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# Modelling characteristics of photovoltaic module load for various light intensity and wavelength

***Streszczenie**. Przeprowadzono badania modułów fotowoltaicznych o różnych rozwiązaniach technologicznych, dla różnych wartości natężenia promieniowania i czterech zakresów długości fali. Wyznaczono charakterystyki mocy generowanej przez moduły o różnych rozwiązaniach technologicznych na obciążeniu, w funkcji zmian tego obciążenia (**Modelowanie charakterystyk obciążenia modułów fotowoltaicznych dla różnych wartości natężenia światła i długości fali**).*

***Abstract**. The photovoltaic modules of various technological solutions have been tested for varying radiation intensity and four wavelength ranges. Characteristics of the power generated by the modules of various technological solutions vs. varying load have been determined (Modeling characteristics of photovoltaic module load for various light intensity and wavelength).*

**Słowa kluczowe**: moduł fotowoltaiczny, długość fali świetlnej, moc obciążenia, dioda LED.
**Keywords**: photovoltaic module, light wavelength, load power, LED diode.

## Introduction

Taking into account that the photovoltaic modules still have relatively low efficiency, the research that might improve their parameters becomes important. Figure 1 presents maximal theoretical and practical efficiency of selected photovoltaic cells.

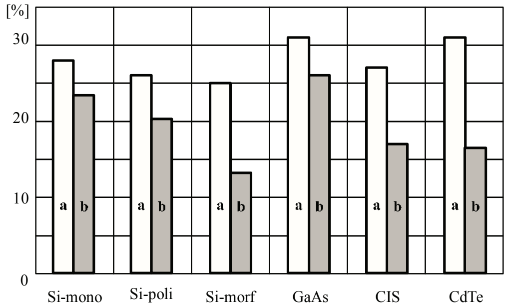


Fig.1. Theoretical and practical efficiency of selected photovoltaic cells

It becomes clear that in all the presented cases significant possibilities of improvement appear. They depend to large degree on absorption effectiveness of the semiconductors they are made of [1,2]. The crystalline silicon is distinguished by such effectiveness in the broadest wavelength range (mainly in visible and infrared light) [3].

Spectrum of solar radiation encloses the wavelength from 0.1 to 1000μm. Each wavelength corresponds to a definite energy. Predominating part of the energy falls to the ranges absorbed by crystalline silicon. Silicon absorbs visible light (from 0.38 to 0.78 μm) that makes 48 per cent of the energy, and a part of infrared energy in the range up to about 1.1 μm. The whole range of infrared radiation (up to 4 μm)transmits about 45.5 per cent of the solar radiation energy [4,5].

Absorption ability of the cells may be improved with the help of a transparent antireflection layer of proper thickness and index of refraction. The best result may be achieved with the use of multi-layer antireflection coats. They should be distinguished by large value of the absorption coefficient and low emission coefficient, that is particularly important [3].

Very good absorption ability occurs in case of the tandem-type cells made of semiconductor material layers in the form of a grid. This is due to various spectrum characteristics of the material used in them. The proposed model having 26 layers is distinguished by the efficiency exceeding 35 per cent [6]. Efficiency of a 70-layer model reaches even 40 per cent. Such cells are designed mainly based on the arsenic and gallium compounds.

## Operation tests

The tests have been made for silicon modules of maximal power 20 W. Table 1 specifies basic parameters of the considered modules under the conditions of AM 1.5 spectral distribution of solar radiation (Air Mass 1.5 corresponds to the distribution for apparent sun altitude of 42°), for the insolation of $S=1000W/m^2$ and temperature t=25°C.

Table 1. Selected parameters of the considered silicon modules

| Module | Off-load voltage [V] | Short-circuit current [A] | Voltage in PMM* [V] | Current in PMM [V] |
|---|---|---|---|---|
| Monocrystalline SUNSET SM 20 | 20,8 | 1,28 | 17,2 | 1,16 |
| Monocrystalline lorentz LA-20-12S | 22,3 | 1,30 | 17,3 | 1,20 |
| Monocrystalline USL 20 | 21 | 1.30 | 17,0 | 1,19 |
| Monocrystalline SUNTECH STP020-12/cb | 21,7 | 1,26 | 17,6 | 1,14 |
| Polycrystalline SUNTECH STP020-12 Cb | 21,7 | 1,26 | 17,6 | 1,14 |
| Amorphous Shell ST20 | 22,9 | 1,54 | 15.6 | 1,29 |

*PMM – Maximal power point – i.e. the point characterizing maximal power emitted at the load resistance [7]

