NUMERICAL PROCEDURES AND THEIR PRACTICAL APPLICATION IN PV MODULE ANALYSES. PART IV: ATMOSPHERIC TRANSPARENCY PARAMETERS - APPLICATION

Abstract: The presented article relates to aspects of PV module testing using natural sunlight in outdoor conditions. It is a continuation of the article Part III: parameters of atmospheric transparency - determining and correlations. This article discusses the practical application of the indexes: atmosphere purity - $k_{TM}$, diffused component content - $k_{SO}$, beam clear sky index - $K_b$ - in testing various modules in outdoor conditions. Their influence on the conversion of modules made from various absorbers and various technologies is demonstrated. Their practical application in module testing in outdoor conditions is described and it - has been demonstrated that the results of the analyses carried out using the indexes conform to the results obtained using spectral parameters of solar radiation (i.e. $APE$ and $UF$). These are the measurements that require the use of very expensive equipment.

Keywords: solar radiation spectrum, sky clearness index, diffused component content index, solar energy, photovoltaics

Introduction

It is difficult to continuously supply electric power from a photovoltaic system in the areas located in higher geographical latitudes. This is due to the fact that such areas are characterised by considerable variability of the climate conditions. Solar energy reaching these areas is variable in both day and year cycles. There are also actually unpredictable changes of cloudiness and precipitation. There are considerable differences in yearly distributions of: average environment temperatures, irradiance and average energy of photons of the solar irradiance spectrum. The yearly distributions of the environment temperatures and irradiance can be determined in a simple, unambiguous and cheap way, problems arise during preparation of the annual solar irradiance spectrum distribution. The performance of an analysis of correspondence of solar irradiation spectrum distribution and Spectral Response $SR(\lambda)$ of the applied PV modules requires the use of expensive and complex measuring equipment. That is why it is very important to design a simple and cheap device for assessing photovoltaic conversion capacity of the selected modules, for operation in dedicated climate and geographic conditions. Such a tool would enable making
estimations of the electric energy yield from a photovoltaic system in defined location conditions. The purity/transparency index $k_{Tm}$, and the respective index of dispersed compound content $k_{s/o}$, can be a tool in estimating the usefulness of modules made from various absorbers and in various technologies for operation in outdoor conditions. The presented indexes are physically connected not only with the irradiance path through the Earth’s atmosphere, which depends on the AM value, but also on the chemical composition and cloudiness of the atmosphere. They depend directly on the local climate conditions. The global value of daily solar irradiance reaching the Earth’s surface and its structure depend directly on these indexes. For this reason, the referred to indexes may supply the sufficient basis for estimating the resources and the very structure of solar irradiance in a given location. They may become a universal tool for characterising so called solar climate conditions for photovoltaic applications. This article was prepared using measurement data generated in two research centres - AGH University of Science and Technology in Krakow and Laboratorium SolarLab in Wrocław University of Science and Technology (WUST). The basic studies were carried out using measurement data from SolarLab in Wroclaw University of Science and Technology, whereas the data generated in AGH Krakow was treated as supplementary, i.e. comparative. A precise description of the lab measuring stations used in the studies, at AGH Krakow and SolarLab in Wroclaw University of Science and Technology, was included in [1, 2] and [3, 4], respectively.

This article is the fourth in the series of four interrelated articles, which discuss the issue of PV modules and cell measurement and testing in outdoor conditions, i.e. in natural sunlight. The first article contains an analysis of the theory and practice of measurements using *Air Mass* and its determination [5]. The second refers to the theory and practice of measurements, using such spectral parameters as *Useful Fraction* and *Average Photon Energy*, and a connection was made with *Air Mass* [6]. The third and fourth articles discuss measurements using atmosphere transparency parameters. For technical and editorial reasons, it was divided into two parts - analytical and measurement Part III: determining and correlations [7] and usage Part IV: application. The first part of the article includes a discussion on the physical sense of the indexes: atmosphere purity - $k_{Tm}$, diffused component content - $k_{s/o}$, beam clear sky index - $K_b$. The very close relation of the indexes with the figures characterising spectral distribution of solar irradiation was demonstrated. Their practical application in module testing in outdoor conditions was described in the second part and it was demonstrated that the results of the analyses carried out using the indexes conform to the results obtained using spectral parameters of solar irradiance (i.e. APE and UF). The above articles were written as a guide for the aforementioned research, with very extensive details of some leads and comments.

**Methodology**

**The object of research**

Two main objectives were set for the research undertaken regarding the influence of sky transparency indexes on the PV conversion of PV cells and modules. The first objective

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2 Due to the occurring shading of the measurement systems in the SolarLab laboratory in the early morning hours (i.e. for very low angles of entry and descent of the Sun in the sky), it was necessary to supplement the data from an independent measuring system from AGH Krakow, free of this type of phenomena. This particularly applies to the presentation of the dependencies of the Useful Fraction (UF) and APE instantaneous values with the *Air Mass* value.
was to demonstrate the correlation between the values of *Useful Fraction* (*UF*) and *APE* indexes and the parameters defining transparency of atmosphere, such as sky transparency index (*k*<sub>TM</sub>), *diffused component content index* (*k*<sub>SO</sub>), or *beam clear sky index* (*K*<sub>b</sub>). The second objective was to demonstrate the influence of these parameters on the PV conversion process of modules made of various absorbers in outdoor conditions. For this purpose, the data from an automatic system for monitoring the basic parameters of the tested PV modules was the subject of the research. The analysis was based on six modules during long-time operation in outdoor conditions. On the basis of the registered measurement results, the main technical parameters were set for each of the PV modules (Table 1). The parameters set were the basis for reference and the obtained study results are presented further in this article.

