THE TEMPERATURE OF PHOTOVOLTAIC PANELS AND THE EFFECT ON THEIR EFFICIENCY

Martin LIBRA[1], Sona GRIGORYAN[1], Vladislav POULEK[1], Tomáš PETRÍK[1], Pavel KOUŘÍM[1], Jan SEDLÁČEK[1], Václav BERÁNEK[2]

[1]*Department of Physics, Faculty of Engineering, Czech University of Life Sciences Prague, Czech Republic*
[2]*Solarmonitoring, Ltd., Czech Republic*

Abstract
When photovoltaic systems operate in areas with extreme climatic conditions, their characteristics can change significantly during operation. The temperature mainly affects the open circuit voltage and the efficiency of the photovoltaic system. Therefore, it is necessary to pay particular attention to the fact that the connected devices can work in the given range of parameters of the photovoltaic power source.

Key words: *photovoltaic system; semiconductor diode; data monitoring; carbon footprint.*

INTRODUCTION

Today, photovoltaic energy conversion has an important place in the energy mix. They are also important in terms of reducing the carbon footprint. Many photovoltaic power plants operate worldwide (*Božiková et al., 2021; Poulek et al., 2021*). Many of them are directly building integrated (*Libra et al., 2016; Pokorný & Matuška, 2020*), including our photovoltaic system on the roof of the Faculty of Engineering (*Libra et al., 2019*) (see Fig. 1). The temperature of photovoltaic panels changes during the year. In Central Europe, the air temperature can change by up to about 60°C during the year, but there are places on Earth (for example in Siberia), where the air temperature changes by up to 100°C.

Fig. 1 Photovoltaic system ($P_{\max}$ = 10 kW_p) on the roof of the Faculty of Engineering in Prague

It is known, that the temperature of photovoltaic cells significantly affects the efficiency of energy conversion. It follows from the semiconductor theory. A photovoltaic cell is essentially a planar semiconductor diode. Photovoltaic panels with silicon-based photovoltaic cells are commonly used on Earth and photovoltaic panels with GaAs-based photovoltaic cells are commonly used in space. Photovoltaic voltage arises at the PN junction due to the different distribution of significant energy levels in areas P and N. If the irradiation is constant, the increasing temperature causes a shift of Fermi energy towards the center of the band gap and a decrease in photovoltaic voltage. However, the increasing temperature also reduces the width of the band gap and increases the electric current. For example, in (*Meral & Dincer, 2011*) the results of measuring *I-V* characteristics of a photovoltaic cell based on monocrystalline silicon were presented and discussed, but the temperature range was relatively small (20°C ÷ 60°C).

We performed similar measurements in the maximum possible temperature range of photovoltaic systems, which can work even in extreme climatic conditions or in space (-170°C ÷ +100°C) and we presented the results in (*Libra et al., 2021*). In this article, we discuss in more details the influence of temperature dependences of important characteristics of photovoltaic cells and panels on photovoltaic systems.

MATERIALS AND METHODS

Using our monitoring system Solarmon (*Beránek et al., 2018*), we evaluate data from 85 photovoltaic power plants in the Czech Republic, Slovakia, Romania, Hungary, Chile. The dispatching center is at the Czech University of Life Sciences Prague, Faculty of Engineering. We compare the results with the assumed values according to the solar calculator (Photovoltaic Geographical Information System). Description of the activity associated with high technologies of real-time monitoring of the Earth surface and solar energy conversion is in the work (*Rezk et al., 2015*). A data acquisition system has designed and implemented with facilities for monitoring meteorological data and solar radiation. The system of our colleagues uses photovoltaic monitoring equipment and was developed for taking images of the Earth from satellites. It can forcast meteorological parameters and incoming solar radiation.

When photovoltaic modules operate on the Earth's surface without radiation concentration, their temperature can change from about -100°C to +100°C. When using a photovoltaic system in space, temperature can change over an even larger temperature range during one Earth orbit.

