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THE ASSESSMENT OF THE INFLUENCE OF MECHANICAL COOLING ON THE INCREASE IN SILICONE PHOTOVOLTAIC CELLS EFFICIENCY

Summary

The aim of the paper was to show how cooling of silicone photovoltaic cells influences the amount of electrical energy they produce. The research was conducted both in the laboratory and under real outdoor conditions. Current-voltage characteristics for two different thermal states of PV cells were outlined. Obtained power values for a PV cell working under the influence of refrigerant and without such an influence were compared. As a result of mechanical cooling of PV cells, an increase in photovoltaic cell efficiency was proved.
***Key words**: photovoltaics, silicone PV cells efficiency, temperature power coefficient in silicone PV cells*

OCENA WPŁYWU MECHANICZNEGO CHŁODZENIA NA WZROST WYDAJNOŚCI KRZEMOWYCH OGNIW PV

Streszczenie

Celem pracy było wykazanie, w jaki sposób chłodzenie krzemowych ogniw PV wpływa na ilość produkowanej przez nie energii elektrycznej. Badania przeprowadzono w warunkach laboratoryjnych i rzeczywistych. Opracowano charakterystyki prądowo-napięciowe dla różnych stanów termicznych ogniw PV. Porównano wartości pozyskiwanych mocy panelu fotowoltaicznego pracującego bez chłodzenia i z chłodzeniem. Wykazano wzrost wydajności, panelu fotowoltaicznego w wyniku mechanicznego chłodzenia ogniw PV.
***Słowa kluczowe**: fotowoltaika, sprawność krzemowych ogniw PV, współczynnik temperaturowy mocy krzemowych ogniw PV*

1. Introduction

Photovoltaics is a term covering the conversion of solar energy into electrical energy using photovoltaic cells (known as photovoltaic effect). Antoine Cesar Becquerel was first to observe this phenomenon in 1839. In 1916, a Polish chemist and an outstanding researcher, Jan Czochralski elaborated a method of obtaining pure silicone monocrystals, which is used until today and which contributed to the development of photovoltaic cells. The efficiency of PV cells in mid-20th century reached 6% [3]. The development of photovoltaics over the years resulted in making the technology available for numerous individual consumers. Continuous research on new materials and methods of production aims above all at increasing the efficiency and decreasing the costs of PV cells. In the context of the history of PV cells development, they can currently be divided into three groups [4]:

a) I generation – cells produced on the basis of crystalline silicon reaching the laboratory efficiency of 20-24% (monocrystalline silicon Si is until now obtained using the Czochralski method),

b) II generation – thin-film solar cells built of thin layers up to 4 micrometers thick, deposited on an inexpensive substrate such as glass, polymer or metal, reaching the efficiency of 7-15%,

c) III generation – represented by multi-junction cells, consisting of three layers of photocells (semiconductors) with different band gap values matching the wavelength of the sunlight spectrum which allow them to absorb a broader spectrum of electromagnetic radiation; such cells reach the efficiency of 44% and more.

On the other hand, Dusza et al. [2] elaborated an effective and inexpensive method of photovoltaic cells production based on perovskite minerals characterized by a high light absorption capability, elasticity (thanks to which they can be applied to any material and their surface is thinner than that of silicone cells) and a shorter energy payback time. Perovskite cells reach the laboratory efficiency of up to 15% (it pertains to cells with 1 cm^2 surface area). It is predicted that their further development will allow to reach the efficiency of even 30% [6]. The implementation of this technology on the photovoltaics market will surely lead to competition with traditional silicone cells. Before it happens, however, some intense research on the improvement of large-scale manufacturing process and elimination of technical obstacles – such as the inclusion of environmentally harmful lead, instability caused by water-solubility as well as application of perovskites to large surfaces – must be conducted. Therefore, it is still a long way to go before a massive production of perovskite-based photovoltaic cells becomes a fact. Planning a photovoltaic investment, it is also worth noticing that prices of silicone PV cells have recently been significantly dropping, which cannot be said of perovskite PV cells. Thus, it seems justified to search for a technical solution which increases the efficiency of widely available and used silicone photovoltaic cells.

