC) [A]	U_m(STC) [V]	P_m(STC) [Wp]	I_{SC}(STC) [A]	U_{OC}(STC) [V]	*Rs* according to IEC 60891 [36] Ω
M96_a-Si_SJ	0.82	34	28	1.05	50.7	3.7
M48_a-Si_TJ	3.34	16.3	55.3	4.24	23	0.17
M28_c-Si	4.65	7.74	33	4.68	9.7	0.07
M39_CIS	0.44	20.74	9.3	0.5	26	3.19
M30_mc-Si	4.66	7.44	34.6	5.08	9.8	0.04
M35_mc-Si	4.66	7.9	35.5	4.83	9.8	0.043

[a] [M96]_a-Si_SJ – numer of the tested module (M96), [a-Si_SJ] mark of the used absorber in a PV module, where: c-Si - monocrystalline silicon, mc-Si - multicrystalline silicon, CIS - with CuInSe$_2$ absorber, a-Si_SJ - modules from amorphous silicon one and a-Si_SJ - and three-junctions.

ranges of spectral sensitivity, and does not inform about the intensity of solar irradiance present during the measurement or daily value of irirradiance energy. In the article, all determined values of *APE* and *UF* are related to the integration range of the measuring device B = (0.3; 1.7) μm.

Methodology determination of APE and UF

In this article, the average photon energy of solar radiation incident on the plane of array (*POA*) is determined with the *solar spectrum* [19] proprietary software, jointly developed by Dr. T. Żdanowicz and Prof. M. Ząbkowska-Wacławek, used to determine the solar radiation spectrum distribution based on instantaneous measurement data from a local weather station. The developed corresponding ddl. library has enabled to automate the studies/calculations. In order to verify the correct determination of *APE*, the measuring range of the equipment used was the same as at CREST (Center for Research in Engineering, Science and Technology, UK) laboratory, i.e. between 0.3 and 1.7 μm. The spectrum creation model applied in solar spectrum uses SEDES2 software codes by Nann and Bakenfelder [20,21], which is a modified version of the 1986 SPECTRAL2 model by Bird and Riordan [22–24], with the Perez model in order to determine the diffuse component value on the inclined surface of *POA* modules [25,26], extended by the empirical modification model of the cloud day spectrum [27,28]. The cloud day modifier used is a function of wavelength, Air Mass (*AM*), broadband ratio of global irradiance: measured in the plane of the horizon and from the determined bright sky spectral distribution. This simulator calculates the solar radiation spectrum within the range between 0.3 and 2.5 μm. However, the application working with the simulator calculates *APE* and *UF* from the radiation incident on POA that is much below 25 W/m^2. This measurement procedure is an inexpensive general purpose method to determine *APE* and *UF*. In the completed studies, the measurement range corresponding to a typical spectroradiometer of B = (0.3÷1.7) μm was assumed.

Limitations of the APE *and* UF *determination procedure*

The determination of spectral parameters of *APE* and *UF* requires that the solar radiation spectrum be determined. This can be done with the use of a broad band spectroradiometer or it can be generated in a simulator, for the set meteorological conditions. Precision classes of SMARTS2, SPECTRAL2, MODTRAN or BRITE type of simulator are within 5% and are comparable with the data obtained from spectroradiometers [29–32]. The main problem is a very long term spectrum scanning by spectroradiometers, which makes it impossible to capture the dynamics in measurements carried out outdoor and, in the case of simulators, estimation error of the instantaneous content of water vapour in the air. This is one of the main input parameters for a simulation and amounts to approximately $\delta_w \cong 20\%$ [29,33]. In the case of the degree of conformity used typical for a given cell absorber /*SR* response characteristic module, it should be noted that in fact, within one material group, these differences can be quite significant. In these times of fast technological progress in cells/modules manufacturing, attempts to increase their efficiency - actual characteristics of spectral sensitivities may differ considerably, even within one group of cells.

Objective of study

The objective of the research was to present a prepared method for determining the values of the coefficients: *UF* and *APE* and connecting determined coefficients with operation of modules made of different absorbers in outdoor conditions. For this purpose, the most complete data from an automatic system for monitoring the basic parameters of the tested PV modules were the research subject. On the basis of the recorded measurement data [34] their parameters were determined and included in Table 2 and became the basis for presenting the above mentioned results.

Adjustment of the influence of temperature and solar irradiance intensity on study results

Demonstrating in the experimental (physical) way the influence of *UF* and *APE* coefficients on the photovoltaic conversion capacity of modules made of different absorbers in outdoor conditions, requires compensating the influence of temperature change of the tested modules and solar irradiance value on the parameters obtained by the modules. It can be done with reference to:

1) constant standard temperature of cells T_C = 25 °C and irradiance intensity G_{POA} = 1000 W/m^2, or

2) constant standard temperature of cells T_C = 25 °C and conversion to 1 W of intensity G_{POA} of the irradiance falling on *POA*.

The first method is carried out with the use of standard formulas of translation to STC conditions [13] for all values of currents and voltages of the maximum power point, according to Blaesser's method [36–39] described by the following Eqs. (8–10):

$$I_m(25\,^oC;\ 1000\,W/m^2) = I_m(t)\frac{1000}{G_{POA}(t)}\left(1+\alpha_m\cdot(25-T_C(t))\right), \tag{8}$$

$$U_m(25^oC;\ 1000\,W/m^2) = U_m(t)+\beta_m\cdot(25-T_C(t)) + N\frac{kT}{q}ln\left(\frac{1000}{G_{POA}(t)}\right) - R_S\cdot\left(I_m(25^oC;\ 1000\,W/m^2)-I_m(t)\right), \tag{9}$$

$$P_m(25^oC; 1000W/m^2) = I_m(t)\cdot U_m(t), \tag{10}$$

where N- quantity of cells in the PV module's string, R_s- serial resistance of a module.

