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Experimental Study and Performance Analysis of the Photovoltaic System Output under Real Weather Conditions

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Abstract: The aim of this study is to evaluate PV output, considering PV module temperature and real meteorological parameters. An experimental investigation was performed in warmest month, July, and the following parameters were measured: PV module temperature, PV voltage and current, solar irradiation, air temperature, and wind velocity. It was shown that increasing PV module temperature above 25 °C leads to voltage drops and decreased electrical efficiency. The minimum measured average daily PV module temperature was 40.86 °C and the maximum was 42.59 °C. It is shown that when the PV module temperature exceeds 25 °C, the electrical efficiency starts to decrease at a rate of 0.449 – 0.455%/°C. It can be concluded that for approximately 2.2 °C above 25 °C leads to a 1 % reduction in the PV module's electrical efficiency. These results are significant for designing PV systems and evaluating energy yield considering the climate parameters in which they will operate.

Keywords: experimental study; photovoltaic output; temperature dependence; weather conditions

1 INTRODUCTION

Climate changes and secure energy supply chains are key factors in the transformation processes of energy systems. The sixth Intergovernmental Panel on Climate Change report concludes that global greenhouse gas emissions must be reduced by 43% by 2030 to achieve the goal of limiting global warming to 1.5 °C [1]. To fight with all these issues, different scenarios to use various types of renewable energy sources by many researchers have been suggested [2, 3]. These scenarios propose how to reduce fossil fuels and to use more renewable energy sources. Since 1990, the adoption of renewable energy has been rising in both developed and developing countries. This shift is primarily driven by technological progress, lower costs, government support for renewable energy, climate change concerns, and a desire to reduce dependence on foreign energy [4, 5]. European Union proposes to increase the target in the Renewable Energy Directive [6]**.** In 2023, renewable energy capacity globally increased by almost 50% and this is fastest growth rate in the past two decades [7]. According to STEPS (Stated Policies Scenario), by 2030, 80 % of new capacity will be renewable energy sources. Solar PV alone are set for more than half, solar PV alone are set [8]. Over the coming five years, renewable energy milestones that expected to be achieved are: renewable energy sources will overtake coal and will become the leading source of electricity generation in 2025 and solar PV will overtake nuclear electricity generation in 2025 and 2026 respectively [7]**.** In addition to the standard benefits of reducing greenhouse gas emissions, improving air quality, and protecting natural resources, the transition to renewable energy sources stimulates economic growth, creates new jobs, and contributes to a more sustainable and environmentally friendly energy system [9].

The photovoltaic (PV) technology is the most used technologies available for solar energy utilization. Despite all the challenges, solar energy is one of the most favourable renewable energy resources [7, 10, 11]. Solar energy provides many advantages, including great potential, the affordability of the prices per individual system, zero or decreased greenhouse gas emissions, no noise emission and no need for fossil fuels [12]. The potential of solar energy is unlimited, because it is available virtually everywhere. For example, in less than 9 minutes, the Earth is illuminated with as much solar energy as humanity needs in a year [13]. Solar energy is a renewable resource capable of replacing large amounts of conventional energy, but its utilization is restricted by technological, economic, and geographical limitations [14]. In 2023, solar PV alone took three-quarters of renewable capacity worldwide [7]. As part of the REPowerEU plan, EU Solar Energy Strategy aims to bring over 320 GW of solar photovoltaic by 2025 and almost 600 GW by 2030 [15]. Solar PV and wind energy will take 95% of worldwide renewable capacity by 2028.

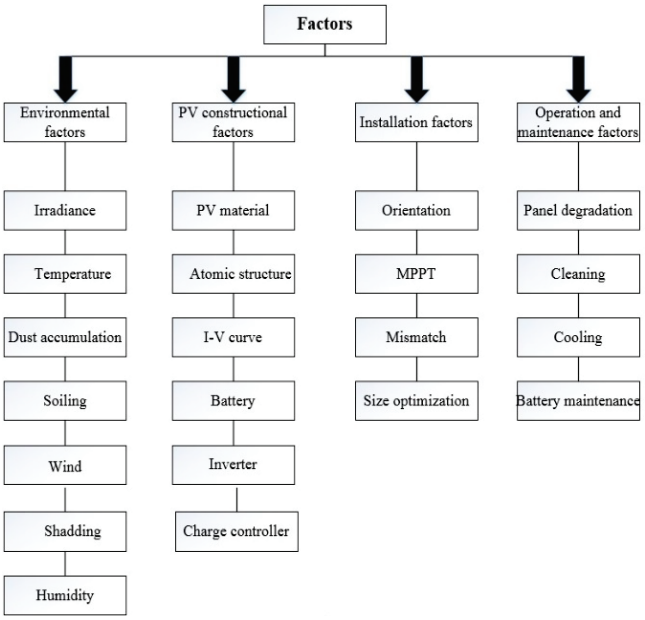


Figure 1 PV panel efficiency degradation factors

1.1 Overview: Solar PV Efficiency

Typical PV module convert up to 23% of the solar energy into electricity while the rest is mainly converted into

