IMPACT OF AIR TEMPERATURE AND WIND SPEED ON THE EFFICIENCY OF A PHOTOVOLTAIC POWER PLANT
An Experimental Analysis

by

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For each photovoltaic power plant, it is extremely important to perform an analysis of its efficiency, as well as an analysis of all parameters that may affect efficiency. The electric energy of the photovoltaic system, which is delivered to the electric power system on a daily basis, is determined through the average daily insolation, the surface of the panel and the average efficiency value. One of the parameters that affect the conversion efficiency of a photovoltaic power plant is a decrease in the conversion efficiency due to an increase in panel temperature. In this paper an example is a real photovoltaic power plant with a nominal power of 50 kW, which is installed on the rooftop of the building of the Institute "Mihajlo Pupin", located in Zvezdara forest, Belgrade, Serbia. The correlation analysis of the estimated temperature of the photovoltaic panel was performed using two models and the measured temperature of the photovoltaic panel. The temperature of the photovoltaic panel was estimated using models, one of which does not take into account, and the other takes into account the influence of wind speed on the temperature of the panel.

Key words: *photovoltaic power plants, efficiency, temperature, wind speed*

Introduction

Due to the increasing pollution of the atmosphere and the environment, as well as due to the great need to reduce emissions, renewable energy technology is a technology that is increasingly present, around the world. Solar energy is the largest and most important source of renewable energy and it is the basis of many other renewable sources. Precisely for these reasons it is noticeable the development and significant increase in installed photovoltaic (PV) power plants in recent years. According to [1] it is estimated that by 2050 the total power of installed PV power plants will be around 962 GWp in Europe.

In the project development phase of the PV power plant, it is important to assess productions of that power plant, but it is also significant to determine its efficiency [2, 3]. The parameters that affect the conversion efficiency of a PV power plant are:
– losses in production due to panel contamination and unpaired modules in the panel,
– reduction of conversion efficiency due to increase of panel temperature, and
– losses in power output due to losses in the inverter.

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Since the current-voltage characteristic of the PV module changes with the change of insolation and temperature, the standard test conditions (STC) were established in order to compare the PV modules. The PV module manufacturers provide basic module characteristics related to STC. The efficiency coefficient shows which part of the Sun's energy is converted into electricity and it is defined for STC.

The STC includes the following conditions [4, 5]:

– solar irradiation on the surface of the panel is 1000 W/m^2 (one Sun),
– the temperature of the PV cell is 25 °C, and
– he coefficient of air mass is 1.5.

These terms are accepted by International Electrotechnical Commission (IEC) and American Society for Testing and Materials (ASTM). Reference test conditions are used by PV module manufacturers to define specified PV module parameters. PV modules are tested indoors where the temperature and intensity are adjusted artificially [6].

Under these conditions, the coefficient of efficiency of the PV module is defined as the ratio of the maximum power of the module and the power of solar radiation on the surface of the module:

$$\eta_c = \frac{V_\mathrm{m} I_\mathrm{m}}{1000\ \mathrm{W/m^2} A} \tag{1}$$

where A [m^2] is the effective surface of the PV module, V_m [V] and I_m [A] – the rated voltage and rated current under STC.

Real working conditions deviate from the standard ones, so that the efficiency of the PV panel and other technical parameters in real operating conditions differ to a greater or lesser extent from the standard ones.

Figure 1 shows how the current-voltage characteristic of PV module changes when the power of the solar irradiation changes and when the temperature of the module changes.

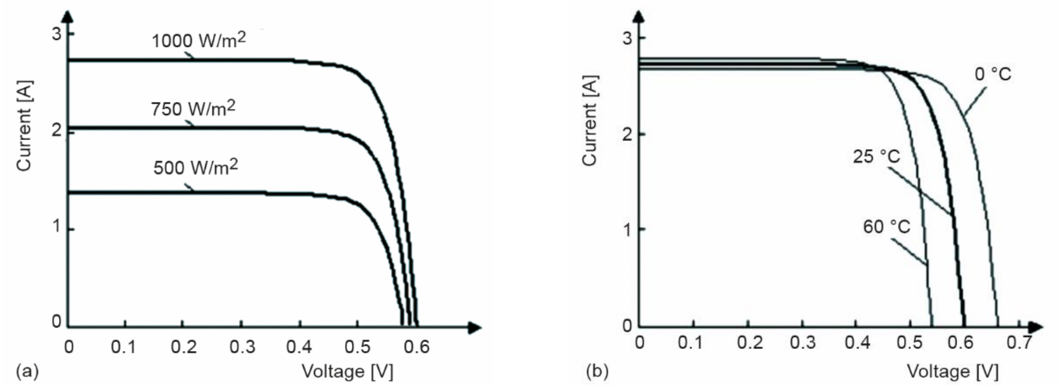


Figure 1. The dependence of the U-I characteristic on irradiation and temperature [4]

The current of a PV cell is directly proportional to the irradiation. On the other hand, irradiation has very little effect on the voltage of the PV cell. It can be concluded that the current will be halved if the irradiation is halved, and thus the power, because the cell voltage remains unchanged. The voltage of the PV cell is directly proportional to the temperature. Temperature has very little effect on cell current [4, 7].