In the case of the second method, partial translation is carried out, i.e. only translation of currents and voltages values of maximum power point of a module, to temperature T_C = 25 °C, i.e. using Eqs. (11–15):

$$I_m(25\,^oC) = I_m(t)+\alpha_m(t)\cdot(25-T_C(t)), \tag{11}$$

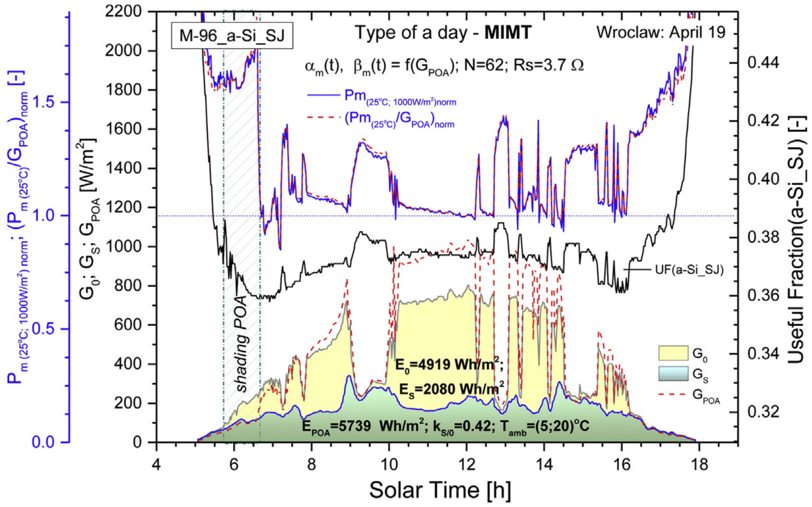

Fig. 2. Comparison of differences of the results obtained with reference to the constant standard temperature of cells $T_C = 25\,^\circ C$ and irradiance intensity $G_{POA} = 1000\,W/m^2$, and with reference to the constant standard temperature of cells $T_C = 25\,^\circ C$ and conversion to 1 W of intensity G_{POA} falling on the *POA* plane. The normalisation was carried out up to the value obtained at 12 local solar time.

$$U_m(25^oC) = U_m(t) + \beta_m(t) \cdot (25 - T_C(t)) - R_S \cdot \left(I_m(25^oC) - I_m(t)\right), \quad (12)$$

$$\alpha_m(t) = \alpha_m(G_{POA}) \cdot G_{POA}(t), \quad (13)$$

$$\beta_m(t) = \beta_m(G_{POA}) \cdot G_{POA}(t), \quad (14)$$

$$\frac{P_m(25^oC)}{G_{POA}} = f\,(UF; APE). \quad (15)$$

In this case, a module power at *maximum power point* (*MPP*), divided by the value of intensity of the irradiance falling on the plane of the tested modules (G_{POA}), i.e. reference function in the form of $\frac{P_m(25^oC)}{G_{POA}} = f\,(UF; APE)$ - illustrates the influence of the value of *UF* and *APE* coefficients on the PV conversions of the tested modules.

Initially, the temperature coefficients α_m for the current (I_m) and β_m for the voltage (U_m) at *MPP*, were determined for each module. Considering that temperature coefficients strongly depend on the value of solar irradiance intensity [40–43], it was determined by step every 50 W/m², increasing the density in the range of very low irradiance values, i.e. for the following intensity values: 25 ± 3 W/m², 50 ± 3 W/m², 75 ± 5 W/m², 100 ± 5 W/m², 150 ± 5 W/m², 200 ± 5 W/m², 250 ± 5 W/m²,. . ...1150 ± 5 W/m². Taking into consideration large spread of their values (the effect of strong connection with solar irradiance intensity), in order to increase precision of translation, they were approximated with the polynomial of degree 7. In this way the functions of temperature coefficients were obtained: $\alpha_m(G_{POA})$ and $\beta_m(G_{POA})$ - define actual values of temperature coefficients for the set values of intensity. Further in the article, the coefficients were used to estimate the actual power output of modules, in line with Eqs. (11,12 and 15).

In Fig. 2(a) comparison of differences in the progress of PV conversion normalised[3] graphs, determined in line with method 1 and 2, was presented. In spite of a considerable difference in the physical interpretation of these values, they actually represent very close values. It is evident that the method 2-a, i.e. presentation with reference to 25 °C and in conversion to 1 W G_{POA}, is the same, in the range of high intensity values of solar irradiance, with the progress presented with reference to STC conditions (method 1). Noticeable differences occur only in the range of large and very large deviations from 1000 W/m², i.e. in early morning and late evening.

In Fig. 3(a) the influence of accepting the erroneous value of serial resistance R_S. was presented. Accepting the understated resistance $R_S = 0.1\ \Omega$ *vs.* the actual one, which was calculated according to IEC 60891 [35] for the module M96_a-Si_SJ amounts to $R_S = 3.7\ \Omega$, and results in occurrence of two separate trajectories. One applies to measurements taken before noon and the other in the afternoon. Each trajectory is an approximate linear function [see Fig. 3a)]. Adjusting the values of serial resistance to its actual value $R_S = 3.7\ \Omega$, causes mutual convergence of the trajectories and change of their distribution, which is approximated by exponential function [Fig. 3b)]. This mutual divergence of the trajectories, which illustrate before noon *vs.* afternoon data points in the graph of the *UF* function, illustrates the lack of sufficient compensation of third factors, which disturb the analysis carried out. The compensation was increased by refraining from the use of average temperature value coefficients and the use of the function $\alpha_m(G_{POA})$, $\beta_m(G_{POA})$, thanks to which, in line with (13-14) it is possible to define them individually for the specific value of G_{POA}. Application of this procedure resulted in a total convergence of before- and afternoon trajectories. Fig. 3(c), the remaining points along the exponential approximation line are the effect of, among others, the so-called inertia of the system for measuring the temperature of the *p-n* junction cell in the tested PV module.