A testing stand has been designed and made, provided among others with LED modules (the assemblies of the diodes connected in series, while for the consecutive branches connected in parallel [8]) in order to ensure homogeneous irradiation of the cell surface, since the photo-current density generated in the entire system is delimited by the number of the carriers produced in the unit of time in the partial cell to which the lowest number of photons falls. The LED modules have been used as simulators of solar radiation. The diode emits the light of definite colour, according to the material it is made of. This results in radiation of a definite wavelength [9, 10]. The blue ML - BB34X5F-B92.4, green ML - BG34X5F-G8-2.4, red ML - BR33A5F - F6 - 2.4 and yellow ML-BY33A5F - Y11C-2.4 diodes have been used. The PCB (Printed Circuit Board) has been designed with the help of the Protel 99 SE software. The boards have been preprocessed with the thermo-transfer method. Figure 2 presents maximal values of the diode normalization factors vs. the wavelength.

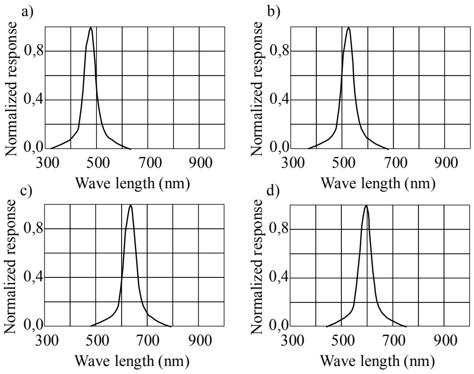


Fig. 2. Maximal values of the diode normalization factors vs. the wavelength for the following diodes: a) blue, b) green, c) red, and d) yellow

The module operation has been tested for various visible light ranges: $\lambda$ = 465 – 470nm, $\lambda$ = 515 – 525nm, $\lambda$ = 588 – 592nm, $\lambda$ = 620 – 630nm. The measurement has been carried out in the light intensity range from 20 to 140 lx. Various load resistance values have been taken into account.

Variation of the power generated at the load of each of the modules has been determined.

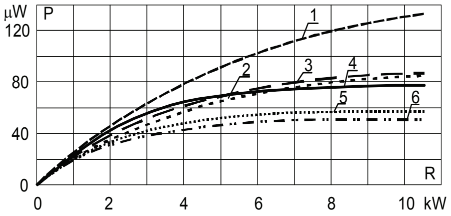
The load was provided by a decade resistor. The measurements have been made with the use of digital multimeters, the Sinometer luxmeter, HT Italia pyranometer, and touchless thermometer.

Figure 3 shows the tested monocrystalline and polycrystalline photovoltaic modules SUNTECH STP 020-12/cb and pyranometer.

Fig. 3. The tested monocrystalline and polycrystalline photovoltaic modules SUNTECH STP 020-12/cb

## Results of the measurement

Example results of the measurement are presented in Figures 4, 5, 6.



a.)

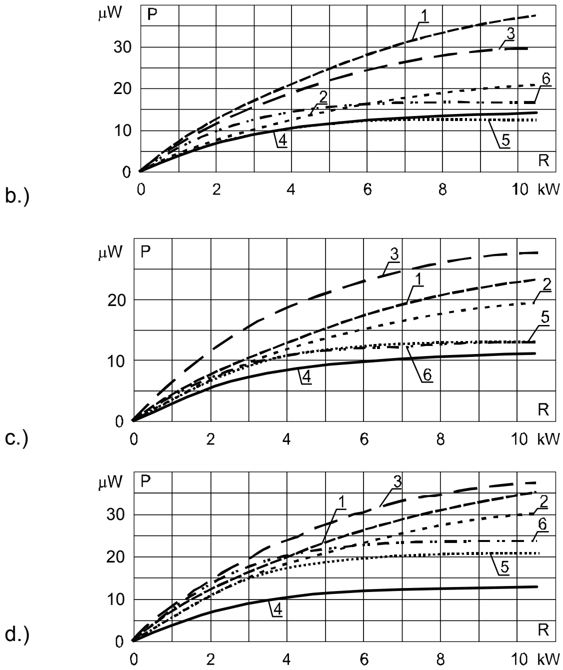


Fig. 4. Load characteristics of the modules for $E_x$=23 lx, (a) $\lambda$=620-630 nm, (b) $\lambda$=588-592 nm, (c) $\lambda$=515-525 nm, (d) $\lambda$=465-470 nm. Denotation: (1) STP020-12/Cb mono, (2) LA20-12S, (3) SUNSET SM20, (4) STP020-12/Cb poly, (5) Shell ST20, (6) USL 20W

