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# Thermographic Research of Photovoltaic System Operating in Shaded Conditions

**Abstract**

Results of infrared research conducted on a photovoltaic system which works in an on-grid mode for over a year are presented in the article. The installation described is regularly shadowed by a cooling system. Thermograms of photovoltaic modules in strong and light shadow were conducted. These images show that even in very weak shadow the PV cells are overheated. This has led to small point damages in the amorphous panels and in the future it may also lead to the destruction of polycrystalline modules.

**Keywords**: photovoltaic systems, polycrystalline cells, shaded photovoltaics, overheating of PV cells, thermovision in photovoltaics.

## 1. Introduction

Renewable energy source based systems are becoming increasingly popular all over the world. This is caused by, among other things, striving for energy independence and the need to reduce the cost of building electricity usage. What is more, the necessity to reduce conventional energy sources consumption and greenhouse gases emission (which result from the obligations towards the European Union) has caused renewable energy sources to become a rapidly developing energy sector.

This applies especially to solar energy. This particular kind of power is an inexhaustible, cheap and easily available source of energy. In the longer term, virtually all of the energy sources are related to the sun (except nuclear fuels). For example solar energy is accumulated in biomass via photosynthesis and it also causes winds via irregular heating of the Earth's surface. Thanks to the sunlight, even fossil fuels were created over millions of years. Therefore, solar radiation is unlimited, environmentally-sound and a widely available source of energy. It is primarily used in conversion processes to produce heat and electricity. And electric power is the most desirable form of energy. Among the known methods of converting solar radiation to electricity, the photovoltaic cells are the easiest and the cheapest solution.

To obtain the required in-grid voltage, terminals of PV modules are connected in series (the current intensity has the same value as a single module while the voltage value is the sum of each of the modules' voltage). The main problem in the series type of connection is that all of the modules in one string can generate maximally as much current as the least efficient panel. Thus, at the stage of system design it should be kept in mind that all of the modules in a single string should be made in the same technology, from the same manufacturer, oriented to the same direction and installed at the same angle. Attention should also be paid to the possible occurrence of shadow. As it was previously mentioned, even a single cell shading can contribute to reduce the amount of energy produced by every single module connected to the same string.

The shadow causes not only a significant decrease of MPP (Maximum Power Point) but also has an effect on energy characteristic distortion [2]. Even as weak as coming from, for example, branches of trees, shading changes the current-voltage characteristic shape by affecting formation of the two or more maximum power points. The typical energy characteristic distortion in weak shading is presented in Figure 1. This may cause additional energy losses in the photovoltaic installation that is not equipped with a maximum power point tracing system (even 20% more losses compared to the installation with MPPT).

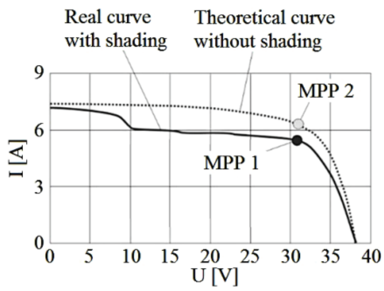


Fig. 1. Current and voltage characteristics of a PV module with and without shading [2]

What is more, if part of a module is shaded, then the cell without sunlight changes its polarization and becomes a resistance – the current flows in the opposite direction. The temperature of shadowed PV cells can rise and via overheating can lead to damage. In this situation, a small white point called a "hot spot" can be seen on the module. In order to protect cells against the effects of partial shading, bypass diodes are used [3]. During the operation of evenly lighted modules, diodes are polarized in the blocking direction. When the cell is changing its polarization (due to the shadow) then, the bypass diode is forward biased in the conduction direction. Electricity generated by other strings of cells bypasses the partly shaded string and flows through the diode. Usually, in the polycrystalline panels, a bypass diode is used for a group of several cells.

The use of a thermal imaging camera allows to perform research on negative effects of shading on the PV modules. Thermographic measurements of photovoltaic installation works in shading conditions were performed for over a year and extrapolated. Analysis of these studies is presented in this article.

## 2. Description of the studied system

In the Faculty of Energy and Fuels building in the AGH University of Science and Technology in Krakow there is a photovoltaic laboratory called "RWE AGH Solar Lab". The installation was created by the RWE Polska S.A. company in partnership with the Department of Sustainable Energy Development. The PV system works in an on-grid mode and its total capacity is 7,5 kW.