### Table 1

| Type<sup>3</sup> [no. absorber] | *I*<sub>m</sub>(STC) | *U*<sub>m</sub>(STC) | *P*<sub>m</sub>(STC) | *I*<sub>SC</sub>(STC) | *U*<sub>OC</sub>(STC) | *R*<sub>s</sub> determined acc. IEC 60891<sup>[9]</sup> | Monitoring period |
|-----------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-------------------|-----------------|
| M-96_a-Si_SJ               | 0.82            | 34              | 28              | 1.05            | 50.7            | 3.7               | 1-9             |
| M-48_a-Si_TJ               | 3.34            | 16.3            | 55.3            | 4.24            | 23              | 0.17              | 1-12            |
| M-28_c-Si                  | 4.65            | 7.74            | 33              | 4.68            | 9.7             | 0.07              | 1-9             |
| M-39_CIS                   | 0.44            | 20.7            | 9.3             | 0.5             | 26              | 3.19              | 1-12            |
| M-30_mc-Si                 | 4.66            | 7.44            | 34.6            | 5.08            | 9.8             | 0.04              | 6-12            |
| M-35_mc-Si                 | 4.66            | 7.9             | 35.5            | 4.83            | 9.8             | 0.043             | 1-12            |

**Compensation of temperature and irradiance intensity**

The physical demonstration of the influence of spectral and atmosphere transparency parameters on PV conversion capacity of PV modules made from various absorbers, in outdoor conditions, required compensating the influence of module cell temperatures and irradiance intensity on the obtained parameters. This can be done with reference to:

1) **constant standard temperature of cells** *T*<sub>C</sub> = 25 °C and irradiance intensity *G*<sub>POA</sub> = 1000 W/m<sup>2</sup> (i.e. to STC conditions), or

2) **constant standard temperature of cells** *T*<sub>C</sub> = 25 °C and conversion to 1 W of intensity *G*<sub>POA</sub> of the irradiance falling on POA.

A detailed analysis of the differences occurring, the presentation of the results and the applied methodology are presented in [6].

Further in the article, during implementation of the studies of the influence of atmosphere transparency parameters on the conversion capacity of PV modules and its imaging, the following was applied:

1) **A reference to the constant standard cell temperature** *T*<sub>C</sub> = 25 °C and irradiance intensity *G*<sub>POA</sub> = 1000 W/m<sup>2</sup> (i.e. to STC conditions), during the presentation of the influence of the above-mentioned factors on the value of a short-circuit current (*I*<sub>SC</sub>) of modules and the influence of the above-mentioned factors on the value of *spectral error of mismatch of measurement of the current* *I*<sub>SC</sub> for the selected PV modules,

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<sup>3</sup> M-96_a-Si_SJ - [M-96] number of the tested module, [a-Si_SJ] mark of the used absorber in a PV module, where: c-Si - monocrystalline silicon, mc-Si - multicrystalline silicon, CIS - with CuInSe<sub>2</sub> absorber, a-Si SJ - modules from amorphous silicon one and a-Si_TJ - and three-junctions.
i.e. carried out using standard procedures of translation to STC conditions for all current values, according to Blaesser’s method [9-12] described by the relation:

$$I_{SC} (25 \, ^{\circ}C; 1000 \, \text{W/m}^2) = \frac{1000}{G_{POA}(t)} \left( I_{SC}(t) + \alpha \cdot (25 - T_c(t)) \right)$$  

(1)

2) A reference to constant standard cell temperature \(T_C = 25 \, ^{\circ}C\) and conversion to 1 W of the intensity \(G_{POA}\) of irradiance falling on POA, during presentation of the influence of the above-mentioned indexes on the value of module power \(P_m\) and on the values of daily/monthly PV energy yield, i.e. partial translation was carried out, i.e. only translation of current and voltage values of maximum power point of a module, to temperature \(T_C = 25 \, ^{\circ}C\), i.e. using the relations:

$$I_m (25 \, ^{\circ}C) = I_m(t) + \alpha_m(t) \cdot (25 - T_c(t)), \quad (2)$$

$$U_m (25 \, ^{\circ}C) = U_m(t) + \beta_m(t) \cdot (25 - T_c(t)) - R_s \cdot (I_m (25 \, ^{\circ}C) - I_m(t)), \quad (3)$$

$$[P_m (25 \, ^{\circ}C) / G_{POA}]_{norm} = f (k_{Tm}, k_{\mu I0}, K_b, \ln(K_b)) \quad (4)$$

In this case, the module power in the maximum power point (MPP) divided by the value of irradiance intensity value \(G_{POA}\) falling on the plane of the tested modules illustrates the influence of atmosphere transparency indexes on the PV conversion capacity of the tested modules. Due to the differences in power of the tested PV modules, for the purpose of comparison, the result was normalised to the power obtained in STC conditions (i.e. \(P_{m,STC}\)) for 1 W of the falling irradiance intensity, i.e. to the value of \(P_{m,STC}/1000 \, \text{W/m}^2\). However, in the initial stage of the study, values of their power \(P_{m,STC}\) were determined independently and the obtained results are presented in Table 1.

**Identification of the mistakes of shading**

The study object was located on a platform with a variable inclination angle, i.e. 37\(^{\circ}\) during summer and 55\(^{\circ}\) from autumn to winter. It was shaded by permanent structures, such as buildings, for the sun elevation angle of below 17.3\(^{\circ}\), or by a nearby tree and shrubbery - 28.8\(^{\circ}\), i.e. for the AM values higher than 3.23 and 2.05, respectively. Identification of these objects is quite important, because the shading by the trees can be observed with full foliage, i.e. from the end of May/beginning of June. Whereas in the earlier months (January-May) it does not cause any significant measurement errors (Fig. 1). The following three types of shading occurred in the analysed system: 1) part of the plane of the tested modules shaded; no shading of meteo station (bright hatched area (Fig. 1)); 2) shading of the PV modules plane system and shading of meteo station (dark hatched area (Fig. 1)); 3) instantaneous shading of CM-21 measuring device installed in POA plane of the tested PV modules (Fig. 1b).

Of all the shadings, only 2) did not cause disturbances and measurement errors and, due to maintaining equal measurement conditions, it enlarged the study results with the range of PV module responses to enforce only the diffused component of irradiance. The remaining shadings had to be removed. Whereas in the case of analyses of instantaneous value progression within a given day it is possible to simply identify the occurrence of major measurement errors caused by shading and to filter them manually; in the case of analyses over a month/year, it is necessary to apply the appropriate identification technique in order to remove such errors (Fig. 2).
Numerical procedures and their practical application in PV module analyses. Part IV: …

One of them involves determining minimum elevation angles of the sun or a respective AM value, when the plane of the tested PV module is not yet shaded by the local buildings or trees (Fig. 1). Next, the data is filtered and examined for the potential measurement disturbances/errors. This method provides independence from changes of shading times occurring all year round. The disadvantage is the need to assume the symmetrical location of the shading objects. If this condition is not met, one has to consider potential loss of data or the occurrence of disturbances/noise in the results obtained (Fig. 1b).