The typical change in these values for crystalline silicon PV cells is: ΔV_{OC} = = –0.3% per °C, ΔI_{SC} = 0.05% per °C, and $\Delta P_{DC\max}$ = –0.4% per °C. In order to take this influence into account, it is necessary to know the temperature of the PV cell.

The temperature of the PV cell changes not only due to the change of the ambient temperature but also due to the change of the irradiation per cell. In PV cells a small part of the energy of solar radiation is converted into energy and most of it is absorbed and converted into heat.

In order to be able to determine the efficiency of a panel under different ambient conditions, it is necessary to calculate the temperature of that panel. The temperature of the PV panel is predominantly influenced by the power of the solar irradiation and cooling conditions, *i.e.* ambient temperature and wind.

The temperature of PV cell is one of the important parameters that affect the efficiency of the cell itself. An increase in cell temperature causes a significant decrease in efficiency.

For each photovoltaic power plant, it is extremely important to perform an analysis of its efficiency, as well as an analysis of all parameters that may affect efficiency [2, 8].

Under operating conditions, the temperature of PV panels can be directly measured and its influence on the efficiency of PV conversion can be considered. However, in the planning phase of the power plant, to assess its production, it is necessary to estimate the temperature of the panel based on the measured meteorological parameters. There are many models through which the temperature of the PV cell, T_c, is expressed depending on meteorological parameters such as: ambient temperature, T_{amb}, local wind speed, v, and solar irradiation, I_c. The aim is for models that describe the correlation between solar irradiation, ambient temperature, wind speed and PV module temperature to be as precise as possible in determining the operating temperature of a PV cell. There are several mathematical models for determining the temperature; each of them has its own approximation error.

David Faiman's photovoltaic module temperature model

David Faiman's model is given from the energy balance for a PV module:

$$T_m = T_{amb} + \frac{I_c}{U_0 + U_1 v} \tag{2}$$

where T_m [°C] is the PV module temperature, T_{amb} [°C] – the ambient temperature, I_c [Wm^{-2}] – the solar irradiation on the surface of PV module, v [ms^{-1}] – wind speed, U_0 [W°C^{-1}m^{-2}] – the coefficient describing the effect of irradiation on the module temperature, and U_1 [Ws°C^{-1}m^{-3}] – coefficient describing the effect of wind cooling.

The coefficients U_0 and U_1 were obtained experimentally: U_0 = 26.89 and U_1 = 6.18 for desert areas (experiments were performed in the Negev desert in southern Israel), U_0 = 28.04 and U_1 = 7.77 for mountain areas (experiments were performed in the Alps).

The real operating temperature of the module (ROMT) can be obtained, given by the following equation [9]:

$$ROMT = 20° + \frac{800\ \text{W/m}^2}{U_0 + U_1 v} \tag{3}$$

For the modules for which experiments were performed in the Negev desert, ROMT had an average value of 43.7 °C, while its real value was 45.5 °C. This temperature is obtained by keeping the PV modules at the point of maximum power through resistive load. Equation (3) proved to be very good for determining the temperature of PV module, even after only one month of desert monitoring, while mountain climate requires a longer-term measurement period to obtain comparable results [9].

The NOCT temperature model of photovoltaic module

For each PV cell, the manufacturer defines the temperature under normal operation cell temperature (NOCT). The NOCT is the cell temperature at an ambient temperature of 20 °C, solar irradiation of 800 W/m^2 and a wind speed of 1 m/s. The NOCT parameter under normal operating conditions was obtained from the manufacturer of PV panels [4, 10, 11].