RESULTS AND DISCUSSION

Fig. 2 shows the most important characteristics of the electricity source (in this case an irradiated photovoltaic cell based on monocrystalline silicon) at three selected temperatures. We measured similar characteristics at other temperatures in the above mentioned temperature range (*Libra et al., 2021*). Temperature dependences of the efficiency of photovoltaic energy conversion were measured in (*Gordon et al., 2021*) as well.

If the photovoltaic system operates in places with extreme climatic conditions, especially with extreme temperature changes during the year, the electrical voltage of the photovoltaic panels will change significantly. This can be seen in Fig. 3 and there is also a decrease in the energy conversion efficiency with increasing temperature. Thus, in the stated temperature range, the open circuit voltage can up to double. This must be taken into account when designing a photovoltaic system, including connected devices. If the photovoltaic system is connected to the network, the stability of the grid can also be affected (*Petrík et al., 2020*).

For example, in Oymyakon, (Siberia, 63° north latitude, 750 m altitude), the lowest temperature was - 72°C (on 26th January 1926) and the highest temperature was +35°C (on 28th July 2010). At night, the temperature of the photovoltaic panels is usually lower than the air temperature due to radiation. In the winter morning at sunrise, the temperature of the photovoltaic panels can approach up to the value - 100°C. When using a photovoltaic system in space, temperatures can be even lower in the Earth's shadow, and our measurements are very important especially for these applications. Conversely, the use of radiation concentrators can significantly increase maximum operating temperatures. In this case, it is necessary to assess whether the increased radiation intensity on the photovoltaic panels pays off in comparison with the reduced energy conversion efficiency at the higher temperature of the photovoltaic panels. The decrease in the efficiency of photovoltaic energy conversion with increasing temperature shows an approximately linear dependence, as can be seen in Fig. 3. At the temperature 25°C, the decrease is 0.36 %/°C. These values differ slightly for different PV cell designs and different irradiation.

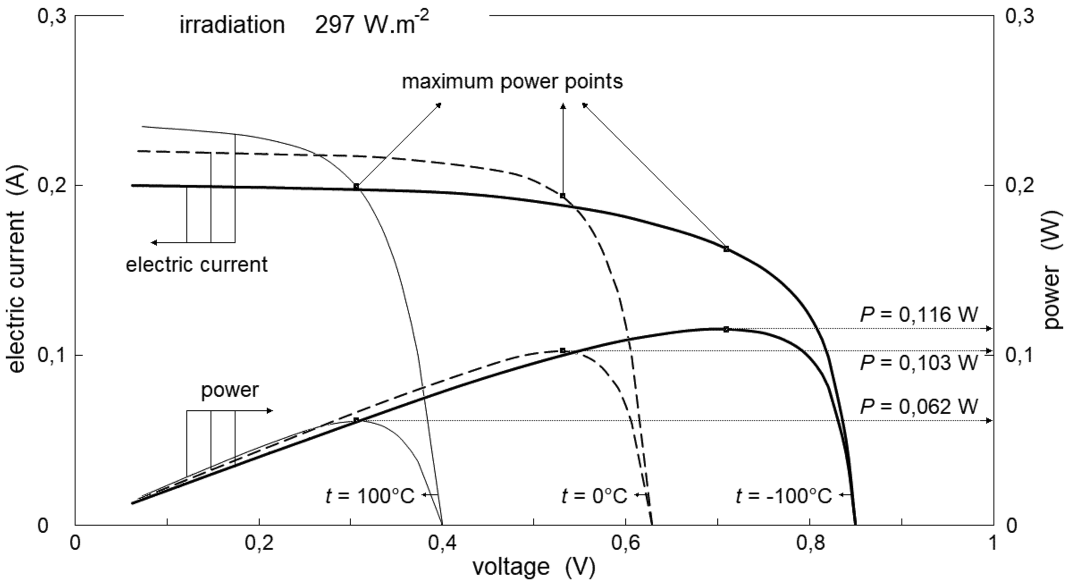

Fig. 2 Important characteristics of an irradiated photovoltaic cell at three different temperatures