The presented method of elimination of the interferences caused by shading from local objects is effective; however, this applies only when their quantity is low and medium. In the case of such locations as Laboratory SolarLab WUST Wroclaw, the obtained results contained “noise” and were difficult to analyse even after the filtering - the application of more intense filtering causes the loss of precious data, which was interesting from the point of view of the research carried out. Taking this into consideration, the above-mentioned studies were extended with analyses of energetic values, i.e. daily/monthly values (see chapter 3 in [7]). Then, the instantaneous interferences caused by, for example, shading during sunrise or sunset, for the large values of AM and even others, occurring at other times of a day (as long as they are instantaneous/short), cause very little energetic
interference in the values (see Fig. 3) and do not cause major errors in the total energy balance on the scale of day, month or year.

![Figure 2](image.png)

Fig. 2. Power conversion capacity in the function of useful fractions content. Identification of measurement errors caused by shading and their imaging. The research was carried out for the meteorological conditions occurring at SolarLab WUST Wroclaw

![Figure 3](image.png)

Fig. 3. Percentage distribution of irradiance energy content for different AM value ranges: a) yearly, b) monthly. The research was carried out for the meteorological conditions occurring at SolarLab WUST Wroclaw [5]

**Conclusion**

1. Studies using *daily/monthly values of energy yield* are carried out with reference to 1 Wh of irradiance energy falling on 1 m² of POA plane of the tested module. In this case, translating instantaneous values of the parameters of PV modules to STC conditions *serves no purpose*, as:
   a) we do not get rid of the interferences from shading of PV modules for higher AM values, but we emphasise them;
   b) *we cannot relate* the results to 1 Wh of the energy falling on a PV module.
2. The analysis using energy values is resistant to instantaneous shading during the hours of the sun setting and rising. Shading of the object during those hours, i.e. for the large AM values, as well as during short periods in other hours, carry very little values of energetic interferences (see Fig. 3), they are minimised and do not carry major errors in the energy balance of a day, month or year.

Results and discussion
Study of the influence of atmosphere transparency parameters on power conversion capacity

Fig. 4. The influence of clear sky index value \( k_{Tm} \) on the conversion capacity of PV modules made from various absorbers, i.e. for: a) crystalline silicon (c-Si), b) monocrystalline (mc-Si), c) CIS, d) amorphous single junction (a-Si_SJ) and e) amorphous triple junction (a-Si_TJ). The results were presented in reference to module constant temperature \( T_c = 25^\circ \text{C} \), instantaneous value of falling irradiance intensity and air mass value from the range \( AM = (1.2;1.5) \). (SolarLab WUST Wroclaw: 51.12N;17.01E. POA Modules: S-facing, Slope 37/55°)
Fig. 5. The influence of diffuse component content index of solar radiation ($k_{so}$) on the conversion capacity of PV modules made from various absorbers, i.e. for: a) crystalline silicon (c-Si), b) monocrystalline (mc-Si), c) CIS, d) amorphous single junction (a-Si_SJ) and e) amorphous triple junction (a-Si_TJ). The results were presented in reference to module constant temperature $T_C = 25 \, ^\circ\text{C}$, instantaneous value of falling irradiance intensity and air mass value from the range $AM = (1.2;1.5)$. (SolarLab WUST Wroclaw: 51.12N;17.01E. POA Modules: S-facing, Slope 37/55°)
Fig. 6. The influence of beam clear sky index value ($K_b$) on the conversion capacity of PV modules made from various absorbers, i.e. for: a) crystalline silicon (c-Si), b) monocrystalline (mc-Si), c) CIS, d) amorphous single junction (a-Si_SJ) and e) amorphous triple junction (a-Si_TJ). The results were presented in reference to module constant temperature $T_c = 25 \, ^\circ C$, instantaneous value of falling irradiance intensity and air mass value from the range $AM = (1.2;1.5)$. (SolarLab WUST Wroclaw: 51.12N;17.01E. POA Modules: S-facing, Slope 37/55°)

Subsequent figures present conversion capacity of PV modules made from various absorbers, in the function of clear sky parameters, namely: clear sky index value $k_{im}$ - Figure 4 and Figure A-1.1-3, diffused component content index value $k_{d\phi}$ - Figure 5 and Figure A-1.4-6, beam clear sky index ($K_b$) - Figure 6 and Figure A-1.7-9, and logarithm of beam clear sky index $\text{ln}(K_b)$ - Figure 7 and Figure A-1.10-12. The distribution was made for

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4 Due to the very large number of graphs presented - the article presents graphs only from the first group of $AM$ values. Graphs from the second and other groups are placed in the Attachment of the article, marking them as Figures A-xx. The Attachment is available at the paper page.
$AM$ values in the four basic ranges: (1.2;1.5) - measurements of cells and PV modules, (2.6;3) and (3.5;4) testing PV conversion in natural conditions, and for $AM > 4$, i.e. observation of phenomena in the conditions of very high diffused component content. Due to the very large number of the presented graphs, the article contains graphs only from the first range of $AM$ values. Graphs from group two and others are contained in the annex hereto, marked as Figure A-x.yy.

![Graphs showing the influence of logarithm of beam clear sky index value $\ln(K_b)$ on the conversion capacity of PV modules made from various absorbers.](image)