The temperature of a PV cell at different irradiation and ambient temperature can be determined based on the following equation:

$$T_\mathrm{c} = T_\mathrm{amb} + \frac{NOCT - 20°}{800\ \mathrm{W/m^2}} I_c \tag{4}$$

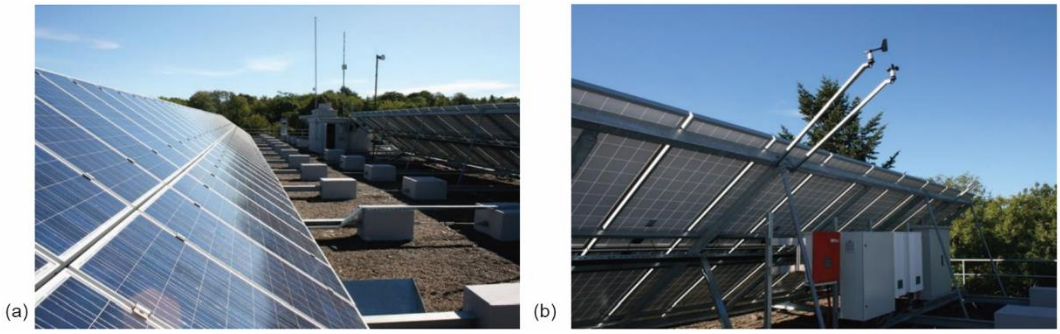
where T_c [°C] is the PV cell temperature, T_amb [°C] – the ambient temperature, and I_c [Wm^{-2}] – the solar irradiation on the surface of PV module.

The experimental analysis of photovoltaic panel temperature estimation in real operating conditions

The description of the analyzed system

As an example, a real PV power plant with the nominal power of 50 kW was taken, which was installed on the rooftop of the building of the Institute Mihajlo Pupin (IMP) which is located in Zvezdara Forest, Belgrade, Serbia. The geographical coordinates of this PV power plant are: N44°48'22" and E20°30'23". In fig. 2 the real PV power plant on the rooftop of the IMP is shown. The available rooftop area was sufficient to install 180 polycrystalline 280 W PV modules from manufacturer Solar Schutten.

Under the influence of increasing temperature, the voltage decreases, and thus the power decreases, while the change in current is small. Typical changes of these values for PV cells of this type of PV modules manufactured by Solar Schutten, which are: $\Delta V_{OC} = -0.346\%$ per °C, $\Delta I_{SC} = 0.065\%$ per °C, and $\Delta P_{DC\max} = -0.488\%$ per °C.



(a) (b)

Figure 2. The PV power plant on the rooftop of Institute Mihajlo Pupin

The efficiency of these type of PV modules, STP6-280/72, manufactured by Solar Schutten is 14.9%. With the development of technology, silicon PV panels today have a significant higher efficiency exceeding 22% for monocrystalline PV panels. Increase efficiency ensures higher production of electricity per unit surface that is covered with PV panels. In addition, the increase efficiency to a certain extent also affects the reduction of the active temperature of the surface of the PV module because the greater part of the irradiated solar energy is converted into electricity, i.e. a smaller part of the radiated energy is turns into heat. This effect has significance in terms of additional increase efficiency of PV panels in real conditions of exploitation.

For the observed period of five years, from 2015 to 2020, fig. 3 presents the average monthly values of PV power plant production. The maximum and minimum values of the average monthly production are also presented for this period.

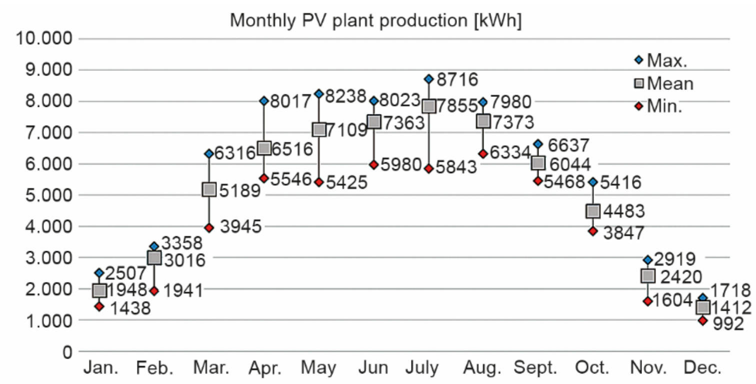


Figure 3. Average monthly PV power plant production in the period from 2015 to 2020

In fig. 4, annual PV plant production for the observed period from 2015 to 2020 is depicted. To understand the variation in annual plant production, the figure also contains accumulated solar insolation for the power plant location (orange line). As expected, the total production is correlated with the insolation, while the slight deterioration in the overall plant efficiency can be observed in fig. 5.