On the roof of the building there are two types of photovoltaic modules (Fig. 2):

- 28 polycrystalline modules (made of Silicon) with nominal capacity of 245 W and efficiency of 14,9% each,
- 12 thin-film modules (made of amorphous Silicone) in glass-glass technology with a capacity of 135 W and efficiency of 9,6% each.

The above-mentioned two types of photovoltaic panels are oriented to three world directions: 14 polycrystalline modules are directed to the east, another 14 modules to the west (inclined at an angle of 10°). These panels are connected in four serial strings (7 panels in each string) which are in turn connected to two inverters with capacity of 3 kW each. The thin-film panels are directed to the south (inclined at an angle of 7,5°) and connected via two serial strings (6 panels in each one) to an inverter with capacity of 1,5 kW.

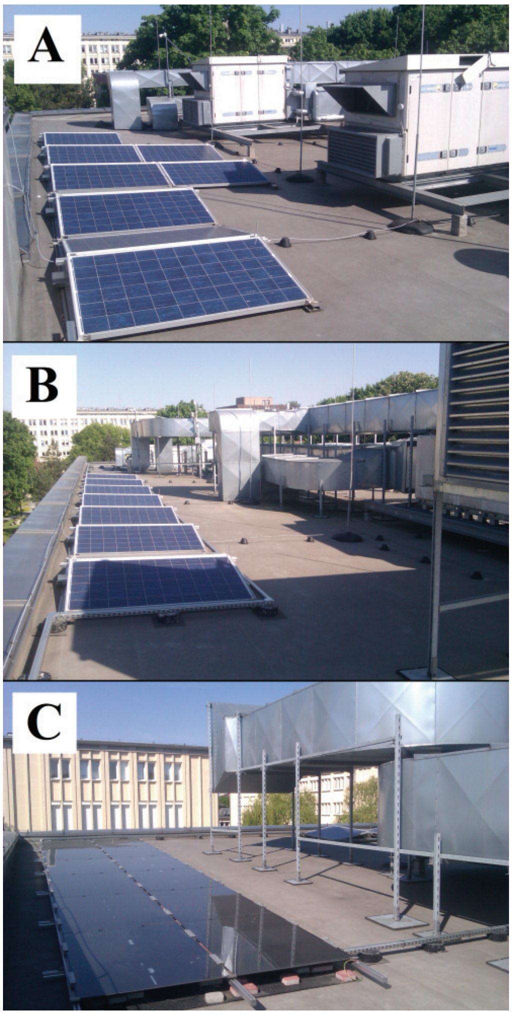


Fig. 2. View of photovoltaic installation positioned in three places: A, B – 4 strings, each consisting of 7 polycrystalline panels faced east and west (two differently directed chains in place A and B), C – 12 amorphous panels directed to the south (two strings)

On the Faculty of Energy and Fuels building roof there are a lot of cooling installation devices. This has forced designers to divide the PV system and to locate it in three different places where there is available space on the roof. As it can be seen in Figure 2, two strings of east and west directed panels are located in one place (Fig. 2A), following same connection is located in the second place (Fig. 2B) and two strings of amorphous panels are located in the third place (Fig. 2C).

In spite of the division of the PV system as shown in Figure 2, it was unable to avoid partial shading which changes depending on the seasons and times of day. The described photovoltaic system has been working since January 2015. It produces energy for the electrical needs of the Faculty of Energy and Fuels building. The instantaneous values of power with distinguishing between east, west and south side are constantly recorded in the laboratory. Also weather conditions parameters are stored (intensity of solar radiation, air temperature, humidity and pressure, precipitation and solar spectrum). Measuring devices are connected to the automatic system based on a modular programmable logic controller (PLC). Measuring of alternating current power quality is also possible in the laboratory. What is more, the laboratory is equipped with an electronic load with a maximum power of 2400 W. This device allows us to measure and hence to create the energy characteristic of particular strings in PV installation. Visually apparent thin-film amorphous panels hot spots have driven the author to perform the thermal research. These hot spots are the result of PV cells overheating, which in turn is caused by partial shading conditions. However, the article focuses primarily on polycrystalline modules thermal studies. It is caused by the fact that, performing thermograms of glass-glass type amorphous PV panels whose surface emissivity is low and its angle of inclination is only 7,5° is very difficult. This kind of glass reflects the infrared radiation coming from the cooling system presented in Fig. 2C. A large area occupied by cooling devices makes it more difficult to perform the measurements at a proper angle.