Fig. 7. The influence of logarithm of beam clear sky index value $\ln(K_b)$ on the conversion capacity of PV modules made from various absorbers, i.e. for: a) crystalline silicon (c-Si), b) monocrystalline (mc-Si), c) CIS, d) amorphous single junction (a-Si_SJ) and e) amorphous triple junction (a-Si_TJ). The results were presented in reference to module constant temperature $T_c = 25 \, ^{\circ}C$, momentary value of falling irradiance intensity and air mass value from the range $AM = (1.2;1.5)$. (SolarLab WUST Wroclaw: 51.12N;17.01E. POA Modules: S-facing, Slope 37/55°)
Figure 4 and Figure A-1.1-3 illustrate the influence of clear sky index on the power conversion capacity of individual PV modules. Referring to the definition of the above-mentioned index and to the physical interpretation presented in chapter 3 [7], this is a relation of the value of instantaneous global irradiance falling on the plane of horizon to the value of extraterrestrial beam of irradiance falling in the upper atmosphere on the plane parallel to horizon. It determines what part of the falling global irradiance reaches the Earth’s surface through the phenomena of absorption, diffusion, and reflection that occur in the atmosphere. It is the index of PV conversion capacity in the areas of very low irradiance values. The analysis in Figure 4 shows that the modules made from amorphous silicon, single-(a-Si_SJ) and triple junction (a-Si_TJ) operate much better in the range of very low values of clear sky indexes \(k_f\). Together with the increase of the value of \(k_f\) index, the power conversion capacity in these modules exponentially decreases. The lack of a PV conversion activation threshold is a characteristic feature of these modules. Whereas the modules made from crystalline (c-S), polycrystalline (mc-Si) and CIS silicone demonstrate the increase of conversion capacity, together with the increase of \(k_f\) index. The occurrence of the PV conversion threshold activation can be observed here. This is connected with the purity of PV absorber used in manufacturing of a PV cell/module. More information on the characteristics of the atmosphere clearness index in [13-16] and the application of estimates of energy generation capacity by PV modules in [17-20].

Figure 5 and Figure A-1.4-6 present the influence of the value of diffused component content index \(k_{sd}\) on the PV module conversion capacity. Referring to the definition of the above-mentioned index and to the physical interpretation presented in chapter 3 [7], this is a relation of the diffused component content value to the value of global irradiance falling on the plane of horizon. Taking into consideration that the diffused component of irradiance is a high-energy component, the direct component is low energy and the global irradiance is a superposition vector of the above-mentioned components, physically, the index of diffused component content \(k_{sd}\) presents an average energy of photons on the irradiance spectrum [6, 7]. More information on the above mentioned topic and the practical application of the above mentioned index in [21-24] and [25-28].

Figure 6 and Figure A-1.7-9 present beam clear sky index \((K_b)\), and Figure 7 and Figure A-1.10-12 - beam clear sky index logarithm \(\ln(K_b)\). The logarithm \(K_b\) \(\ln(K_b)\) reflects atmosphere turbidity for the direct component of irradiance (see chapter 3 [7]). Whereas the presented graphs of PV module power conversion in the function \(\ln(K_b)\) illustrate PV conversion susceptibility at various levels of attenuation and absorption of the direct component of irradiance falling on a PV module. Similarly, as with other indexes, they characterise their susceptibility to PV conversion individually in strictly defined climate conditions. Together with relevant maps of yearly/monthly distributions of these indexes, they make it possible to optimise selection of module type for the dedicated operation locations. Additionally, knowledge of their distribution allows absorbers used in PV modules to be identified, similar to what is demonstrated in [6] using spectral parameters of irradiance. Very similar results during own research were obtained in [19, 20].

**Study of the influence of atmosphere transparency parameters on power yield capacity**

The daily values of indexes used in the analyses were determined according to (22), (23) and (24) from [7].
The analyses of daily/monthly values of energy yield were carried out with reference to 1 Wh of daily/monthly value of energy of the global (total) irradiance falling on the POA plane of the tested modules. It seems appropriate not to apply complete translation to STC conditions here, i.e. using only the translation of the obtained power \( P_m(t) \) of PV modules to the values achieved at temperature \( T_C = 25 \) °C. That is because the integral from the power \( (P_m(t)) \) for a period of a day and a month produces the value of the parameter \( E_{PV\ day\ in\ 25\ °C} \), \( E_{PV\ month\ in\ 25\ °C} \) which, in reference to 1 Wh of the energy falling during a day/month on the plane of PV modules, is the analysed yield parameter in the so-called energy yield method. The main characteristics of the studies using energy values is the fact that instantaneous interferences of measurement, occurring due to shading of the plane of the tested PV
modules, during times of sunrise and sunset, occurring for high values of AM (see Fig. 3), and occurring even at other times of day (instantaneous), and causing very small values of energetic interferences are minimised and do not cause noticeable errors in total energy balance on the scale of day, month or year.

Fig. 9. The influence of values: a) beam clear sky index ($K_b$), b) logarithm of beam clear sky index ($\ln(K_b)$), c) diffused component content index $k_{slo}$ on power conversion capacity ($P_m$), and respectively (d-f), capacity of daily accumulation of energy of the single junction modules made from amorphous silicon (a-Si SJ). (SolarLab WUST Wroclaw: 51.12N;17.01E. POA Modules: S-facing, Slope 37/55°)

Figures 8 and 9, Figure A-2.1-4 present the influence of values: beam clear sky index ($K_b$), logarithm of beam clear sky index ($\ln(K_b)$), diffused component content index $k_{slo}$ on power conversion capacity $P_m$ and, respectively, capacity of daily accumulation of energy of the modules made from various absorbers. Due to the large amount of the
above-mentioned material, this article presents the results referring to the silicon crystalline (mc-Si) (Fig. 8) and amorphous, single junction (a-Si_SJ) module only (Fig. 9). The results for other modules are presented in the attachment (Fig. A-2.1-4). In order to illustrate the advantages of using the energy values analyses, figures marked a), b), c) show graphs of instantaneous values, whereas figures d), e), f) show the respective analyses of daily energy values. One may conclude from an analysis of these figures that the obtained results for daily values of energy yield demonstrate trends in accordance with the respective instantaneous values. They are certainly more legible. The more unclear the instantaneous values are, the more useful the figures. For example, analysing the values from Figure 9, the level of conformity and legibility of the trends in instantaneous value graphs is similar to the values of energy graphs. This is caused by the fact that single junction modules from amorphous silicon demonstrate very good PV conversion characteristics, in the range of very low insolation; therefore, instantaneous value graphs contain few interferences. Graphs related to other modules are quite different, e.g. from c-S (Fig. 8) or from CIS (Fig. A-2.3), in which a reliable trend demonstrates energy values. Very similar results during own research were obtained in [19, 20].