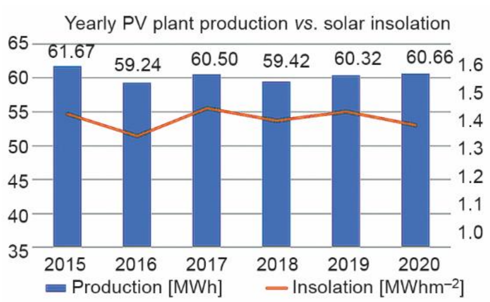


Figure 4. Total yearly PV plant production in the period from 2015 to 2020

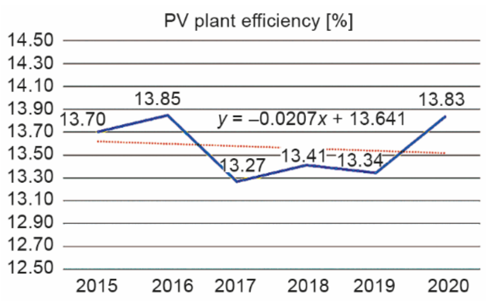


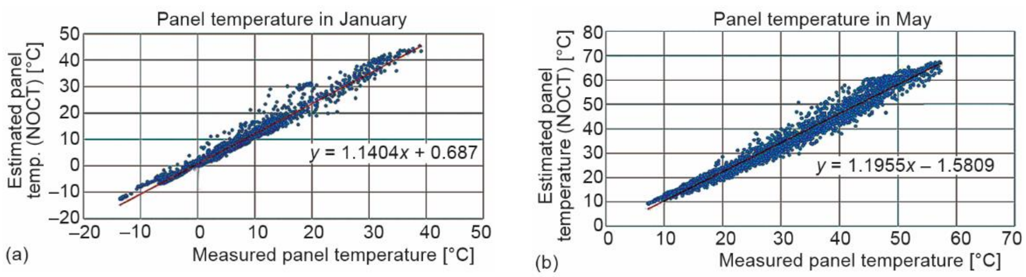
Figure 5. The PV plant efficiency in the period from 2015 to 2020

As depicted in fig. 5, the overall plant efficiency shows a decreasing trend (orange line) although some deviations from expected decrease can be observed. Namely, this refers to the last year of the dataset, year 2020, which was caused by the large plant maintenance activity that involved thorough cleaning and replacement of some malfunctioning panels.

The analysis of PV panel temperature estimation in real operating conditions

For further analysis, three characteristic months were selected for the winter, spring and summer seasons, namely January, May, and August during one year in the observed period from 2015 to 2020. The analyses were performed on the basis of available measurements of the relevant operating parameters of the mentioned PV power plant. The data included measurements of ambient temperature, PV panel temperature, wind speed, PV panel production, insolation, as well as PV panel efficiency.

The correlation analysis of the estimated temperature of the PV panel was performed using two models and the measured temperature of the PV panel. In first analysis, based on ten-minute measurements of ambient temperature and solar irradiation at the mentioned location, the temperature of the PV panel was estimated using eq. (4) of NOCT model. A comparison of the estimated PV panel temperature based on the mentioned model and the measured PV panel temperature is shown in fig. 6 for all three characteristic months. The following characteristics of the PV module were taken into account: NOCT = 46 °C and the coefficient of temperature change of efficiency –0.488% per °C.



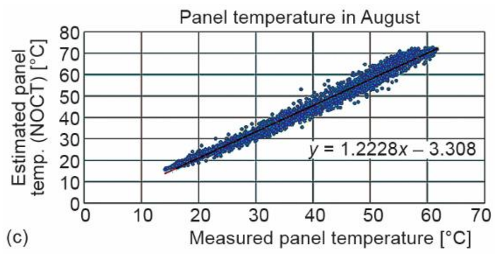


Figure 6. Comparison of estimated (NOCT model) and measured PV panel temperatures for January, May, and August

Based on the analysis of fig. 6 it can be concluded that the estimated temperature of PV panel using the NOCT model is on average higher than the measured one. This can be explained by the fact that the NOCT model assumes a very low wind speed, of only 1 m/s, so the real cooling conditions are often better than expected. For this reason, the actual temperature is lower than the estimated temperature.

In second analysis, based on ten-minute measurements of ambient temperature, solar irradiation, and wind speed the temperature of the PV panel was estimated using David-Faiman's model. The values considered for the coefficients are U_0 = 27.47 and U_1= 6.98. A comparison of the estimated PV panel temperature based on the David Faiman's model and the measured PV panel temperature is shown in fig. 7 for all three characteristic months.