## 3. Description of thermal camera and measurement parameters

In order to carry out the temperature measurements of PV panels throughout the whole photovoltaic system, a Thermo Tracer NEC H2640 thermal camera was used. This device is based on an infrared detector array with dimensions of 640×480. The refresh rate is 30 Hz and the field of view (FOV) is 21,7°×16,4°.

The research was performed on a sunny, cloudless day. In addition, in Figure 8 thermograms made on other kinds of days are presented (more or less cloudy). Because of the fact that polycrystalline panels are protected by glass, the emissivity of infrared thermal radiation was set to 0,8. Bearing in mind that cooling devices are located around the PV system and also that the roof surface is warm, the ambient temperature was set to 10°C. Thermal photos were taken from a distance of about 1-3 meters. Due to the fact that the panels are inclined at an angle of only 10°, the proper performance of measurements was quite difficult. In order to take a thermal photos at right angles (90°) support elements of the cooling system were used where it was possible (Fig. 2).

## 4. Results and analysis of thermographic research

As previously mentioned, the analyzed photovoltaic system is systematically shaded by extensive cooling installations. In the Figure 2B it can be seen that one of the polycrystalline modules directed to the west is almost entirely in the shade. Two measurements of this panel in various phases of shading were performed. The results are presented in Figures 3 and 4.

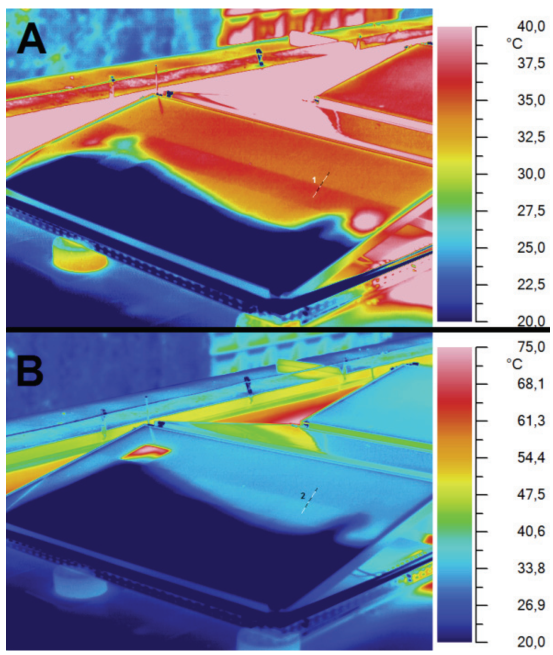


Fig. 3. Thermogram of directed to the east polycrystalline module in two shading phases (navy blue color)

Figure 3 shows that 1/3 of the panel is covered by the shadow. The interesting thing is that thermogram 3A shows the higher heat emission caused by the serial string of 10 cells (compared to the totally lighted part of the module). These photovoltaic modules have three bypass diodes each. That is one diode for 20 PV cells. Increased temperature of the string may be due to the fact that the bypass diode was not activated (in spite of the fact that a significant part of cells were shadowed). This caused the formation of a diffusion current and consequently heat generation. After a few minutes another thermogram, (Fig. 3B) which shows the visible increase of shading, was taken. In spite of the shading of about 2/3 of the panel (more than half of the cells connected to one diode are in shadow) the bypass diode still did not activate. Thermograms Fig. 3A and Fig. 3B should be considered carefully because the temperature scale was changed. In order to better illustrate this phenomenon in Figure 4 temperature distribution graphs as marked in Fig. 1A and B sections (black and white colors) are presented. These sections of the curve relate to the heated and standard temperature cells.

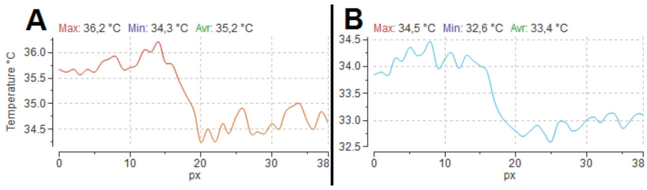


Fig. 4. The temperature distribution graphs of heating and non-heating PV cells: A - 1/3 of shadow on panel, B – 2/3 of shadow on panel

On the graphs in Figure 4 it can be seen that the temperature in the first measurement (Fig. 4A, 5A) is generally lower than in the second measurement (Fig. 4B, 5B). This change may be caused by wind. In spite of that, the temperature difference between heated and the normal part of the panel (fully lighted) is very similar ie. about 2°C.