**Qualitative verification of the influence of atmosphere transparency parameters on the power conversion capacity of the selected PV modules**

![Fig. 10. Comparison: a) progress of power conversion capacity and b) useful fractions distribution (UF) for the selected absorber of a PV module, in the function of variable air mass value AM and atmosphere transparency index $k_{Tm}$. Study results for the modules made from crystalline silicon (c-Si). (SolarLab WUST Wroclaw: 51.12N;17.01E. POA Modules: S-facing, Slope 37/55°; $B = (0.3;1.7) \ \mu m$)](image)
Fig. 11. Comparison: a) progress of power conversion capacity and b) useful fractions distribution (UF) for the selected absorber of a PV module, in the function of variable air mass value $AM$ and atmosphere transparency index $k_{Tm}$. Study results for the modules made from multicrystalline silicon (mc-Si). (SolarLab WUST Wroclaw: 51.12N;17.01E. POA Modules: S-facing, Slope 37/55°; $B = (0.3;1.7)$ μm)

Fig. 12. Comparison: a) progress of power conversion capacity and b) useful fractions distribution (UF) for the selected absorber of a PV module, in the function of variable air mass value $AM$ and atmosphere transparency index $k_{Tm}$. Study results for the modules made from multicrystalline silicon (CIS). (SolarLab WUST Wroclaw: 51.12N;17.01E. POA Modules: S-facing, Slope 37/55°; $B = (0.3;1.7)$ μm)
Fig. 13. Comparison: a) progress of power conversion capacity and b) useful fractions distribution (UF) for the selected absorber of a PV module, in the function of variable air mass value AM and atmosphere transparency index $k_{tm}$. Study results for the modules made from amorphous silicon (a-Si_SJ). (SolarLab WUST Wroclaw: 51.12N;17.01E. POA Modules: S-facing, Slope 37/55°; $B = (0.3;1.7) \mu m$)

Fig. 14. Comparison: a) progress of power conversion capacity and b) useful fractions distribution (UF) for the selected absorber of a PV module, in the function of variable air mass value AM and atmosphere transparency index $k_{tm}$. Study results for the triple junction modules made from amorphous silicon (a-Si_TJ). (SolarLab WUST Wroclaw: 51.12N;17.01E. POA Modules: S-facing, Slope 37/55°; $B = (0.3;1.7) \mu m$)
Fig. 15. Comparison: a) progress of power conversion capacity and b) useful fractions distribution ($UF$) for the selected absorber of a PV module, in the function of variable air mass value $AM$ and diffused component content index $k_{s/o}$. Study results for the modules made from crystalline silicon (c-Si). (SolarLab WUST Wroclaw: 51.12N; 17.01E. POA Modules: S-facing, Slope 37/55°; $B = (0.3;1.7) \mu m$)

Fig. 16. Comparison: a) progress of power conversion capacity and b) useful fractions distribution ($UF$) for the selected absorber of a PV module, in the function of variable air mass value $AM$ and diffused component content index $k_{s/o}$. Study results for the modules made from multicrystalline silicon (mc-Si). (SolarLab WUST Wroclaw: 51.12N; 17.01E. POA Modules: S-facing, Slope 37/55°; $B = (0.3;1.7) \mu m$)
Fig. 17. Comparison: a) progress of power conversion capacity and b) useful fractions distribution (UF) for the selected absorber of a PV module, in the function of variable air mass value AM and diffused component content index $k_{s/o}$. Study results for the modules made from CIS. (SolarLab WUST Wroclaw: 51.12N;17.01E. POA Modules: S-facing, Slope 37/55°; $B = (0.3;1.7) \mu m$)

Fig. 18. Comparison: a) progress of power conversion capacity and b) useful fractions distribution (UF) for the selected absorber of a PV module, in the function of variable air mass value AM and diffused component content index $k_{s/o}$. Study results for the single junction modules made from amorphous silicon (a-Si_SJ). (SolarLab WUST Wroclaw: 51.12N;17.01E. POA Modules: S-facing, Slope 37/55°; $B = (0.3;1.7) \mu m$)
Fig. 19. Comparison: a) progress of power conversion capacity and b) useful fractions distribution \((UF)\) for the selected absorber of a PV module, in the function of variable air mass value \(AM\) and diffused component content index \(k_{o/o}\). Study results for the triple junction modules made from amorphous silicon \((a\text{-Si} _{\text{TJ}})\). (SolarLab WUST Wroclaw: 51.12N;17.01E. POA Modules: S-facing, Slope 37/55°; \(B = (0.3;1.7) \mu m\))

Fig. 20. Comparison: a) progress of power conversion capacity and b) useful fractions distribution \((UF)\) for the selected absorber of a PV module, in the function of variable air mass value \(AM\) and beam clear sky index \(K_b\). Study results for the modules made from crystalline silicon \((c\text{-Si})\). (SolarLab WUST Wroclaw: 51.12N;17.01E. POA Modules: S-facing, Slope 37/55°; \(B = (0.3;1.7) \mu m\))
Fig. 21. Comparison: a) progress of power conversion capacity and b) useful fractions distribution ($UF$) for the selected absorber of a PV module, in the function of variable air mass value $AM$ and beam clear sky index $K_b$. Study results for the modules made from multicrystalline silicon (mc-Si). (SolarLab WUST Wroclaw: 51.12N;17.01E. POA Modules: S-facing, Slope 37/55°; $B = (0.3;1.7) \mu m$)

Fig. 22. Comparison: a) progress of power conversion capacity and b) useful fractions distribution ($UF$) for the selected absorber of a PV module, in the function of variable air mass value $AM$ and beam clear sky index $K_b$. Study results for the modules made from CIS. (SolarLab WUST Wroclaw: 51.12N;17.01E. POA Modules: S-facing, Slope 37/55°; $B = (0.3;1.7) \mu m$)
Fig. 23. Comparison: a) progress of power conversion capacity and b) useful fractions distribution (UF) for the selected absorber of a PV module, in the function of variable air mass value $AM$ and beam clear sky index $K_b$. Study results for the single junction modules made from amorphous silicon (a-Si_SJ). (SolarLab WUST Wroclaw: 51.12N; 17.01E. POA Modules: S-facing, Slope 37/55°; $B = (0.3; 1.7)$ µm)

Fig. 24. Comparison: a) progress of power conversion capacity and b) useful fractions distribution (UF) for the selected absorber of a PV module, in the function of variable air mass value $AM$ and beam clear sky index $K_b$. Study results for the triple junction modules made from amorphous silicon (a-Si_TJ). (SolarLab WUST Wroclaw: 51.12N; 17.01E. POA Modules: S-facing, Slope 37/55°; $B = (0.3; 1.7)$ µm)