heat, depending on the different factors [16-19]. PV efficiency depends on many parameters (Fig. 1). There are developed standard test procedure to determine the characteristics of photovoltaic modules from different manufacturers under equal conditions. These conditions are known as standard test conditions (STC). The standard conditions determine that the module testing is performed at a total irradiance of 1000 W/m^2, air mass AM (defined by standards ISO 9845-1:2022 and ASTM G173-03) 1.5, and that the temperature of the cells is 25 °C. Under these conditions, all the operating parameters of the PV panel, as well as its electrical efficiency, are specified. In real conditions, the irradiance is lower and the temperature of the cells inside the module is higher than the values of STC. The authors [20] concluded that approximately 50% of the analysed articles focused on the impact of environmental factors on PV performance. The most important environmental factors are: solar irradiance, wind velocity, air temperature, dust accumulation, soiling and effect of shading [20-25].

In [26] it is found that water droplets on the PV panel improved the PV power output by at least 5.6% while birds fouling the PV module surface reduce the PV system performance by about 7.4%. The PV panel output significantly depends on solar irradiance. Irradiance varies due to the meteorological parameters such as weather, geographical location, seasonal changes, sun position in the sky and period of the day. As the irradiance drops below 1000 W/m^2, the *I-V* characteristic of the PV panel changes. The short - circuit current (I_{sc}) decreases in direct proportion to the decrease in irradiance. The short-circuit current is the current in solar cell at the zero voltage across the solar cell. The open circuit voltage (V_{oc}) also decreases, but its percentage change is far less compared to the change in current. The open circuit voltage is the maximum voltage available from the solar cell, and this occurs when the net current thorough device is zero. Temperature is also one of the physical quantities that have a significant impact on the performance of photovoltaic modules. The open - circuit voltage (V_{oc}) decreases with increasing temperature, while the short – circuit current (I_{sc}) increases. As a superposition of temperature variations of current and voltage, the power produced by PV modules also changes depending on temperature. A more intense decrease in voltage dominates compared to a milder increase in current, resulting in the fact that the power decreases as the temperature increases [27]. Temperature of PV cell higher than 25 °C negatively affect the PV electrical efficiency [28, 29]. It is an interesting phenomenon that the photovoltaic panel produces more power when the day is clear and cold than when it is clear and hot. The heat flux generated will increase the module temperature and decrease the electrical efficiency of the PV module. There is a strong relationship between module temperature and the bandgap energy of the PV cell material. When the operating temperature soars, the energy bandgap in materials tends to shrink. This shift allows the cell to soak up photons with longer wavelengths, which can be quite beneficial. This rise in temperature often extends the lifespan of those minority carriers, enhancing overall efficiency. Different mounting systems can have influence on the airflow and ventilation around the PV module. This can affect the heat dissipation of the panel and the module temperature. Tab. 1 gives range of annual PV performance loss due to temperature effect for the different mounting systems [30]. The PV, which are mounted on the sloped roof, have the largest annual loss. Reason for this is the little air circulation between the roof and the panel. This leads in rise of the module temperature. A free - standing and flat roof mounting system allow airflow around the panel which gives a better cooling of the panel, and more heat dissipation occurred.

Table 1 Annual PV performance loss due to temperature effect for the different mounting systems

	Temperature rise (K)	Annual loss due to temperature effect (%)
Sloped roof	20 - 55	1.7 - 11.3
Facade integrated	46 - 52	5 - 7
Free-standing	20 - 26	1.7 - 5
Flat roof	25 - 28	2.5 - 4.0

2 MATERIALS AND METHODS

2.1 PV Module Efficiency as a Function of the Operating Temperature of a Photovoltaic Cell/Module

Operating temperature of a photovoltaic (PV) cell/module has significant impact on its electrical efficiency [31]. There are many correlations, which are analysing the PV cell temperature (T_c) as a function of meteorological variables: the ambient temperature (T_a), solar radiation (G_T), local wind velocity (v), as well as material and system dependent properties [32-36]. The temperature of the back surface of the photovoltaic module (T_m) and the temperature of the photovoltaic cell (T_c) can differ for high intensities of solar radiation [37]. At solar radiation of 1000 W/m^2, this temperature difference is typically 2 – 3 °C for flat - plate modules. This temperature difference can be assumed to be zero for flat – plate with a thermally insulated back surface [37]. As the maximum measured average daily solar radiation for the given location is less than 700 W/m^2, these differences were ignored and $T_c = T_m = T_{PV}$ was adopted. There are wide number of correlations which are analysing temperature dependence of the PV module's electrical efficiency [38]. The effect of temperature on the electrical efficiency of a PV cell/module can be define by using Eq. (1) [38-42]:

$$P_m = I_m \cdot V_m = (FF) \cdot I_{sc} \cdot V_{oc} \tag{1}$$

In this expression, subscript "m" refers to the maximum power point in the module's *I–V* curve. Both the open circuit voltage and the fill factor decrease substantially with temperature while the short-circuit current increases. This leads to a linear relation for the electrical efficiency of a PV given in Eq. (2) [38 - 39]:

$$\eta_{el} = \eta_{STC} \cdot \left[1 - \beta \cdot \left(T_c - T_{STC}\right) + \gamma \log_{10} G(t)\right] \tag{2}$$

which η_{STC} is the module's electrical efficiency at the reference temperature, T_{STC} = 25 °C, and at solar radiation flux of 1000 W/m^2 [39]. The temperature coefficient, β, and the solar radiation coefficient, γ, are mainly material

properties, having values of about 0.004 K^{-1} and 0.12, respectively, for crystalline silicon modules [38-40]. The last part of the Eq. (2), however, is usually taken as zero [38-40], and Eq. (2) reduces to Eq. (3):

$$\eta_{el} = \eta_{STC} \cdot \left[1 - \beta \cdot \left(T_c - T_{STC}\right)\right] \quad (3)$$

This equation represents the traditional linear expression for the PV electrical efficiency [39 - 42]. Reduction in efficiency of PV module can be estimated as follows in Eq. (4):

$$Reduction\ in\ efficiency = \frac{\eta_{STC} - \eta_{calculated}}{\eta_{STC}} \cdot 100\% \quad (4)$$

2.2 Experimental Setup

Since PV module electrical efficiency depends significantly of geographical areas and climate, an own experimental installation was designed, constructed and built in order to be able to measure the temperature of PV module, voltage and current in real time taking into account relevant meteorological parameters such as air temperature, solar radiation and wind velocity. With these real measured parameters, PV electrical efficiency was calculated. Fig. 2 gives different components used in the experiment. Experimental PV installation used for this study is located outside of the building of the Faculty of Mechanical Engineering, University of Banja Luka (44.46282 N, 17.11502 E) in Bosnia and Herzegovina. The meteorological station is installed on the rooftop of the building. The PV module used for the experiment is a monocrystalline type (SZ-100-36M). Technical specification of the PV module are given in more details in Tab. 2. Temperature of PV module was measured by PT100 thermocouple. These thermocouples were placed on the rear of the PV module in two points. These locations were chosen to determine if there was a difference in the temperature distribution across the panel. For this reason, two diametrically different points were chosen for positioning the thermocouples (left corner down and upper right, Fig. 2c). The average value of these two temperatures was used for analysis. Accuracy of PT100 is ±(0.15 + 0.002×|T|) °C for validity range from –50 °C to 300 °C.

When designing the installation itself, it was decided to place the panels on a metal pillar. The reason for this is to ensure an undisturbed flow of wind around the panel and thus to obtain the most relevant data on its influence on the temperature of the panel. Meteorological data including solar radiation, ambient temperature and wind velocity were measured by the meteorological station Luft WS10. Technical data for meteorological station are given in Tab. 3.

The datasets were collected during the period of 3 days (from July 15 to July 17, 2023) so that measurements results could be monitored and evaluated. Month July was selected for these analysis as a warmest month in the year for analysed geographical area. Measurements were performed from 10 AM to 4 PM with a 10-minute recording interval and stored via EASY-E4-UC-12RC1 data acquisition.