In Fig. 3d) the results with the use of the second method were presented, i.e. with reference to 1 G_{POA} in Fig. c) for comparison. Remarks:

- the courses from Fig. 3c) and 3d) have the same ranges and distribution;
- the use of presentation for 1 W G_{POA} (i.e. method 2) gives better concentration of points around the exponential approximation line.
- the method used does not require knowledge of the number of cells (N) serially connected in the tested module. The data recorded in the measuring system is sufficient.
- it enables simple transfer to the studies with the use of energy values.

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[3] In the following part of the article, all the normalisation procedures were carried out up to the values that the modules obtained during the zenith hours of the sun (i.e., at 12 LST).

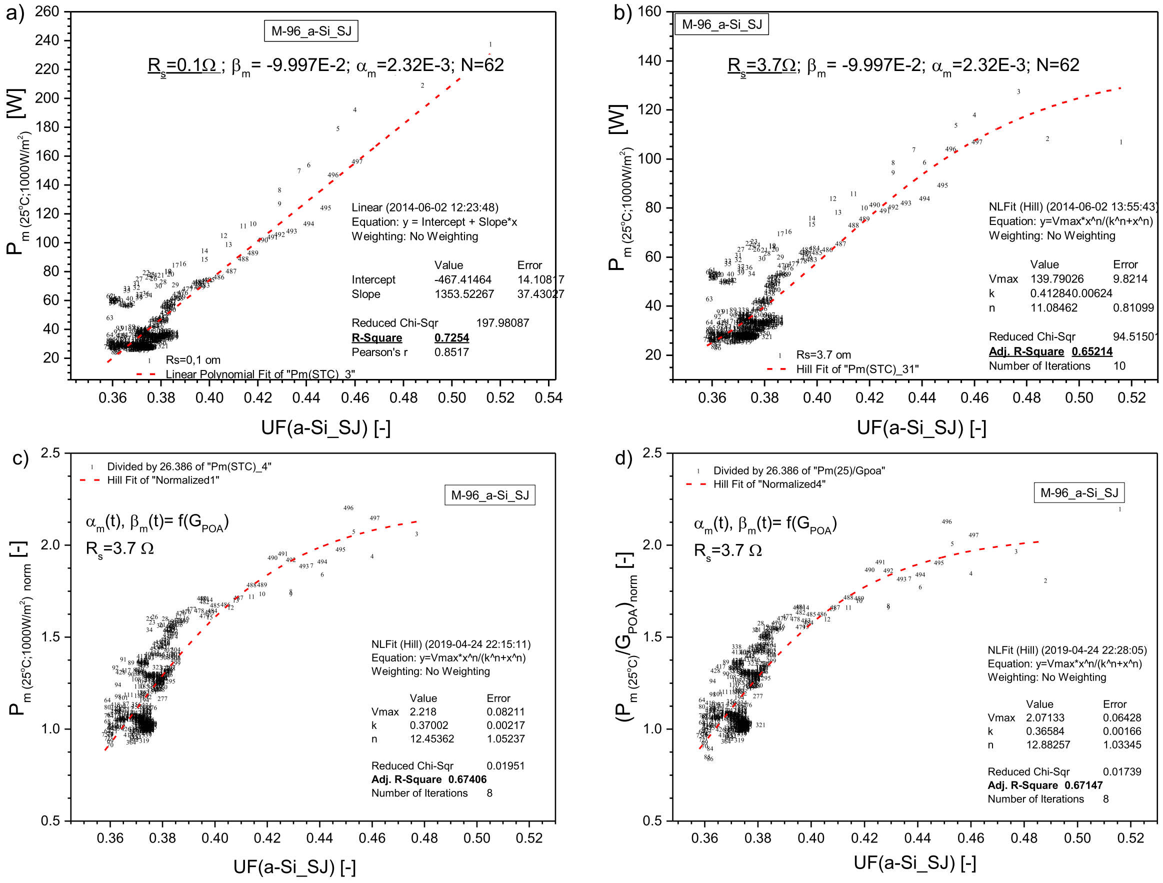

Fig. 3. The influence of the illustration method from Fig. 2 on PV conversion characteristics according to *UF* contents for a module with a-Si_SJ: a) for the understated value of resistance $R_s = 0.1\ \Omega$ (a typical resistance for thick-layer silicon cells was assumed); b) specific resistance $R_s = 3.7\ \Omega$ and averaged constant values of temperature coefficients; c) with the use of standard formulas of power P_m to STC conditions; d) with the use of standard translation formulas of cell temperature to $T_C = 25\,°C$ and conversion to 1 W of intensity G_{POA} of irradiance falling on *POA*. All graphs were subject to normalisation up to the Pm value at 12 LST.