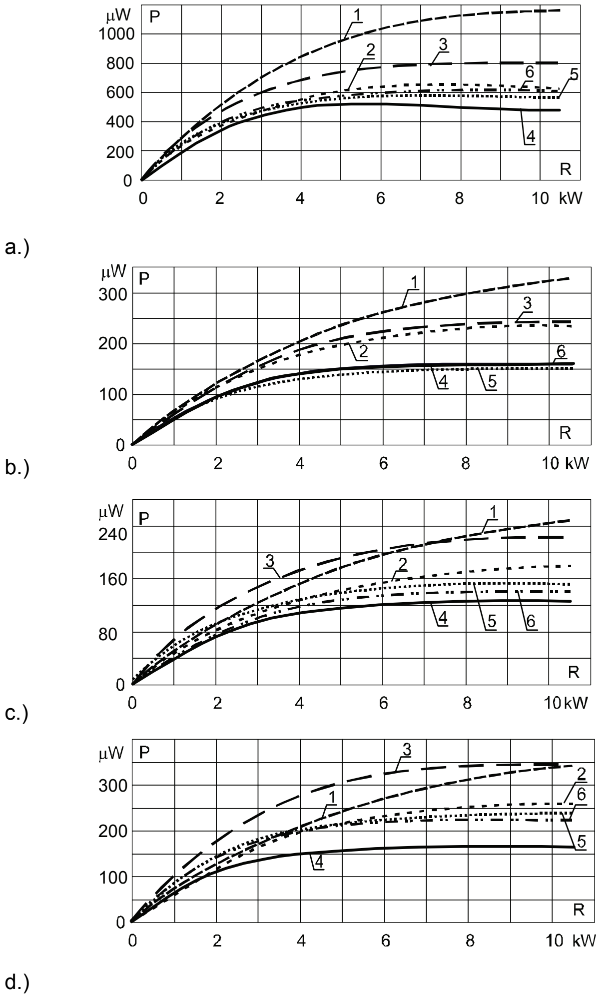


Fig. 5. Load characteristics of the modules for $E_x$=80 lx, (a) $\lambda$=620-630 nm, (b) $\lambda$=588-592 nm, (c) $\lambda$=515-525 nm, (d) $\lambda$=465-470 nm. Denotation: (1) STP020-12/Cb mono, (2) LA20-12S, (3) SUNSETSM20, (4) STP020-12/Cb poly, (5) Shell ST20, (6) USL 20W

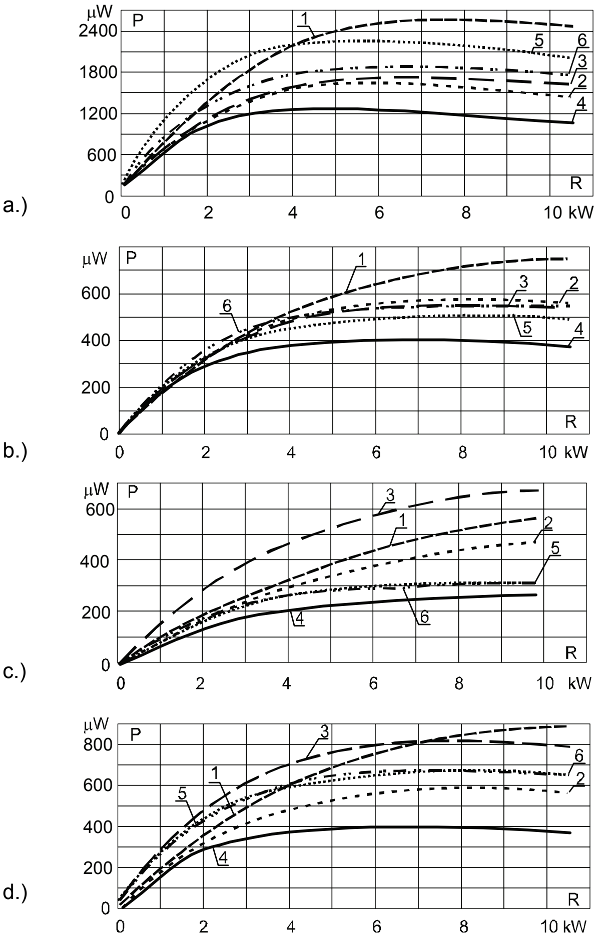


Fig. 6. Load characteristics of the modules for $E_x$=140 lx, (a) $\lambda$=620-630 nm, (b) $\lambda$=588-592 nm, (c) $\lambda$=515-525 nm, (d) $\lambda$=465-470 nm. Denotation: (1) STP020-12/Cb mono, (2) LA20-12S, (3) SUNSET SM20, (4) STP020-12/Cb poly, (5) Shell ST20, (6) USL 20W

## Conclusions

The obtained results allow to formulate the following conclusions.