The temperature scale on A and B in Figure 3 thermograms is changed due to the emergence of a highly heated single cell. In the example of the thermogram in Figure 3B, part of the shadow reaches one of the single cells which is connected to the bypass diode with other fully lighted 19 cells. The temperature of this cell is significantly different compared to the others. The performance of a more detailed temperature distribution is presented in Fig. 5.

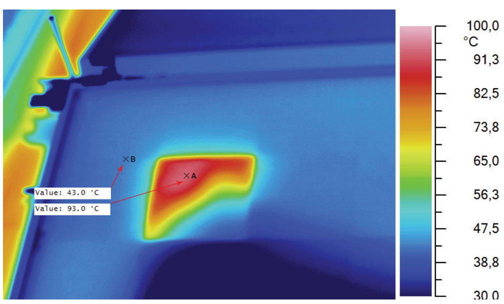


Fig. 5. Thermographic photo of heating cell in light shadow (navy blue color)

Figure 5, compared to Figure 3A, clearly shows that the impact of shading to temperature and work of photovoltaic cells is very significant. In case of light shading (mazarine, and blue for presented cell), temperature had increased from about 43°C, to almost 93°C. Thus, the difference reaches almost 50°C. This shows that the higher temperature is not caused by the movement of the shadow (nonuniform insolation) but by the extra current. It can be seen that even a fully lighted cell (Fig.5 - B) has lower temperature that the partly shadowed one (A).

The appearance of light shading is sufficient to induce effects of polarity changing. Such shading could be caused e.g. by power line or lightning protection systems. On the roof of the building of Energy and Fuels Faculty, beyond the photovoltaic and air conditioning installations, there are also lightning rods.

Fig. 6. The view of a lightning rod casting a shadow on photovoltaic installation

The lightning rod which throws a shadow on the photovoltaic system is well visible in the picture included as Figure 5. Moreover, there are more of them on the roof, along the cooling system installation, which can be seen in Figure 2. Therefore, a thermography measurement was made for cells overshadowed by longitudinal, but thin shadows. Results are presented in Figure 7. On this thermogram, shadow is visible in the colors green and yellow. Moreover, there is also a reference picture included, where analyzed cells and characteristic points (visible also in the thermograph) are marked in red.

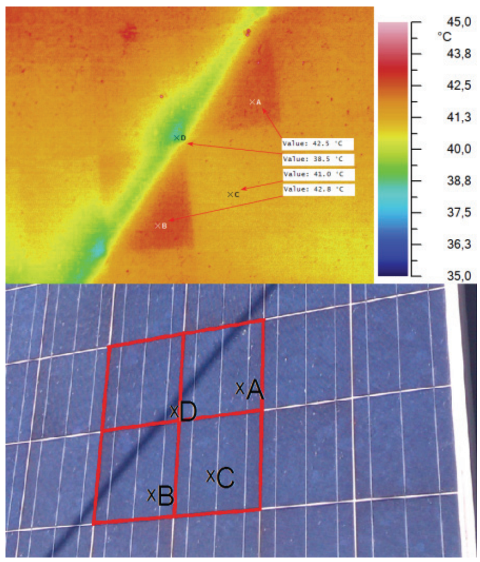


Fig. 7. Thermogram of polycrystalline cells shaded by lightning rod and the view of shaded part of PV module

Figure 7 shows that even such slight shading from a single lightning rod, causes shaded cells to start to heat up. The temperature at points A and B on heated cells is more than 42.5°C, while the non-shaded cell has a temperature of about 41°C (point C). However, at point D temperature is slightly lower than the rest of the module (about 38.5°C). This is due to the fact that the shadow causes a decrease in temperature (less solar radiation reaches the surface) and the cell is not so shaded in order to change its polarization, so it does not heat up.

A similar situation was observed on the days of higher or lower intensity of solar radiation. The results are shown in Figure 8. Shadow cast by the lightning rod extends along the panels, which results in the heating of several cells. It was noted using the thermograms that the greatest difference in temperature occurs in

Figure 8C. The difference between the heated cell, and the rest of the panel is 21°C.