Conclusions

1. The studies with the use of: daily/monthly values of energy yield - carried out with reference to 1 Wh of energy of the solar irradiance falling on 1 m^2 of the *POA* plane of the tested module. In this case, the translation of instantaneous values of the PV parameter modules to STC conditions serves no purpose, as:
2. we do not get rid of the interferences from shading of PV modules for higher AM values, but we emphasise them;
3. we cannot refer the results to 1 Wh of the energy falling on a PV module.
4. The analysis with the use of energy values is resistant to the momentary shadowing at sunset and sunrise. The shadowing of the object during these hours, i.e. for the large AM values, as well as during short periods in other hours, involves very small energetic interference values [44], as they are minimised and do not imply major errors in the daily, monthly or annual energy balance.

Results and discussion

Influence of UF/APE *parameters on PV module operation*

Analysis of instantaneous power values

Figure 4 and Figure A1-11[4] present a comparison of the course of power function P_m according to (15) for different modules with instantaneous: a) content of *UF*; c) *APE* value - according to time of day and the course of power reference function P_m from: b) *UF* content, d) *APE* value – of solar irradiance spectrum.

The studies have been carried out for different days with various meteorological conditions and the article presents the results focused on warm and hot days, with various cloudiness degrees, from heavy to light with flashes of bright sky, marked in graphs with the symbols: **LIMT**, **MIMT**, **LIHT**, **MIHT**. This was done on purpose, due to the large amount of already collected material an to the fact that during the selected days, the optimum dynamics of *UF* and *APE* of solar irradiance spectrum changes - for the presentation of the influence of the photovoltaic conversion capacity of the modules made of different absorbers, in outdoor conditions.

The day symbols used in these figures were taken from the IEC 61853 project described in Refs. 45–48 and in Refs. 49,50, which differentiates six different days as typical for external conditions for PV modules operation, relevant for different locations and seasons of the year. They can be briefly characterised as:

1) **HIHT** (**h**igh **i**rradiance, **h**igh **t**emperature) - typical very hot and sunny summer day in a desert location with peak irradiance 1100 W/m^2 and peak ambient temperature as high as 45 °C;
2) **MIHT** (**m**edium **i**rradiance, **h**igh **t**emperature) -typical very hot but cloudy and humid summer day with medium irradiance below 600 W/m^2 and ambient temperature $T_{amb} = 27 \div 33\,°C$;
3) **HILT** (high irradiance, low temperature - day typical for early spring season with high value of irradiance exceeding 1000 W/m^2 and low ambient temperature $T_{amb} = -1 \pm 3\,°C$;

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[4] Due to the large number of figures, the article contains only one example figure, while the others are included in the Supporting Information.

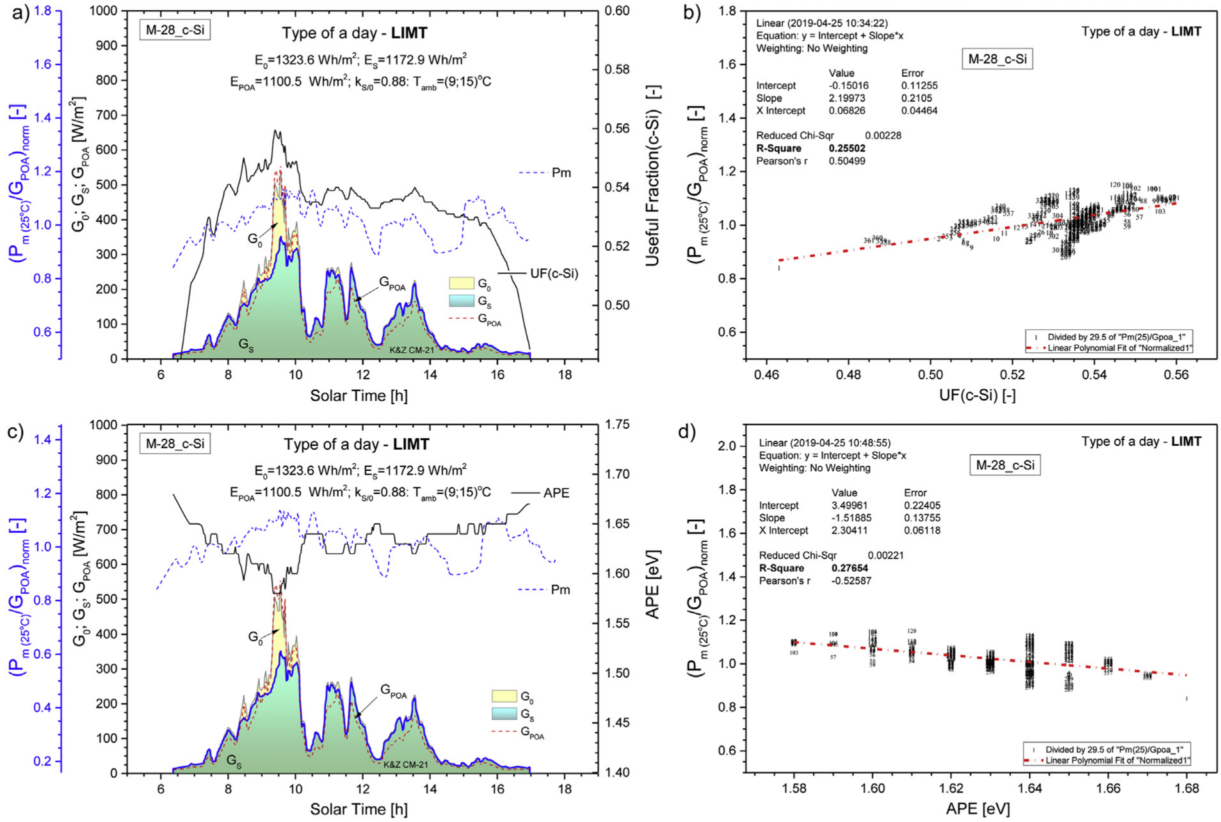

Fig. 4. Summary of the course of normalised power function P_m according to (15) with instantaneous: a) content of *UF*; c) *APE* value - according to time of day and the course of power reference function P_m from: b) *UF* content, d) *APE* value - of solar irradiance spectrum. The study included monocrystalline silicon modules (M-28_c-Si) during a cool and cloudy April day, referred to as LIMT.