Figures 10-24 present a comparison of conversion capacity of PV modules made from various absorbers with useful fractions (UF) distribution of the spectrum of the irradiance falling on the modules. Already an initial analysis shows a large correlation between the graphs of useful fractions and the respective graphs of PV modules conversion capacity. Only in one case, for the module M-35 with mc-Si absorber, a certain inconsistency of these graphs - function of $k_{s/o}$ index - was observed. It occurs in the range of air mass values $3.5 > AM > 6$ (see Fig. 16a,b) and low value of $k_{s/o} < 0.45$. That is in the morning and evening (see Fig. 11 in [7]) for summer days with clear sky. In the situation when the falling irradiance contains a low amount of diffused component (i.e. Blue and UV radiation) and its direct component contains high amounts of infrared radiation (the effect
of red setting and rising sun). This is caused by the divergence of the applied SR characteristics for the mc-Si absorber and the actual one, covering all tested PV modules.

The use of atmosphere transparency parameters for identification of the absorber used in a PV module

Considering that each of the applied indexes has a different physical interpretation (see chapter 3 in [7]), e.g. index $K_b$ - beam clear sky index, and $k_{s/o}$ - content of diffused component in global irradiance falling on a module surface, they characterise different areas of the spectrum of irradiance falling on the POA surface of the tested PV modules. Considering the above, a precise calculation of instantaneous power $P_m$ of a module in the function of their distribution, and carrying out a comparative analysis on that basis, should make it possible to prepare a table showing variability of instantaneous power values for characteristic areas of operation. Therefore, on the basis of the analyses of instantaneous power distribution carried out in the function of atmosphere transparency parameters, as presented in Figures 10-24, the tendencies in fluctuation of instantaneous power $P_m$ characteristics of the tested modules were defined, in the function of change of the selected atmosphere transparency parameters for characteristic areas (Table 2). Such a table may be used for the identification of the applied absorber in the tested PV modules.

| AM  | M-28_c-Si | M-35_mc-Si | M-96_a-Si_SJ | M-48_a-Si_TJ | M-39_CIS |
|-----|------------|------------|--------------|--------------|----------|
|     | $k_{tm}$   | $k_{s/o}$  | $K_b$        | $k_{tm}$     | $k_{s/o}$ |
| 1+3 |             |            |              | $K_b$        |          |
| 3+6 |             |            |              | $K_b$        |          |
| 6+12|             |            |              | $K_b$        |          |

Table 2

Table illustrating fluctuation of $P_m$ power values in the function of atmosphere transparency parameters

As can be clearly observed, verification between two groups of absorbers a-Si_SJ; a-Si_TJ and c-Si, mc-Si, CIS is trouble-free, whereas identification within these groups often requires the implementation of additional analyses. In every case, the quality and workload level of the performed analyses for identification of the used absorber depends on:

- precision of calculation temperature coefficients of the tested modules,
- stability (lack of change) in the architecture of the nearby objects,
- shading level of the system by nearby objects and tree branches, including the level of uneven shading of the meteo station sensors and tested modules, in particular the measuring unit $G_{POA}$. 
In order to increase the precision of identification of $P_m$ power values fluctuation in the function of atmosphere transparency, i.e. in order to enable an analysis within a group of modules, a table can be prepared with five sub-ranges of AM value changeability, on the basis of a comparative analysis from Figures 4-7 and Figure A-1.1-12, or even with nine sub-ranges, which were defined in Figure 11 in [7]. Due to the extensive scope of the above-mentioned article, the issue was just referred to.

The presented method of absorber identification is dedicated for a specific environment of the testing station. Any change in the architecture of the surrounding area, e.g. the erection of a GSM pole, a new building or construction, a vehicle, or moving the location of PV modules POA plane frame, may cause a change of albedo large enough to disturb the above-mentioned analysis.

The influence of atmosphere transparency parameters on the level of spectral mismatch error in $I_{SC}$ current measuring in PV modules

![Fig. 25. The influence of the values: a) atmosphere transparency index $k_{Tm}$, b) diffused component content coefficient $k_{s/o}$, c) beam clear sky index $K_b$, on the level of spectral mismatch error level of $I_{SC}$ current measurement in PV modules made from crystalline silicon (c-Si). (SolarLab WUST Wroclaw: 51.12N;17.01E. POA Modules: S-facing, Slope 37\degree/55\degree; $B = (0.3;1.7)$ µm)](image-url)
Fig. 26. The influence of the values: a) atmosphere transparency index $k_{Tm}$, b) diffused component content coefficient $k_{s/o}$, c) beam clear sky index $K_b$, on the level of spectral mismatch error level of $I_{SC}$ current measurement in PV modules made from multicrystalline silicon (mc-Si). (SolarLab WUST Wroclaw: 51.12N;17.01E. POA Modules: S-facing, Slope 37/55°; $B = (0.3;1.7) \, \mu m$)

Comparison of the level of occurrence of spectral error of mismatch of $I_{SC}$ current measurement in PV modules made from various absorbers

| Module type | Changeability range $\delta(I_{SC})$ [%] acc. to Figures 25-29 | Changeability range $\delta(I_{SC})$ [%] acc. to Figures 19-23 with [5] | Sensitivity level |
|-------------|-------------------------------------------------|-------------------------------------------------|-----------------|
|             | $k_{Tm}$                                      | $k_{s/o}$                                      | $K_b$           | $AM = (1.2; 3), \beta = (0; 0.4)$ | 1 - min., 5 - max |
| c-Si        | $(-3.95; 7.4)$                                | $(-3.8; 8.3)$                                  | $(-4.3; 7.1)$   | $\pm 4.7 = 9.4$             | 2                |
| mc-Si       | $(-0.75; 10)$                                 | $(-0.5; 11)$                                   | $(-1.25; 11.9)$| $\pm 7.1 = 14.2$            | 3                |
| CIS         | $(-1.8; 4.6)$                                 | $(-4; 3.8)$                                    | $(4; 3)$        | $\pm 2.7 = 5.4$             | 1                |
| a-Si_SJ     | $(-12; 16.8)$                                 | $(-13.6; 16.3)$                                | $(-9.8; 17.5)$  | $\pm 19 = 38$               | 5                |
| a-Si_TJ     | $(-15; 13.5)$                                 | $(-10; 12.3)$                                  | $(-12; 9.9)$    | $\pm 12.5 = 25$             | 4                |
Numerical procedures and their practical application in PV module analyses. Part IV: …