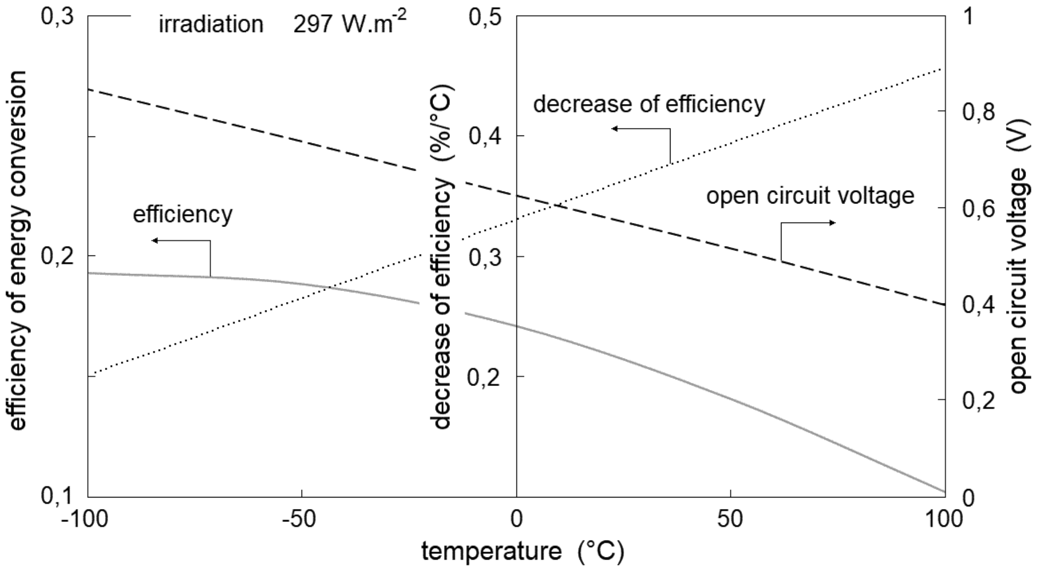

Fig. 3 Dependences of open circuit voltage and energy conversion efficiency on temperature

This mentioned effect of temperature on the efficiency of photovoltaic energy conversion means that extreme values of solar radiation do not necessarily mean extreme yield of the photovoltaic power plant. Tropical areas have a high intensity of sunlight (especially in Africa, Australia and Central America). The yield of photovoltaic power plants is here good but not top, because the efficiency of energy conversion is lower at higher temperatures. The highest yields are achieved in the much more northern and cold regions of Tibet, Mongolia and Siberia with higher altitudes. The plateaus of Chile in the Atacama Desert are also excellent locations. Also on the coast of Antarctica, there can be achieved similar annual yields as in subtropical areas.

For example, we have been operating the photovoltaic system in Fig. 1 (P_{max} = 10 kW$_p$) at the Faculty of Engineering in Prague (50° north latitude, 300 m altitude) since 2015, we collect data using our monitoring system Solarmon (*Beránek et al., 2018*). Fig. 1 shows the photovoltaic system in winter period. The yield of electricity produced slightly exceeds the expected values according to the solar calculator

(Photovoltaic Geographical Information System). We achieved the highest energy yield in 2019, as shown in Fig. 4.

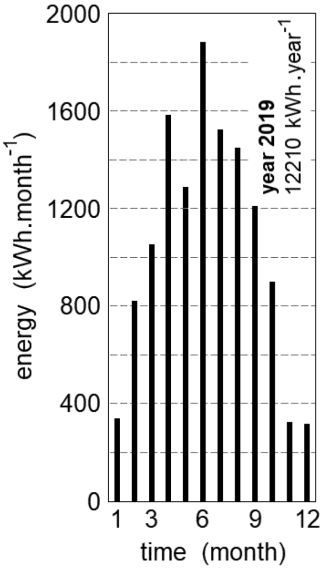

Fig. 4 Electricity produced in the photovoltaic system at the Faculty of Engineering in 2019

CONCLUSIONS

Photovoltaic systems are an important part of the energy mix also with regard to reducing the carbon footprint.

Measurement of important characteristics of photovoltaic cells shows a significant dependence on temperature. The decrease in the efficiency of photovoltaic energy conversion with increasing temperature shows an approximately linear dependence as can be seen in Fig. 3.