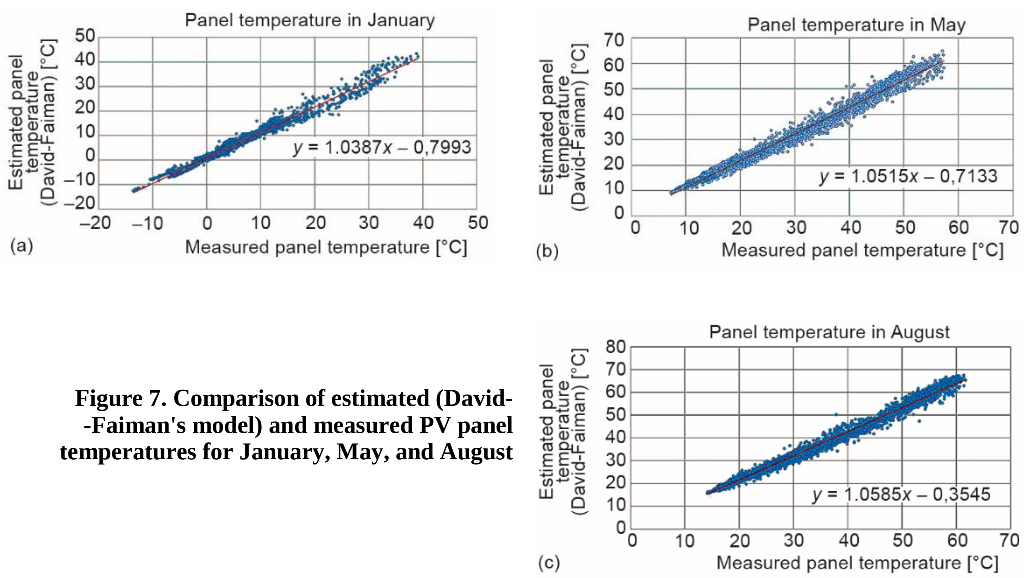


Figure 7. Comparison of estimated (David--Faiman's model) and measured PV panel temperatures for January, May, and August

For all three characteristic months, a better correlation was obtained between the estimated PV panel temperature according to David-Faiman's model, which takes into account the influence of wind speed on PV panel temperature, and the measured PV panel temperature, than according to the NOCT model. This confirms the claim that the temperature of the PV panel, in addition to solar irradiation, is predominantly influenced by wind.

In tab. 1 the values of the correlation coefficient are shown when the measured temperatures of PV panel and the estimated temperatures of the PV panel are compared according to the NOCT model and according to David-Faiman's model for all three characteristic months.

Table 1. Correlation coefficient values

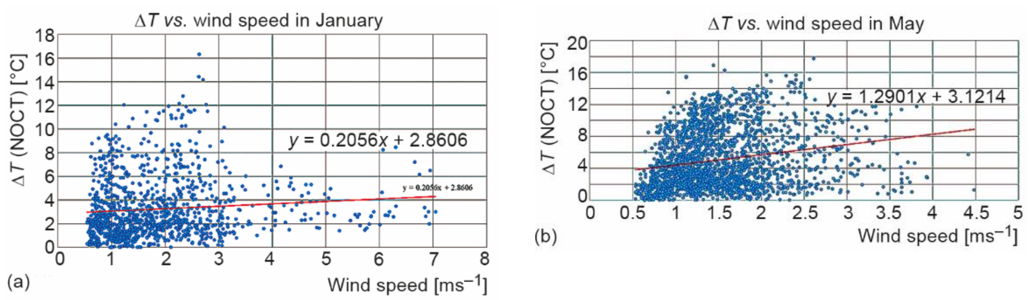
Month	The correlation values	
	NOCT model	David-Faiman's model
January	0.9852	0.9890
May	0.9784	0.9805
August	0.9759	0.9769

The change in the temperature error of PV panel depending on the measured wind speed was performed. Temperature error was determined using the following expression:

$$\Delta T = T_{\text{estimated}} - T_{\text{measured}} \tag{5}$$

where $T_{\text{estimated}}$ is the estimated PV temperature of the PV panel is estimated using NOCT model or David-Faiman's model.

The change in the temperature error of PV panel depending on the wind speed, using NOCT model is shown in fig. 8 and the change in the temperature error of PV panel depending on the wind speed using David-Faiman's model is shown in fig. 9.