4) **LILT** (**l**ow **i**rradiance, **l**ow **t**emperature) - typical winter day in Central Europe with low irradiance $G_{max} \cong 260\,W/m^2$ and $T_{amb} = -0.6 \div 0\,°C$;
5) **MIMT** (**m**edium **i**rradiance, **m**edium **t**emperature) - warm but cloudy day with peak irradiance $G_{max} \cong 350\,W/m^2$ and ambient temperature $T_{amb} = 7 \pm 14\,°C$;
6) **NICE** (**n**ormal **i**rradiance, **c**ool **e**nvironment) -typical summer day in a cool coastal region with peak irradiance $1000\,W/m^2$ and ambient temperature $T_{amb} = 18\,°C$.

In order to fully characterise these days, daily irradiation energy values were included in each graph: global E_0 and that from the diffusion component E_S of solar irradiation falling on the horizon plane, E_{POA} – energy of irradiation falling on the plane of the tested modules, and a daily value of cloudiness index $k_{s/o}$.

Figures (4, A1-11) clearly demonstrate the influence of the spectral parameters of solar radiation, such as: *UF* and the average value of photon energy of solar radiation spectrum, on the efficiency of photovoltaic conversion of modules made of various absorbers in outdoor conditions. A very good spectral match for uni- and three junction modules, made of amorphous silicon, at sunrise and sunset and during operation with predominantly cloudy conditions, deserves special attention. Particularly with regard to MIMT and MIHT type days (Fig. A6-11). As a result of the strong dampening of the long wavelength components of solar irradiation spectrum, with high *AM* values and water vapour content in the atmosphere – the w spectrum becomes more "blue". That is it contains fewer low-energy photons, i.e. so it *APE* and *UF* increase for amorphous modules. A similar phenomenon occurs during momentary covering of the sun by a cloud. Shadowing of the direct solar irradiation component, with a constant level of the diffused component causes a change in its instantaneous distribution. They have different distributions. In effect, the spectrum also becomes more "blue" (i.e., its *APE* increases). In practice, these phenomena are frequently observed during tests of PV module groups in *outdoor* conditions. More information on the above topic is included in Ref. 1. R. Gottschalg [51,52] obtained very similar results of the impact of *APE* and *UF* variations in relation to the I_{SC} current of uni- and three junction modules, made of amorphous silicon a-Si_SJ and a-Si_TJ.

Analysis of daily energy values

Figures 5, 6 present the influence of daily/monthly values of the selected *UF* and an average daily photon energy of solar radiation spectrum, on the energy accumulation capacity of PV modules with absorbers made of different materials. Figures in the graphs illustrate the obtained yield for a selected day in a year, whereas the figures in the box - for a selected month in a year. The studies were carried out in the laboratory of SolarLab PW Wroclaw. The daily/monthly values of useful fractions (*UF*) used in the studies, were determined according to Eqs. (2) and (3). Similarly, the daily average of photon energy values of solar irradiation spectrum (16) were determined, i.e.:

$$APE_{day} = \frac{\int_0^{day}\int_{\lambda_1}^{\lambda_2} G_{POA}(\lambda)d\lambda \cdot dt}{\int_0^{day} q \int_{\lambda_1}^{\lambda_2} \varphi_{ph}(\lambda)d\lambda \cdot dt}. \qquad (16)$$