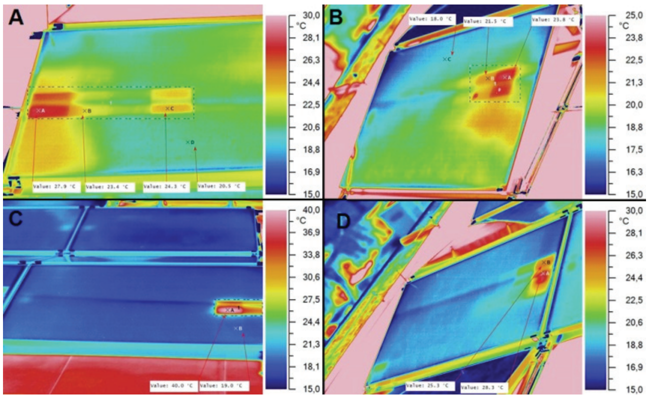

Fig. 8. Thermographic pictures of shadowed by lightning rod polycrystalline PV modules taken in different days

The situation is similar in the case of thin-film amorphous panels. They are systematically shaded by the high cooling system as shown in Figure 2. As previously mentioned, these hot spots observed on the surface of the panels were the initial impetus to make these thermal measurements. Hot spots can be seen in Figure 9. It shows the entire panel, and an approximation of one of the spots. Due to the limited space, small slope of panels and low emissivity of amorphous modules surface made with glass-glass technology, the measurement was difficult. As a result, only several photos were made. However, as can be seen in Figure 9, the visually apparent hot spots, seen in normal images, are also visible on thermograms as points with higher temperature. The Figures 9A and 9B show the same panel in thermovision. Photos were taken from various perspectives, to avoid an impact of reflection of thermal radiation of other elements surrounding the installation.

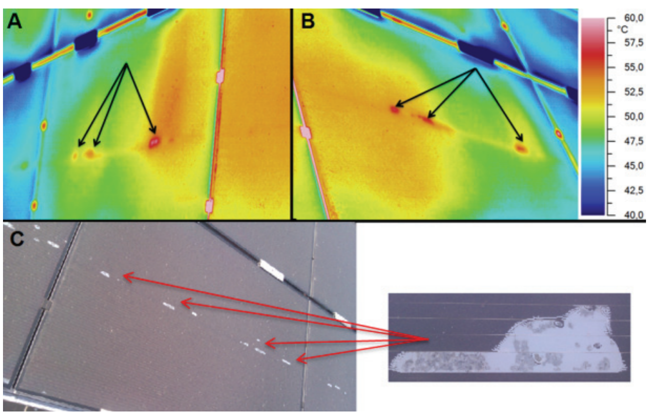

Fig. 9. Thermograms and view of glass-glass type of thin-film amorphous module with visible hot spots

So it is evident, that temperature on the entire surface may vary, depending on the perspective the photo is taken from, but the temperature of hot spots remains unchanged. This shows that there really are points of overheating. This also shows that the hot spots have a higher temperature even when the whole panel is evenly illuminated which means that this damages are permanent.

Studies were carried out on an installation operating for nearly 1,5 years. It shows, that periodical shading of some parts of panels led to permanent damage of amorphous cells, and could also damage polycrystalline cells. Thermovision studies should therefore be performed in following years as well, to monitor the impact of shading on the work of photovoltaic modules.

## 5. Conclusions

The results presented in this article on the thermographic research that was performed are a confirmation that shading adversely affects the performance of photovoltaic panels causing them to overheat. Even a slight shadow created by e.g. electric power cables, falling leaves or nearby trees causes the raise in temperature of the PV installation's various parts. The temperature difference between the particular cells can cause mechanical stress. This in turn can lead to micro-fractures and the breaking of soldering connections – permanent damage of the photovoltaic panel.

Photovoltaic systems have a number of advantages. Besides being a form of renewable energy, it is relatively cheap, safe, and maintenance free. Based on the analysis presented in the article, it can be seen that an extremely important step is to create a proper design of PV system. All elements placed around the planned photovoltaic installation should be considered as one that can cast the shadow. Even the smallest part of shading may lead to permanent damage of modules and at the same time decrease energy production.

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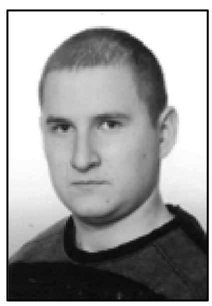

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