1. The power generated by a module depends on the density of the radiation flux. The short-circuit current grows nearly proportionally to the density, while the electromotive force increases logarithmically.
2. Silicon cells absorb only a part of the solar radiation spectrum, with maximal sensitivity falling to wavelength of about 850nm. In case of amorphous hydrogenated silicon this wavelength changes to 600 nm [6, 7].
3. Maximal power was generated by the modules for the wavelength in the range from 620 to 630nm, that confirms the above observations. Another optimal range occurs for 465 to 470 nm.
4. In case of some of the modules the wavelength variation amounting only to 30 nm resulted in fourfold change of their power. This is a confirmation of large sensitivity of the cell operation parameters to the wavelength.
5. The tests show that in case of lower light intensity (e.g. 20 lx) the highest power is generated under the load conditions by the SUNTECH monocrystalline module. This is a case of larger wavelength values, from 588 to 630 nm. The next in the rank is the SUNSET SM20 module, distinguished by the best characteristics in the range from 465 to 515 nm.
6. In case of higher light intensity (80lx) the characteristics of the SUNTECH and SUNSET SM20 monocrystalline modules are more advantageous, with SUNTECH being particularly better for higher wavelength.
7. In case of 140 lx light the SUNTECH module remains better for higher loads. On the other hand, SUNSET SM20 generates maximal power in case of shorter wavelength under lower load level.
8. The worst parameters appeared in case of the SUNTECH polycrystalline module, particularly for shorter wavelength values. For larger loads the module-generated power shows decreasing tendency. Lower efficiency is caused by structural defects that decrease the distance of minority carriers (the photo-current density). Further decrease is a result of dropping short-circuit current, caused by the grain boundaries and the voltage of the open circuit [4, 6].
9. Relatively good results obtained with the amorphous Shell module may be explained by the fact that in nearly entire range of the visible light spectrum the absorption coefficient of hydrogenated amorphous silicon a:Si:H exceeds its value of the crystalline one. In case of light intensity of 140 lx its load characteristics is similar to the one of monocrystalline modules. In doped layers of amorphous silicon the absorption coefficient is still higher. Under AM1 conditions the layer of hydrogenated amorphous silicon of the thickness approximately equal to 1µm is sufficient for absorbing nearly a whole solar radiation of the power exceeding the energy gap of a:Si:H. Dependence of the light absorption coefficient vs. the wavelength is shown, among others, in [12].
10. Operation characteristics of the modules depend to an important degree on outside conditions. Nevertheless, the effect of the production technology [13] should not be omitted.

## REFERENCES

[1 ] Luque A., Hegedus S.: Handbook of Photovoltaic Science and Engineering, John Wiley & Sons, England 2008.
[2 ] Pankove J.: Optical Processes in Semiconductors, Dover Publications,, New York, NY, 1971.
[3] Jastrzębska G.: Odnawialne źródła energii i pojazdy proekologiczne, WNT, wyd. II, 2009.
[4] Castaner L., Silvestre S.: Modelling Photovoltaic Systems, Chichester England, John Wiley & Sons, 2002.
[5] Pluta Z.: Słoneczne instalacje energetyczne, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa, 2003.
[6] Jarzębski Z.M.: Energia słoneczna. Warszawa PWN, 1990.
[7] Spencer D.F.: Basic Photovoltaic Principles and Methods New York, Solar Energy Research Institute, 1984.
[8] Zaremba K., Parameters of model luminaire with high power LED Przegląd Elektrotechniczny,(2007),nr 5, 50-52.
[9] Dybczyński W.: Application of Light Emitting Diodes for local Lighting, Przegląd Elektrotechniczny, (2007), nr 5, 11-14.
[10] Fryc I.: Jakość promieniowania optycznego diody LED, Przegląd Elektrotechniczny (2003), nr 4, s.234-236.
[11] Saleh Bahaa E.A., Teich M.C.:Fundamentals of photonics, John Wiley & Sons, Inc.1991.
[12] Frydrychowicz--Jastrzębska G.: The effect of parameters of a photovoltaic element and the light wave lenght on its quantum efficiency, Monograph ZKwE Computer Appl. in El. Engineering . Poznań, Univ. of Technology, (2005), 250-264.
[13] Patel M.R.: Wind and Solar Systems, Taylor & Francis Group, Boca Raton, London, New York, Singapore, 2006.

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