2. Research aim

Research aim was to show the influence of mechanical cooling of silicone PV cells on the increase in the efficiency of electrical energy production. Scientific publications prove that absorbing sunlight silicone PV cells heat up. An increase in temperature has a negative influence on the efficiency of photovoltaic conversion occurring in the cells, and in consequence, on the electrical power generated by the cells [10]. Since the 1980s, research on the influence of temperature of working PV cells on the obtained efficiency of photovoltaic conversion have been conducted [11]. Theoretically, power output of a monocrystalline PV module decreases by ca. 0.4% with each 1°C increase in silicone temperature above the reference temperature, which equals to 25°C (this temperature is treated as referential in standard PV testing conditions, with radiation strength amounting to 1000 Wm^{-2}) [1]. Manufacturers of monocrystalline silicon photovoltaic panels available on the market declare temperature power coefficient γ at the -0.42%/°C level [5]. It means that for each 1°C increase in temperature of silicone PV cells above the temperature of 25°C, a 0.42% decrease in their power output is generated. On warm and sunny days, when the air is still, cells may heat up to the temperature of above 40, and sometimes even 50ºC (Fig. 1).

Source: author's design / Źródło: opracowanie własne

Fig. 1. A measurement of the PV module surface temperature
Rys. 1. Pomiar temperatury wierzchniej powierzchni modułu PV

Thus, at ΔT = 25°C, a 240 W_p photovoltaic panel will generate the power of:

$P=P_0\,(1-\gamma\cdot\Delta T) = 240W_p\cdot(1\text{-}0.42\%/°C\cdot 25°C) = 214.8\ W_p$,

which means almost 11% less electrical energy than its nominal parameters indicate.

Research on silicone PV cells installed in PV/T hybrid systems, in which heat cumulated within a semiconductor is extracted by refrigerant – water or air, shows that the efficiency of photovoltaic conversion in PV modules improves with a decrease in temperature of their work. Scientific publications on this topic describe changes in the efficiency of PV/T system depending on the amount of air flowing through the system as well as on its temperature at the collector inlet [7, 8].

3. Research methods

The research on the influence of refrigerant on the efficiency of silicone PV cells in electrical energy production was conducted in the Testing Laboratory for Agricultural Machines of the Industrial Institute of Agricultural Engineering in Poznan, Poland. A thermographic camera was used for the indication of temperature. The research included determining the maximum power point P_{mpp} on a current-voltage characteristics in which the highest power of the panel is achieved, for two different thermal states of PV cells, and comparing the results obtained.

$P_{mpp} = I_{mpp}\cdot U_{mpp}$,

where:

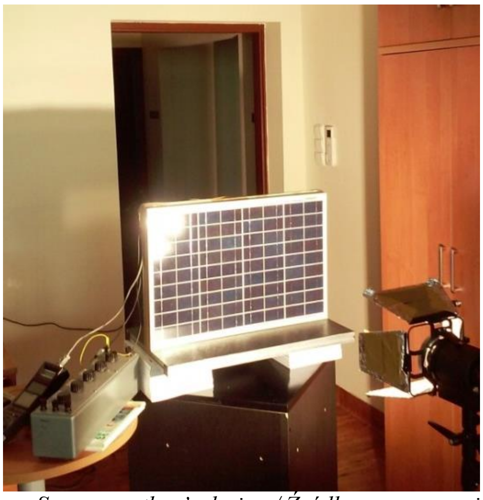
P_{mpp} – panel power at the maximum power point [W],
I_{mpp} – current intensity at the maximum power point [A],
U_{mpp} – voltage at the maximum power point [V].

The research was conducted both in the laboratory, when a halogen lamp generating constant light was used as the source of light, and under real outdoor conditions, when the sun constituted the source of light. The measurements were taken with identical solar exposure (cloudless conditions) for both tested thermal states of the panel over a possibly short time span. The outdoor tests were conducted in July. The air temperature fluctuated between 33 and 35°C. The angle of inclination of the panel was 35º.

The research stand in the laboratory (Fig. 2) consisted of:

- a polycrystalline silicon PV panel with the following features: P_{mpp} = 40 W_p, I_{mpp} = 2.29 A, V_{mpp} = 17.5 V, I_{sc} = 2.54 A, V_{oc} = 22 V,
- a 1250 W halogen lamp,
- a decade resistor with a 0-100 kΩ range,
- an air conditioner playing the role of refrigerant,
- control and measuring instruments including a direct current voltage meter, a direct current intensity meter, a thermo- hygrometer, a thermographic camera.

The source of light was located in front of the PV panel within a distance of 1 m. The thermographic camera was located behind the PV panel within a distance which allowed for clear picture reception. A stream of refrigerant from the air conditioner was directed at the rear surface of the panel.