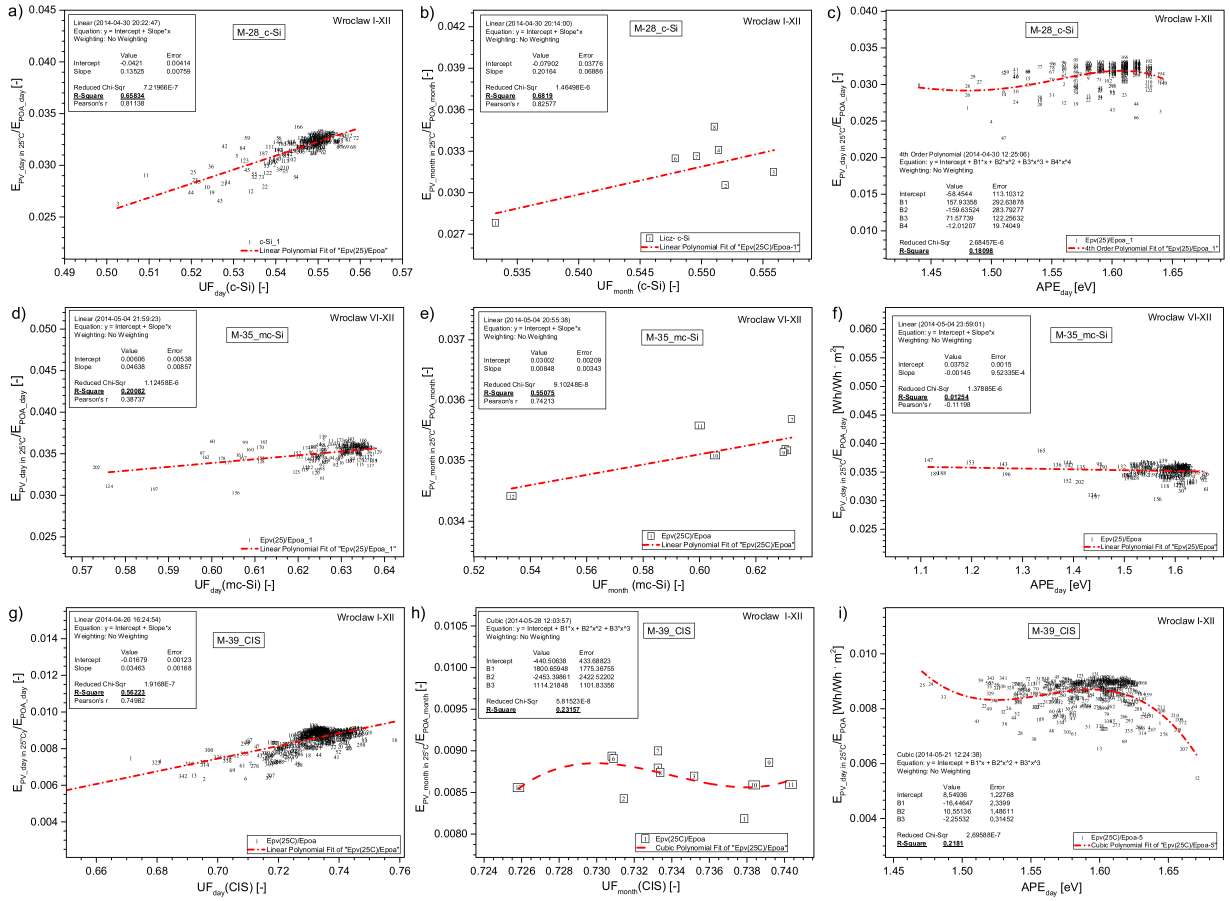

Fig. 5. The influence of daily (a,d,g)/monthly (b,e,h) values of the selected *UF* and the daily *APE* values (c,f,i) of solar irradiation spectrum on the energy accumulation capacity of the selected modules made of monocrystalline (c-Si)(a–c), multicrystalline (mc-Si)(d–f) silicon and with CIS-u(g–i). The studies were carried out for meteorological conditions prevailing in Wroclaw.

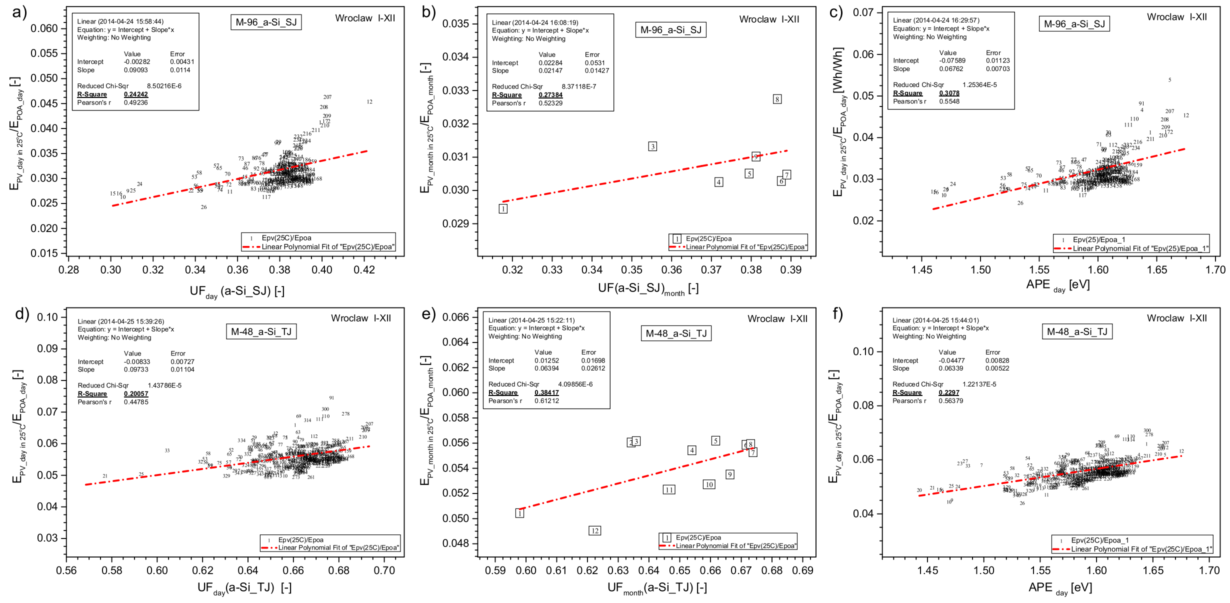

Fig. 6. The influence of daily (a,d)/monthly (b,e) values of the selected *UF* and the daily *APE* values (c,f) of solar irradiation spectrum on the energy accumulation capacity of the uni- and triple junction modules made of amorphous silicon (a-Si_SJ)(a–c) / a-Si_TJ(d–f)). The studies were carried out for meteorological conditions prevailing in Wroclaw.