Fig. 27. The influence of the values: a) atmosphere transparency index $k_{Tm}$, b) diffused component content coefficient $k_{s/o}$, c) beam clear sky index $K_b$, on the level of spectral mismatch error level of $I_{SC}$ current measurement in PV modules made from CIS. (SolarLab WUST Wroclaw: 51.12N;17.01E. POA Modules: S-facing, Slope 37/55°; $B = (0.3;1.7) \mu m$)

In order to eliminate the influence of temperature and intensity of irradiance on the spectral nonconformity error of the current $I_{SC}$, all measured values of $I_{SC}$ of PV modules were translated in STC conditions, i.e. they were referred to the constant standard temperature of cells $T_c = 25 \, ^\circ C$ and irradiance intensity $G_{POA} = 1000 \, W/m^2$. Additionally, in accordance with Blaesser’s procedures [9-12] the nominal value of $I_{SC}$ current was determined in STC conditions, included in Table 1. In this case, the influence of atmosphere transparency parameters on the spectral nonconformity error of $I_{SC}$ current measurement in PV modules is demonstrated in the following form:

$$
\delta(I_{SC}) = \frac{I_{SC \, STC} (k_{Tm}, k_{s/o}, K_b, AM) - I_{SC \, STC}}{I_{SC \, STC}} \cdot 100 \, \% 
$$

(5)

According to (5), the obtained values of spectral nonconformity error in the function of atmosphere transparency parameters for different modules were presented in Figures 25-29, where in each graph, the reference value for $\delta(I_{SC}) = 0$ was marked.
Fig. 28. The influence of the values: a) atmosphere transparency index $k_{Tm}$, b) diffused component content coefficient $k_{s/o}$, c) beam clear sky index $K_b$, on the level of spectral mismatch error level of $I_{SC}$ current measurement in PV modules made from single junction amorphous silicon (a-Si_SJ). (SolarLab WUST Wroclaw: 51.12N;17.01E. POA Modules: S-facing, Slope 37/55°; $B = (0.3;1.7)$ μm)

The purpose of qualitative verification of spectral divergence errors of $I_{SC}$ was determined in an experimental way $\delta(I_{SC})$ with the values estimated theoretically $\varepsilon(I_{SC})$ [5], a summary of their ranges of changeability was prepared in Table 3. Where, the width of the changeability range illustrates the level of sensitivity of spectral mismatch error, due to the particular atmosphere transparency parameter. The analysis of the ranges of mismatch errors of $\delta(I_{SC})$, $\varepsilon(I_{SC})$, shows that the smallest ranges occur for the modules made from CIS and crystalline silicon (c-Si). They are also very small for multicrystalline silicon, whereas they are very large for amorphous silicon - the largest for single junction modules with narrow characteristics of spectral sensitivity, a bit smaller for triple junction modules with wider spectral characteristics.

The quantitative differences occurring between the values of spectral mismatch error for the measurements of $I_{SC}$ of PV modules $\delta(I_{SC})$ and $\varepsilon(I_{SC})$ are caused by many factors, mainly 1) the level of nonconformity of Spectral Response (SR) characteristics of the tested PV modules with the applied models for individual absorbers and 2) different conditions of their determination. Spectral mismatch error $\varepsilon(I_{SC})$ is an instantaneous value determined theoretically in cloudless day conditions, for air mass value $AM \leq 3$ and turbidity $\beta \leq 0.4$. 
Whereas the spectral mismatch error of $\delta(I_{SC})$ is an actual error, measured in the experiment, according to the relation (5), for the actual conditions of a module operation present in a given environment. Additionally, it is determined as a function of atmosphere transparency parameters on the basis of a statistical average from the yearly collection of data in a wide range - of actual changes of air mass $AM$ value changes and turbidity $\beta$. The range of changes was much wider than those applied for theoretical calculations in determining the error of $\varepsilon(I_{SC})$ and the range also includes days with different levels of cloudiness. Additionally, taking into consideration fast technological progress in PV cells/modules manufacturing and improvement of their efficiency, the actual characteristics of spectral sensitivities may differ considerably even within one group; one may expect only qualitative and not full quantitative conformity of the obtained results.

Fig. 29. The influence of the values: a) atmosphere transparency index $k_{Tm}$, b) diffused component content coefficient $k_{s/o}$, c) beam clear sky index $K_{sk}$ on the level of spectral mismatch error level of $I_{SC}$ current measurement in PV modules made from triple junction amorphous silicon (a-Si TJ). (SolarLab WUST Wroclaw: 51.12N;17.01E. POA Modules: S-facing, Slope 37/55°; $B=(0.3;1.7) \mu m$)
Conclusion

The following conclusions can be drawn from the research undertaken:

1. The use of atmosphere transparency indexes - such as atmosphere transparency index $k_{tm}$, diffused component content index $k_{s/o}$, beam clear sky index $K_b$ - is a cheap and very practical method of testing module conversion capacity in actual operating conditions.

2. Making long-term studies of PV module conversion capacity in outdoor conditions provides a full picture of usefulness in specific climate conditions, characteristic for higher geographical latitudes in particular. In this context, the use of transparency indexes in the above-mentioned studies is indispensable. For example, tests using only the index $k_{s/o}$ (Fig. 15-19) show that the optimal conditions for photovoltaic conversion are, for modules made of:
   1) amorphous silicon a-Si_SJ: $k_{s/o}$ - high above 0.5 and $AM$ above 6. In the area of $AM = (1, 6)$ there is a very strong increase in conversion with an increase in $AM$ and very high sensitivity to changes in the $k_{s/o}$ index;
   2) amorphous silicon a-Si_TJ: $k_{s/o}$ - high above 0.3. There is relatively low sensitivity to $AM$ changes, and relatively high sensitivity to changes in the $k_{s/o}$ index;
   3) monocrystalline silicon (c-Si): $k_{s/o}$ - low, the lower the better; $AM$ low - optimal for $AM \approx 3$, PV conversion strongly decreases with $AM$ increase. The influence of the $k_{s/o}$ index disappears from values of $AM 5$ and higher; $AM > 3$ it increases with the increase of $k_{s/o}$;
   4) polycrystalline silicon (mc-Si): For $AM < 3$ - there is a decrease in PV conversion with increasing $k_{s/o}$, low $AM$ - optimal for $AM \approx 3$, moreover, the conversion strongly decreases with increasing $AM$. Whereas for $AM > 3$ it increases with the increase of $k_{s/o}$;
   5) CIS: $k_{s/o}$ - low, the lower the better; optimum for $AM = (2, 7)$.