Source: author's design / Źródło: opracowanie własne

Fig. 2. The PV cell research stand in the laboratory
Rys. 2. Stanowisko do badań ogniw PV w warunkach laboratoryjnych

With the source of light on, the PV panel generated electric current which was dissipated by the decade resistor. After a short amount of time, an increase in the temperature of PV cells was observed. When the temperature stabilized at the level of ca. 51°C, a series of voltage and current intensity measurements was taken with a gradually increased resistance of the decade resistor. An IV-curve I = f(U) of the PV panel was outlined. Then, the air conditioner was turned on. The airstream was directed at the rear surface of the panel. When the PV cell temperature dropped to ca. 42°C, a series of measurements was taken and an IV-curve I = f(U) was outlined. The outdoor experiment was conducted in a similar way except for the air conditioner which was replaced with two axial fans (Fig. 3).

Source: author's design / Źródło: opracowanie własne

Fig. 3. The PV cell research stand under real outdoor conditions
Rys. 3. Stanowisko do badań ogniw PV w warunkach rzeczywistych

4. Research results and analysis

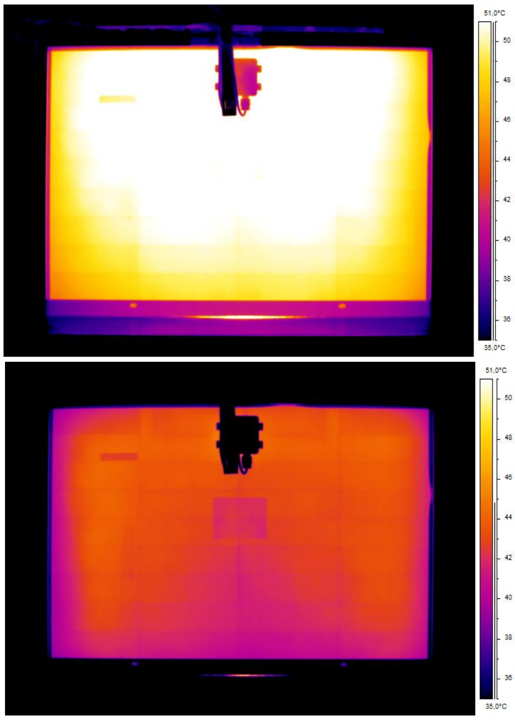
In the laboratory, the thermographic camera recorded the following temperature distribution in the PV cells (Fig. 4). With the air conditioner turned off, the cells worked at the internal temperature of 51°C, whereas with the air conditioner turned on – at the temperature of 42°C.

Under real outdoor conditions, the thermographic camera recorded the following temperature distribution in the PV cells (Fig. 5). With the air conditioner turned off, the cells worked at the internal temperature of 52°C, whereas with the air conditioner turned on – at the temperature of 40°C.

As a result of the laboratory experiments it was determined that the maximal power of PV cells working at the temperature of 51°C reached P_{mpp} = 8.7 W_p, whereas the maximal power of the PV cells working at the temperature of 42°C reached P_{mpp} = 9.2 W_p. It meant a power increase at the level of ΔP_{mpp} = 1.1 W_p and a 12% increase in PV panel efficiency due to cooling down of its structure by 9°C.

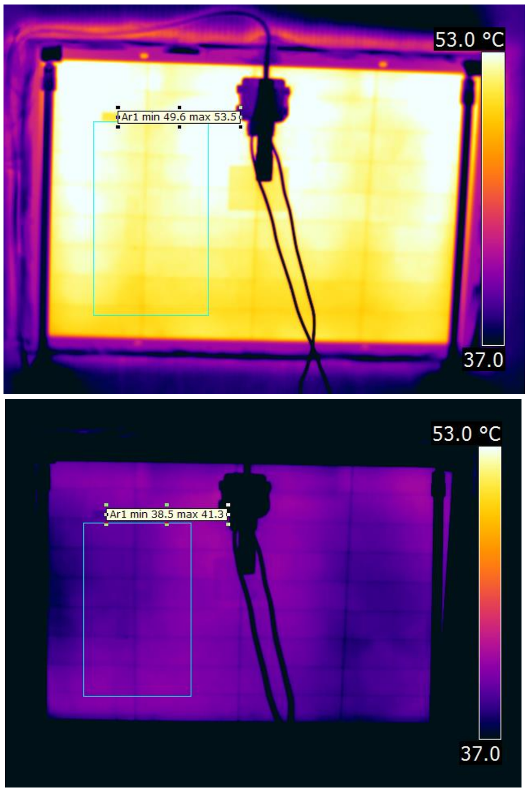
The IV-curve P = f(U) for two different thermal states took the following shape (Fig. 6):