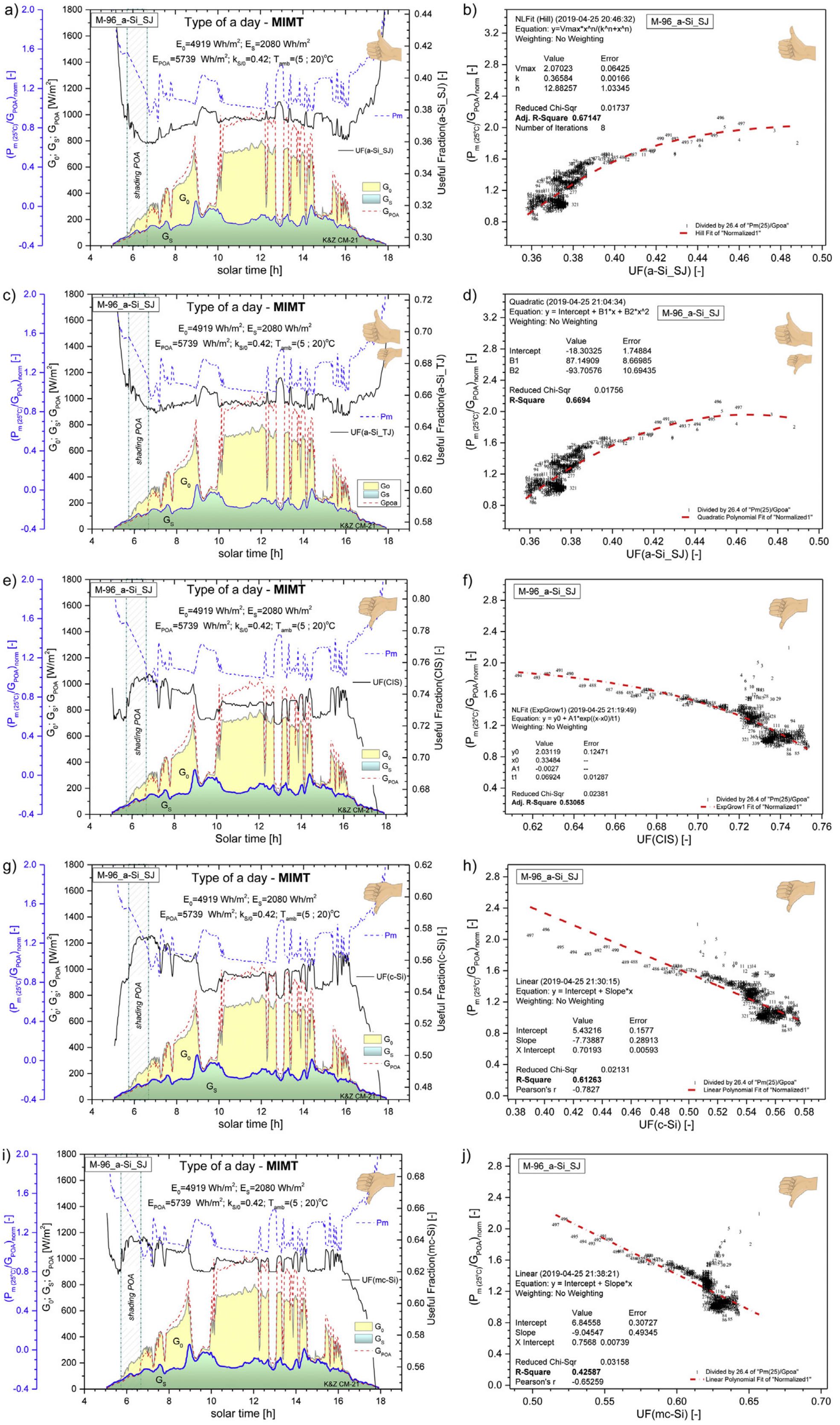

Fig. 7. Verification of the **M96_a-Si_SJ** module absorber. A certain difficulty exists in separating the applied amorphous silicon structure to a uni- /triple junction type. The use of a unijunction is supported by the higher R^2 factor and better concentration of measurement points in the graph b) *vs.* the graph d). The presented graphs e)–j) clearly exclude the use of the *c-Si*, *mc-Si* type absorber. The studies were carried out in the laboratory of SolarLab PW Wroclaw.

Daily/monthly energy yield values - carried out with reference to 1 Wh of energy of the solar irradiance falling on 1 m^2 of the POA plane of the tested module, i.e. according to Eqs. (17) and (18):

$$\frac{E_{PV\,day\,in\,25^{o}C}}{E_{POA\,day}} = \frac{\int_{0}^{day} \mathrm{P}_{\mathrm{m\,in\,25^{o}C}}(t)\,dt}{\int_{0}^{day} \mathrm{G}_{\mathrm{POA}}(t)\,dt}, \tag{17}$$

$$\frac{E_{PV\,month\,in\,25^{o}C}}{E_{POA\,month}} = \frac{\int_{0}^{month} \mathrm{P}_{\mathrm{m\_day\,in\,25^{o}C}}(t)\,dt}{\int_{0}^{month} \mathrm{G}_{\mathrm{POA\_day}}(t)\,dt}. \tag{18}$$

The obtained results confirm the occurrence of a strong influence of daily and monthly values of useful fractions on the energy yield by individual PV modules. In the case of an analysis of the influence of daily *APE* values, one can notice, for the modules with c-Si, CIS, and even mc-Si, in certain areas, the lack of influence or even decrease of energy yield according to *APE* value growth. Moreover, this phenomenon may also be observed in Fig. 5h), where the function of monthly energy value yield from *UF*, for the modules with CIS, also demonstrates growth areas and decrease of inclination. This phenomenon becomes more evident in the modules with the wider bands of spectral sensitivity. This is caused by the fact that in the case of the modules with wider bands of spectral sensitivity (comparable with the first window of solar irradiation spectrum, i.e. to 1.35 μm), changes of the average photon energy values *APE*, and even *UF*, for a defined distribution of solar irradiation spectrum, have a different mode of influence than from the narrow band modules. For the narrow band modules, such as: a-Si_Sj, a-Si_TJ – an increase in the average daily/monthly values of *APE* or *UF* causes an increase in the quantity of photons that may converted in the module [Figs. 6a)–f)].