Thus, the efficiency of energy conversion and open circuit voltage can up to double on Earth in extreme climatic conditions during the year. In space applications, these values can triple in a single satellite orbit around the Earth. This must be taken into account when designing photovoltaic systems. The individual components and especially the overvoltage protectors must be carefully selected so as not to damage or destroy the connected equipment.

REFERENCES

1. Beránek, V., Olšan, T., Libra, M., Poulek, V., Sedláček, J., Dang, M-Q., Tyukhov, I.I. (2018). New Monitoring System for Photovoltaic Power Plants' Management. *Energies*, 11(10), 2495, doi: 10.3390/en11102495.
2. Božiková, M., Bilčík, M., Madola, V., Szabóová, T., Kubík, L'., Lendelová, J., Cviklovič, V. (2021). The Effect of Azimuth and Tilt Angle Changes on the Energy Balance of Photovoltaic System Installed in the Southern Slovakia Region. *Applied Sciences*, 11(19), 8998, doi: 10.3390/app11198998.
3. Gordon, J.M., Moses, G., Eugene A. Katz, E.A. (2021). Boosting silicon photovoltaic efficiency from regasification of liquefied natural gas. *Energy*, 214, 118907, doi: 10.1016/j.energy.2020.118907.
4. Libra, M., Beránek, V., Sedláček, J., Poulek, V., Tyukhov, I.I. (2016). Roof photovoltaic power plant operation during the solar eclipse. *Solar Energy*, 140, 109-112, doi: 10.1016/j.solener.2016.10.040.
5. Libra, M., Daneček, M., Lešetický, J., Poulek, V., Sedláček, J, Beránek, V. (2019). Monitoring of Defects of a Photovoltaic Power Plant Using a Drone. *Energies*, 12(5), 795, doi: 10.3390/en12050795.
6. Libra, M., Petrík, T., Poulek, V., Tyukhov, I.I., Kouřím, P. (2021). Changes in the Efficiency of Photovoltaic Energy Conversion in Temperature Range With Extreme Limits. *IEEE Journal of Photovoltaics*, 11(6), 1479-1484, ISSN 2156-3403, doi: 10.1109/JPHOTOV.2021.3108484.

7. Meral, M.E., Dincer, F. (2011). A review of the factors affecting operation and efficiency of photovoltaic based electricity generation systems. *Renewable and Sustainable Energy Reviews*, 15, 2176–2184, doi: 10.1016/j.rser.2011.01.010.
8. Petrík, T., Daneček, M., Uhlíř, I., Poulek, V., Libra, M. (2020). Distribution Grid Stability - Influence of Inertia Moment of Synchronous Machines. *Applied Sciences*, 10(24), 9075, doi: 10.3390/app10249075.
9. Photovoltaic Geographical Information System (PVGIS), [online] (2021). Available from https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html. Accessed 10.12.2021.
10. Pokorný, N., Matuška, T. (2020). Glazed Photovoltaic-thermal (PVT) Collectors for Domestic Hot Water Preparation in Multifamily Building. *Sustainability*, 12(15), 6071, doi: 10.3390/su12156071.
11. Poulek, V., Šafránková, J., Černá L., Libra, M., Beránek, V., Finsterle T., Hrzina, P. (2021). PV Panel and PV Inverter Damages Caused by Combination of Edge Delamination, Water Penetration, and High String Voltage in Moderate Climate. *IEEE Journal of Photovoltaics*, 11(2), 561-565, doi: 10.1109/JPHOTOV.2021.3050984.
12. Rezk, H., Tyukhov, I., Raupov, A. (2015). Experimental implementation of meteorological data and photovoltaic solar radiation monitoring systém. *Int. Trans. Electr. Energ. Syst.* 25, 3573–3585, doi: 10.1002/etep.2053.

Corresponding author:
Prof. Ing. Martin Libra, CSc., Department of Physics, Faculty of Engineering, Czech University of Life Sciences Prague, Kamýcká 129, Praha 6, Prague, 16500, Czech Republic, phone: +420 22438 3284, e-mail: libra@tf.czu.cz