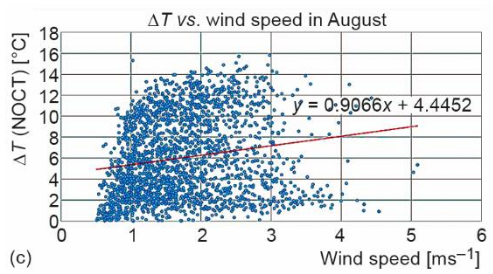
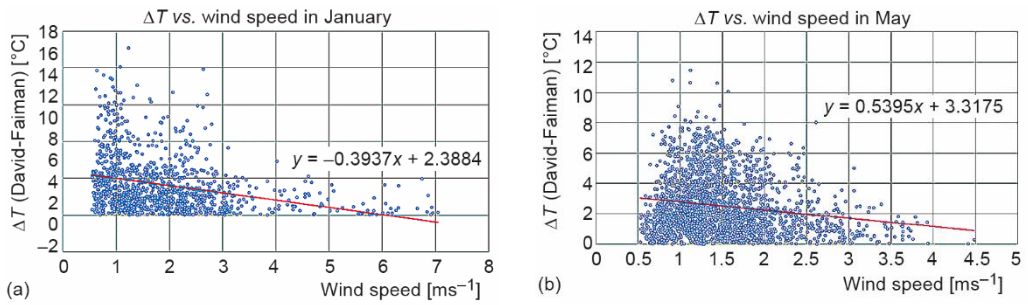


Figure 8. The change of PV panel temperature error depending on wind speed (NOCT model) for January, May, and August



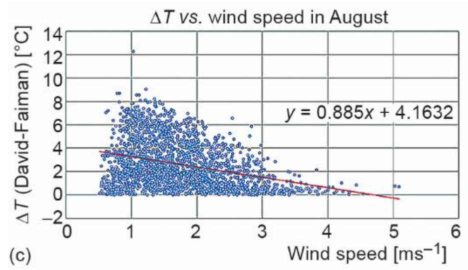


Figure 9. The change of PV panel temperature error depending on wind speed (David-Faiman's model) for January, May, and August

Based on the obtained graphs shown in figs. 8, and 9, it can be concluded that the trend of changing the temperature error of PV panel depending on the wind speed is completely. As the wind speed increases, the error decreases for the case when PV panel temperature is estimated using David-Faiman's model, which takes into account the influence of wind speed, while for the case when PV panel temperature is estimated using the NOCT model, which does not take into account the wind speed, it increases. In this way, it was once again confirmed that wind significantly affects the temperature of PV panel and that it must be taken into account when calculating the efficiency of PV panels.

The experimental analysis of photovoltaic panel efficiency assessment in real operating conditions

In order to determine the output power of a PV system for a known input power of irradiation, it is necessary to know the indicated power of the PV module declared by the manufacturers for STC. In real operating conditions, the power delivered by PV system to the network is less than the DC output power at the module connections under STC due to losses in the system and lower irradiation values per panel in relation to STC. Power delivered to the grid by the PV system:

$$P_{AC} = P_{DC(STC)}\eta \frac{I_c}{1000\ \text{W/m}^2} \qquad \eta = \eta_{\text{INV}}\eta_{\text{T}}\eta_Z\eta_N\eta_M \tag{6}$$

where $P_{DC(STC)}$ is the indicated power of the PV module declared by the manufacturers for STC, I_{c} – the irradiation at the surface of the panel, η_{T}, η_Z, η_N – coefficients that define the decrease in panel efficiency due to increase in module temperature, dirt, unmatched modules, η_{INV} – the inverter efficiency, and η_M – the PV module efficiency.

The total system efficiency level, η, takes into account losses due to fowling of the panel, mismatch between modules in the string, degradation of panel efficiency in the course of exploitation, inverter losses and losses in electrical connections. When the PV module becomes dirty, the power decreases due to the reduction of the absorption of solar energy by the PV module. Unpaired modules cause a decrease in the output power of parallel connected modules due to the fact that the current-voltage characteristics of the module are not identical. In order for the efficiency of the system to be as high as possible, we should strive for the modules that form the panels to be as close as possible to the characteristics. The efficiency of inverters varies depending on the load, so network-connected inverters have an efficiency of over 90%, except at very low loads. The values of inverter efficiency and PV module efficiency are given by their manufacturers [6].