In the case of broadband modules, the increase in the average daily *APE* value causes, in the area of small values: stagnation or very little increase of energy yield capacity, whereas in the area of large values (i.e., *APE* 1.6 eV) - a considerable decrease of energy yield capacity [Figs. 5c) and i)]. In this case, in the area of small *APE* values, the increase of the *APE* value due to a wide band of spectral sensitivity causes very little or no disturbance of the number and energy distribution of the falling photons with PV conversion capacity. Whereas, in the range of large *APE* values (i.e., *APE* 1.6 eV), further increase of *APE* causes dampening of high-energy photons in module construction elements (i.e., cell windows, glass, etc.) which, combined with a simultaneous very large decrease of long-wave photons quantity, causes a statistical change of the volume and distribution of energy of the absorbed photons, which participate in PV conversion in the module.

In the case of modules with CIS, the discussed phenomenon may be observed even in the monthly graphs of energy yield according to monthly values of useful fractions [Fig. 5h)]. This is caused by the fact that making analyses of energy yield capacity according to monthly values of useful fractions is carried out by double averaging of fraction energy - one averaging for a day and one for a month. Moreover, a very wide band of spectral sensitivity present in CIS results in low sensitivity of energy yield according to monthly changes of useful fraction values. R. Gottschalg [51-52] and A. Louwen obtained very similar results of the impact of changes in *APE* and *UF* on PV conversion of investigated modules.

The use of USEFUL FRACTION *factor to identify the absorber used in a PV module*

Figures 7 and Figures A12-13 present, on the example of two modules - M96_a-Si_SJ and M28_c-Si, application of the analysis with the use of daily distribution of *UF* of solar irradiation spectrum, in identification of the used absorber in PV modules. The studies were carried out for different days. As can be noticed, identification between two groups of absorbers: a-Si_SJ, a-Si_TJ and c-Si, mc-Si, CIS causes no problems. Whereas identification within these groups often requires implementation of analyses generated during several days. Additional, deeper analyses are required, including analyses of consolidation of points distributions in the graphs of power functions (15), i.e. $P_m(25^\circ C)\cdot\left[1/G_{POA}(t)\right]_{norm}$, and analyses of the obtained results from daily and monthly values of energy distribution.

In every case, the quality and workload level of the performed analyses for identification of the used absorber depends on:

Conformity of spectral sensitivities in the applied PV absorber models,

1 Precision of defining temperature factors for the tested modules, i.e. $\alpha_m(t) = \alpha_m(G_{POA})\cdot G_{POA}(t)$, and $\beta_m(t) = \beta_m(G_{POA})\cdot G_{POA}(t)$;

2 Occurrence of shading of the meteo station sensors by nearby objects and tree branches. Another factor is uneven shading of the meteo station sensors and tested modules, in particular the measuring unit G_{POA};

3 Precision of the used measuring equipment, i.e. measuring units of the meteo station and electrical parameters of the tested PV modules, precision of the modules temperature measurements and so-called inertia of the temperature measurement unit of *p*-*n* junction of a cell, for the tested PV module.

Conclusions

The following conclusions can be drawn from the research:

1 The study results clearly demonstrate the direct effect of the solar irradiation spectral parameters, such as *UF* value, determined in line with (2-4) or *APE* - on the characteristics of modules for power conversion in outdoor conditions;

2 The effect of *UF* on the capacity of modules for photovoltaic conversion in outdoor conditions is of *qualitative and not quantitative character*. This is caused by two factors: a) precision of determination of the *UF* content for solar irradiation spectrum and b) level of conformity of *SR* characteristics and the approved model for a defined PV absorber. In the case of the degree of conformity used typical for a given cell absorber / *SR* response characteristic module, it should be noted that in fact, within one material group, these differences can be quite significant. In the era of rapid progress in the development of cell / module production technology, striving to improve their efficiency - real characteristics of spectral sensitivity in even within one group of cells may differ significantly. Applying the *modification of useful fraction factor*, i.e. using PV cells spectral response characteristics (SR) relations (5, 6, 7) instead of their transfer band will certainly increase their precision and the achieved parameters. However, this also causes a narrowing of the usefulness range. The obtained results will be dedicated only to an individual module with a defined spectral characteristics, and will refer directly only to the I_{SC} current generation capacity of modules. Therefore, ex definition, the idea of the use of the useful fraction factor is - not quantitative but qualitative reflection of the influence the actual climate conditions on the conversion capacity of the selected PV modules;

3 The inexpensive method to determine the spectral adjustment with the use of such factors as *APE* and *UF* presented in the article, not requiring an expensive spectroradiometer, may be used for *qualitative* analyses using *UF* and *APE* factors in relation to the ability to convert modules outdoors.

This article is a continuation of studies on the determination of solar energy resources for photovoltaic purposes and, together with the maps presented there: daily, monthly, annual values of APE and UF distributions, enables to make the optimal selection of PV modules for dedicated meteorological conditions of a given area. The presented results confirm the usefulness of the procedures for the determination of spectral coefficients of solar radiation (*APE* and *UF*), and enable to prepare distribution maps of these coefficients by other scientific centres that do not have expensive spectroradiometer at their disposal.

The authors hope that publication of this article shall contribute to preparation of local maps and *UF* and *APE* distributions and popularisation of their use in estimating usefulness of modules made from different absorbers, in specific conditions of operations in outdoor conditions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.opelre.2019.05.004.

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