As a result of the experiments conducted under real outdoor conditions, it was determined that the maximal power of PV cells working at the temperature of 52°C reached P_{mpp} = 18.65 W_p, whereas the maximal power of the PV cells working at the temperature of 40°C reached P_{mpp} = 23.5 W_p. It meant a power increase at the level of ΔP_{mpp} = 4.85 W_p and a 21% increase in PV panel efficiency due to cooling down of its structure by 9°C.

a)
b)


Source: author's design / Źródło: opracowanie własne

Fig. 4. Temperature distribution in the PV cells recorded by the thermographic camera in the laboratory: a) without any cooling, b) with cooling
Rys. 4. Rozkład temperatur ogniw PV w warunkach laboratoryjnych zarejestrowany przez kamerę termowizyjną: a) bez chłodzenia, b) z chłodzeniem

a)
b)


Source: author's design / Źródło: opracowanie własne

Fig. 5. Temperature distribution in the PV cells recorded by the thermographic camera under real outdoor conditions: a) without any cooling b) with cooling
Rys. 5. Rozkład temperatur ogniw PV w warunkach rzeczywistych zarejestrowany przez kamerę termowizyjną: a) bez chłodzenia, b) z chłodzeniem

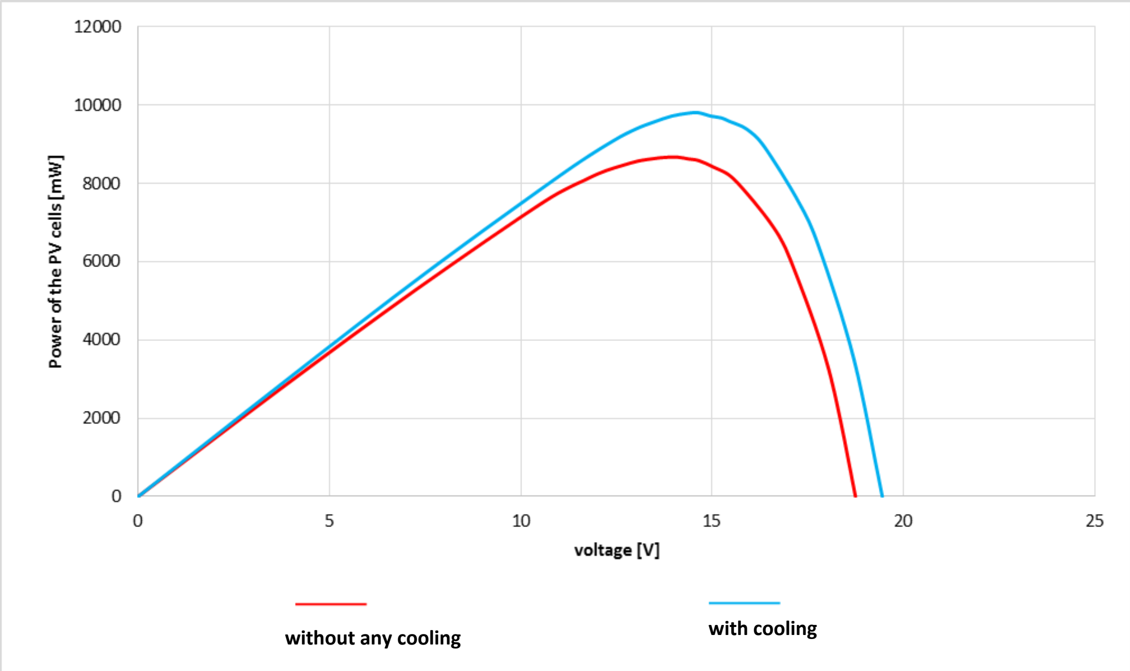


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Fig. 6. A IV-curve P = f(U) for two different thermal states of the PV panel outlined on the basis of the results of experiments conducted in the laboratory

Rys. 6. Charakterystyka P = f(U) baterii ogniw PV dla dwóch różnych stanów termicznych sporządzona na podstawie wyników badań przeprowadzonych w warunkach laboratoryjnych

The IV-curve P = f(U) for two different thermal states took the following shape (Fig. 7).