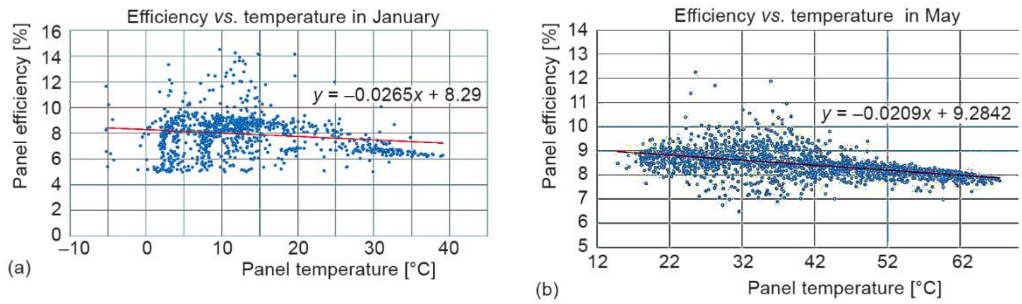
The temperature of PV cell is a very important parameter that affects the conversion efficiency of PV system. An analysis of the efficiency of a real PV power plant on the roof of the building of IMP in a period of one year was performed, showing how the conversion efficiency changes depending on the temperature.

The dependence of the conversion efficiency coefficient on the measured temperature of PV panel is shown in fig. 10 for all three characteristic months during one year. The total area of the PV power plant installed on the rooftop of the building is 332 m^2, and the area of one PV module is 1.84 m^2.

The electric energy of PV system, which is delivered to the electric power system on a daily basis, is determined through the average daily insolation, the surface of PV panel and the average efficiency value. Based on the measurements of solar insolation on PV panel and the daily diagram of PV power plant production the efficiency coefficient was calculated:

$$W_{\mathrm{D}} = A\frac{1}{T}\int_0^T I_{\mathrm{c}}\eta\,\mathrm{d}t \approx I_{\mathrm{c}}A\eta \tag{7}$$

where W_D [kWh] is the daily electricity delivered to the grid, A [m^2] – the available surface where photovoltaic panels are being installed, and I_{c} [Wm^{-2}] – the solar irradiation on the surface of PV panel. The approximation that the efficiency of the system during the day is equal to the average daily efficiency was used [6].



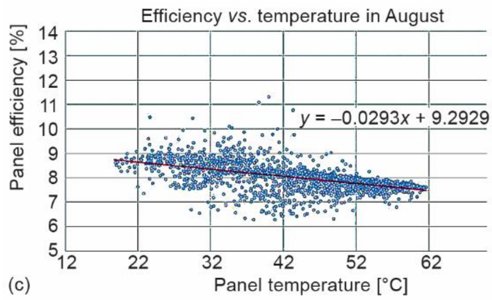


Figure 10. Dependence of the conversion efficiency coefficient on the measured temperature of PV panel for January, May, and August

The conversion efficiency of PV system largely depends on the temperature. It is noticed that if the production of PV power plant is higher, it usually means that the weather conditions are better at a given moment, *i.e.* that the temperature and irradiation are higher. As the temperature increases, the conversion efficiency decreases, so it can be concluded that these two quantities have changes in the opposite direction for the same time.

The value of the theoretical conversion efficiency of PV system is determined using eq. (6). The following characteristics of PV module provided by the manufacturer have been adopted: reduction of conversion efficiency due to panel contamination of 3%, inverter efficiency of 98% and module efficiency of 14.9%. Efficiency reductions due to unpaired modules in the panel have been neglected.

The decrease in efficiency due to the increase in cell temperature above the value of 25 °C under standard test conditions is considered, where the coefficient of temperature change of efficiency is –0.488% per °C:

$$\eta_{\mathrm{T}} = 1 - 0.00488(T_{\mathrm{c}} - 25^\circ) \tag{8}$$

The decrease in conversion efficiency due to temperature increase was determined for two cases, namely the case when PV panel temperature was estimated using a model that does not take into account the influence of wind speed on the panel temperature (NOCT model) and the case when PV panel temperature was estimated using the model panel temperature (David-Faiman's model).

The analysis showed that the measured conversion efficiency of PV system is lower than the theoretical, *i.e.* calculated efficiency. The higher the ambient temperature, the efficiency of the panel decreases during the exploitation period, and thus its production. The closer the ambient temperature is to the temperature declared in standard test conditions, the panel works with the declared conversion efficiency. If the ambient temperature is lower than the declared value, PV panel works with a higher conversion efficiency than the declared one.

For all three characteristic months, a standard deviation was determined according to:

$$\sigma = \sqrt{\frac{\sum_{k=1}^{n}[x_{\text{measured}}(k) - x_{\text{estimated}}(k)]^2}{n}} \tag{9}$$

where x_{measured} is the measured conversion efficiency values and $x_{\text{estimated}}$ – estimated conversion efficiency values using two models (NOCT model and David-Faiman's model).

The standard deviation values were obtained for all three characteristic months shown in tab. 2.