3. The use logarithm of beam clear sky index $K_b$ has become very useful. Preparing a comparison of the function $\ln(K_b)$ causes elongation and precise penetration of the occurring phenomena in the areas of low and very low insolation.

4. The maps of their annual distribution in the dedicated climate zones should be used as the main input parameter in optimising newly created cells and modules dedicated to operating in such geographical and climate conditions.

5. The main problem with measurements with sunlight is its large spectral changeability, which means that the measurement conditions with natural sunlight restrict its possibility. The measurements can be carried out only in the appropriate conditions. In natural conditions, even for the same day, spectral distribution of solar radiation of the same air mass ($AM$) from before and after noon is different, which results in different measurement outputs for the same PV cells and modules. In this context, due to the occurrence of a strong connection between atmosphere transparency parameters and spectral parameters which characterise irradiance, such as $APE$ or $UF$, the atmosphere transparency parameters that are determined in a simple and cheap way are very useful in characterising atmospheric conditions present during the studies.

6. The results of spectral mismatch error $\delta(I_{SC})$, determined in the process of experiment, were confirmed in the qualitative way by theoretically determined error results $\varepsilon(I_{SC})$. This means that in engineering applications, in many cases, the analyses using spectral mismatch error value $\varepsilon(I_{SC})$ can be carried out using $\delta(I_{SC})$. This is important because
the level of complications during calculations of $\varepsilon(I_{SC})$ is much higher than $\delta(I_{SC})$; needless to say, in many cases it is not even possible to calculate.

7. Taking into consideration the occurrence of the strong connection between atmosphere transparency parameters and spectral parameters, such as $APE$ or $UF$, the obtained results can be skilfully used (i.e. with proper understanding) with clearness indexes, which in practice may totally replace the need to carry out studies using spectral parameters of irradiance, which require application of very expensive measuring equipment, i.e. their analysis should lead to the same conclusions that are obtained as a result of research using spectral parameters. For example, as a result of the analyses carried out, the following can be stated: modules made from CIS, crystalline (c-Si) and multicrystalline (mc-Si) due to their very wide range of spectral sensitivity ($SR$), demonstrate very low sensitivity to the changes of atmosphere transparency parameters. The reaction is much bigger in the modules from amorphous silicon, one- and three-junction, due to their much narrower spectral characteristics. They are very sensitive to the changes in the high-energy area of solar radiation spectrum.

The authors hope that this publication shall contribute to popularising the research methods presented as a cheap and effective method of estimating usability of modules to operate outdoors. This will allow research to be intensified on the optimisation of newly created cells and modules to the conditions reflecting actual climatic conditions in specified geographical regions.

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Nomenclature

$AM$ - Air Mass [-];
$AM_p$ - the adjusted value of $AM$ due to instantaneous fluctuations of atmospheric pressure [-];
$APE$ - Average Photon Energy of solar radiation [eV];
$B$ - bandwidth of the spectroradiometer [$\mu$m];
$CM$-21 (i.e. K&Z CM-21) - pyranometer for measuring the global component of solar radiation, Kipp & Zonen;
$E_0$ - daily value of insolation energy [Wh/m²];
$E_{0,H}(0)$ - daily irradiation energy on the Earth surface in horizontal plane [Wh/m²];
$E_{B,H}(0)$ - daily irradiation energy from direct compound on the Earth surface in horizontal plane [Wh/m²];
$E_{c}(0)$ - mean daily value of insolation energy in a month in the upper atmosphere in the horizon [Wh/m²];
$E_{POA}$ - daily value of insolation energy in Plane of Array [Wh/m²];
$E_{S}$ - daily value of insolation energy from diffuse component [Wh/m²];
$E_{S,H}(0)$ - daily irradiation energy from diffuse component on the Earth surface on a horizontal surface [Wh/m²];
$G_0 = G_{0,H}$ - global solar irradiance in the plane of the horizon [W/m²];
$G_B(t)$ - irradiation beam concentration in the plane of array [W/m²];
$G_{B,H}(t)$ - beam irradiance/irradiation on a horizontal surface [W/m²];
$G_{E,ext}$ - extraterrestrial irradiation in the upper atmosphere in the horizon [W/m²];
$G_{external}$ - extraterrestrial irradiance/irradiation on a surface perpendicular to the solar beam [ W/m²];
$G_{POA}$ - global irradiance in plane of array [W/m²];
$G_S = G_{S,0}$ - diffuse component in the plane of the horizon [W/m²];
$h$ - angle of the sun’s rise above the horizon [rad];
$I_0$ - solar constant (1367 ±7 W/m²);
Kb - beam clear sky index - proportion between beam irradiance and extraterrestrial solar irradiance on a horizontal surface [-];
Kn_day - daily diffuse component content index of solar radiation [-];
kTm_day - daily atmosphere clearness index [-];
kTm - atmosphere clearness (transparency) index [-];
Pm_in STC - a module power achieved in STC conditions [Wp];
Pm(25 °C) - a module power achieved at temperature of Tc = 25 °C [Wp];
\[P_m(25 °C)/G_{POA}\]norm - standardised value of a PV module power for Tc = 25 °C for 1 W of the rate \(G_{POA}\) (standardisation is carried out up to the power of \(P_m\_in\_STC\) obtained in STC conditions, for 1 W of the rate \(G_{POA}\) [-];
POA - Plane of array;
Rs - serial resistance of a cell/module [Ω];
Tc - temperature of cells in a PV module [°C];
UF - Useful fraction [-];
w, w_o - content in atmosphere: steam [cm], ozone [atm-cm];
z - angle between a falling beam and normal to horizon [rad];
β - Angstrom turbidity coefficient [-].

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