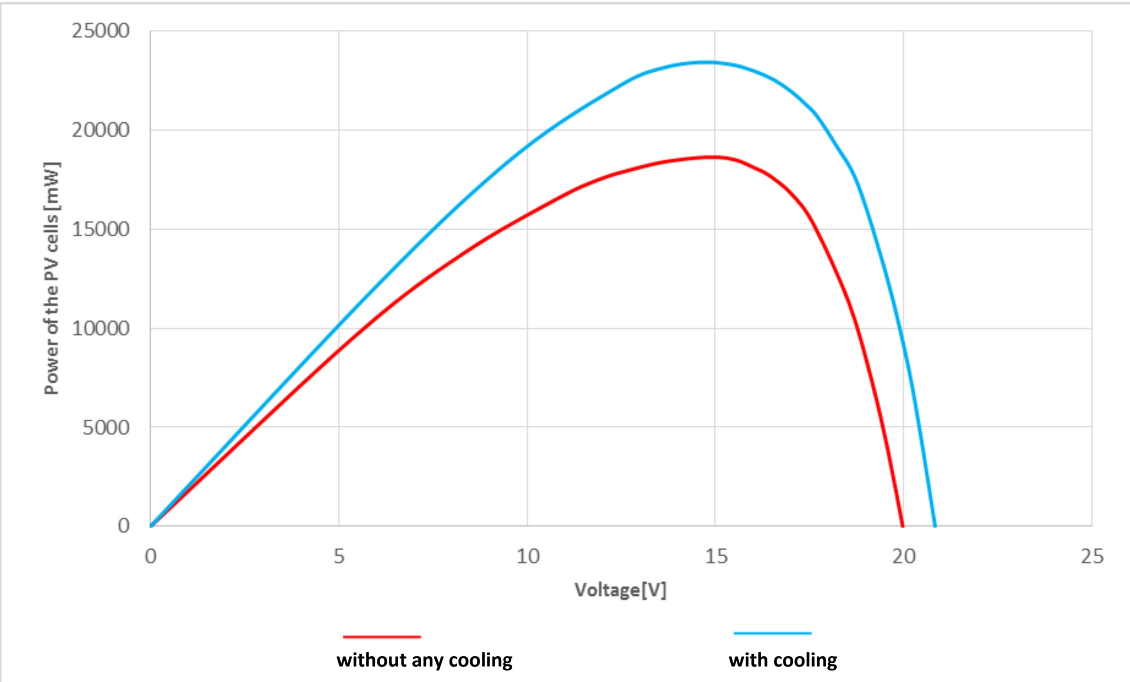

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Fig. 7. A IV-curve P = f(U) for two different thermal states of the PV panel outlined on the basis of the results of experiments conducted under real outdoor conditions

Rys. 7. Charakterystyka P = f(U) baterii ogniw PV dla dwóch różnych stanów termicznych sporządzona na podstawie wyników badań przeprowadzonych w warunkach rzeczywistych

Since power output corrected for temperature power coefficient is equal to

$$P_s = P_0(1-\gamma \cdot \Delta T), \quad (1)$$

thus

$$\gamma = \frac{1}{P_0} \cdot \frac{\Delta P}{\Delta T} \cdot 100\%$$

with

$\Delta P = P_0 - P_s$,

$\Delta T = T_o - T_k$,

where:

γ – temperature power coefficient [%/°C],

P_0 – power at the maximum power point P_{mpp} [W],
P_s – power at the maximum power point corrected for temperature power coefficient [W],
T_o – reference temperature of a given cell determined by its manufacturer [°C],
T_k – temperature of a working PV cell [°C].

Thus, by filling in equation (2) with the results obtained during the experiments conducted under real outdoor conditions, the value of the temperature power coefficient of the tested panel was obtained:

$$\gamma = \frac{1}{23{,}5} \cdot \frac{4{,}85}{-634{,}5} \cdot 100\% = -0{,}76\% / {}^{\circ}C$$

Radziemska [9] conducted a real outdoor experiment in which heat of PV cells was extracted by liquid washing the panel. The results obtained during the experiment showed the temperature power coefficient γ at the level of -0.65%/°C. The value of the temperature power coefficient obtained by the author of this paper was similar to that of Radziemska.

5. Summary and conclusions

On the basis of the research conducted and the results obtained, the following conclusions may be formulated:

1. An increase in the maximum power P_{mpp} of the panel as a result of the extraction of heat from the PV cells structure was observed. An increase in the production of electrical energy by the photovoltaic panel cooled mechanically with air was the final effect.
2. The greatest power increase ΔP_{mpp} = 4.85 W_p was observed during the tests under real outdoor conditions when the PV cells were cooled down by 12°C.
3. The temperature power coefficient of the tested panel reached γ = -0.76%/°C, what suggested high susceptibility to high temperatures of work, and in consequence a drop in electrical energy production.
4. A waste product of the process of PV cells cooling is hot air which can be effectively used, e.g. in drying of agricultural crops, paint shops, construction, etc.

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