Table 2. Standard deviation values

Month	The standard deviation	
	NOCT model	David-Faiman's model
January	11.0429	11.1887
May	4.8038	4.9754
Aaugust	6.5558	6.8193

The analysis showed that David-Faiman's model introduces a larger estimation error. Although the opposite is expected, because David-Faiman's model takes into account the influence of wind speed when estimating the temperature of PV panel as opposed to the NOCT model, the results are quite justified, because the measured conversion efficiency is far lower than both estimated panel efficiencies. Since David-Faiman's model takes into account the influence of wind speed, and thus lowers the estimated temperature of PV panel, these results in higher estimated conversion efficiency of the panel, which causes an even greater error compared to the measured efficiency of panel conversion.

Conclusion

In this paper the influence of air temperature and wind speed on the efficiency of PV panels is analyzed. On the example of a real PV power plant, the correlation analysis of the estimated temperature of PV panel was performed using two models and the measured temperature of PV panel. Models for estimating the temperature of PV panel were used, where one model does not take into account, while the other takes into account the influence of wind speed on the panel temperature. It can be concluded that theoretical models for estimating the temperature of PV panels that take into account wind speed are significantly more reliable and accurate, and that wind speed must be taken into account as an important parameter in assessing the efficiency of PV panels in real operating conditions.

The temperature of PV cell is a very important parameter that affects the efficiency of the photovoltaic cell itself, so it is of great importance to estimate this parameter as accurately as possible in order to see the real production. An analysis of the efficiency of a real PV power plant in a period of one year was performed, showing how the efficiency of conversion changes depends on the temperature. The analysis showed that the measured conversion efficiency of PV system is lower than the theoretical, *i.e.* calculated efficiency. The higher the ambient temperature, the efficiency of the panel decreases during the exploitation period, and thus its production. The closer the ambient temperature is to the temperature declared in the standard test conditions, the panel works with the declared conversion efficiency. If the ambient temperature is lower than the declared value, the photovoltaic panel works with higher conversion efficiency than the declared one.

The conducted analyzes regarding the impact of ambient temperature variation on the efficiency of PV panels are of important practical importance, because they enable a better understanding of uncertainties in assessing the efficiency of PV systems due to changes in ambient conditions.

References

[1] Zervos, A. L. C. M. J., *et al*., 100% Renewable Energy Vision for the Europien Union-Re-thinking 2050, 2010
[2] Kaldellis, J. K., *et al*., Temperature and Wind Speed Impact on the Efficiency of PV Installations. Experience Obtained from Outdoor Measurements in Greece, *Renewable Energy, 66* (2014), June, pp. 612-624
[3] Bhattacharya, T., *et al.*, Effects of Ambient Temperature and Wind Speed on Performance of Monocrystalline Solar Photovoltaic Module in Tripura, India, *Journal of Solar Energy, 2014* (2014), ID 817078
[4] Master, G., *Renewable and Efficient Electric Power Systems, Stanford University*, John Wiley & Sons, New Jersey, N. Y., USA, 2004 ISBN 0-471-28060-7
[5] Ma, T., *et al*., Solar Photovoltaic System Modeling and Performance Prediction, *Renewable and Sustainable Energy Reviews, 36* (2014), Aug., pp. 304-315
[6] Mikulović, J., Đurišić, Ž., Solar Energy (in Serbian), Energetika, Akademska Misao, Belgrade, 2019
[7] Tiwari, G. N., *et al*., Photovoltaic Modules and Their Applications: A Review on Thermal Modelling, *Applied Energy, 88* (2011), 7, pp. 2287-2304
[8] Mitiu, M. A., *et al*., Efficiency of Polycrystalline Photovoltaic Parks in Romania, *Thermal Science, 22* (2018), Suppl. 2, pp. S665-S671
[9] Koehl, M., *et al.*, Modeling of the Nominal Operating Cell Temperature Based on Outdoor Weathering, *Solar Energy Materials and Solar Cells, 95* (2011), 7, pp. 1638-1646
[10] Bharti, R., *et al.*, Nominal Operating Cell Temperature (NOCT): Effects of Module Size, Loading and Solar Spectrum, *Proceedings*, 34th IEEE, Photovoltaic Specialists Conference (PVSC), Philadelphia, Penn., USA, pp. 1657-1662
[11] Alonso Garcia, M. C., Balenzategui, J. L., Estimation of Photovoltaic Module Yearly Temperature and Performance Based on Nominal Operation Cell Temperature Calculations, *Renewable Energy, 29* (2004), 12, pp. 1997-2010

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