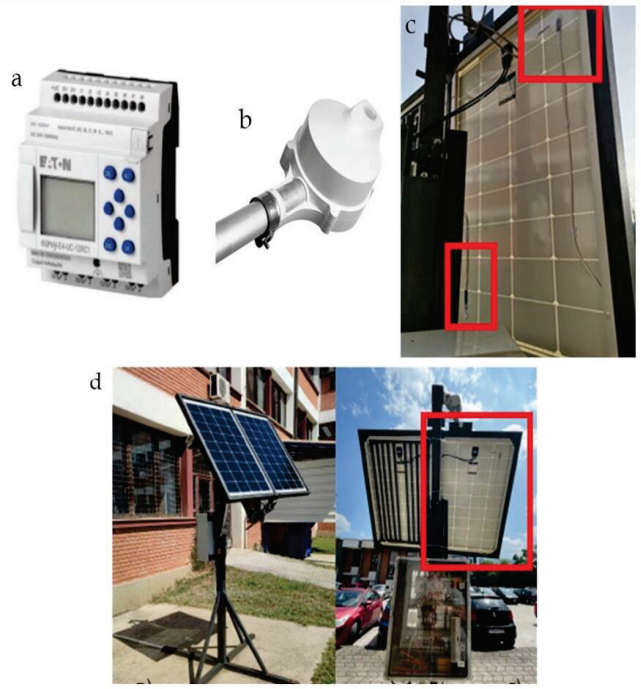


Figure 2 Different outdoor experimental facilities (a - EASY-E4-UC-12RC1 data acquisition, b - meteorological station Luft WS10, c - positions of thermocouples for measuring the PV module temperature, d - experimental setup)

Table 2 Technical specification of the PV module

Standard Test Conditions AM = 1.5, E = 1000 W/m², T_C = 25 °C	
Nominal Power	100 W
Cell Type/Efficiency	Monocrystalline / 17.66 %
Maximum Power Current (I_m)	5.41 A
Maximum Power Voltage (V_m)	18.50 V
Open-circuit Voltage (V_{oc})	22.50 V
Short-circuit Current (I_{sc})	5.92 A
Working Temperature	–40 °C to +80 °C
Module Dimensions	1020 × 670 × 35 mm

Table 3 Technical specification of the meteorological station Luft WS10

Air temperature	PTC, –40 °C to +60 °C (±1.0 °C)
Irradiance	Silicium - Pyranometer, 0 ÷ 1500 W/m² (±10 % or ±120 W/m²)
Wind velocity	0 - 40 m/s (±1 m/s or 5 %)

3 RESULTS

The maximum and minimum values of meteorological data recorded during experiment are presented in the Tab. 4. The analyzed data showed that solar radiation (G_T), ambient temperature (T_a) and wind velocity (v) ranged from 457 - 822.3 W/m², 30.7 - 40.8 °C and 1.3 - 13.5 km/h, respectively.

Table 4 The maximum and minimum values of meteorological data recorded during experiment

Day		G_T (W/m²)	Ta (°C)	v (km/h)
15.7.2023	Max	822.3	37.9	10.3
	Min	457	30.7	1.3
16.7.2023	Max	810.4	39	13.5
	Min	453.3	32.7	1.6
17.7.2023	Max	806.7	40.8	9.3
	Min	461	34.8	1.6

Experimental measured PV module temperature was above 25 °C for whole period of measurement. Average values of meteorological data (air temperature, wind velocity and irradiance) for the whole period of measurement as well as daily average measured PV module outputs are in the Tab. 5.

Table 5 Average values of meteorological data as well as measured PV module outputs in period of measurement on July 15-17, 2023

	On July 15, 2023	On July 16, 2023	On July 17, 2023
Daily average measured air temperature, °C	34.71	36.99	38.72
Daily average measured wind velocity, km/h	5.10	5.34	4.67
Daily average measured irradiance, W/m	703.62	698.15	686.63
Daily average measured PV module temperature, °C	40.86	42.43	42.59
Daily average current, A	4.55	4.40	4.47
Daily average voltage, V	15.41	15.38	15.13
Daily average PV power output, W	70.27	67.67	67.60
Daily average PV electrical efficiency	0.164	0.162	0.161
Daily average reduction in electrical efficiency, %	7.13	7.91	8.00

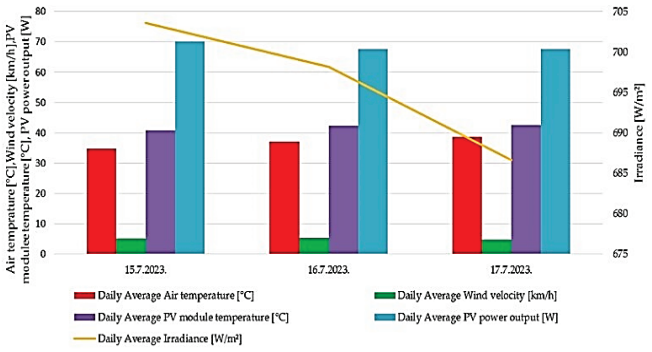


Figure 3 PV power output and average daily meteorological parameters for all three days of measurements

Maximum average daily air temperature was on July 17 (2023) with 38.72 °C and minimum was on July 15 (2023) with 34.71 °C. Maximum average daily PV module was on July 17 (2023) with 42.59 °C and minimum on July 15 (2023) with 34.71 °C. On July 16 (2023), average daily wind velocity had maximum value compared to other two days when experiment was run. Maximum PV power output was on July 15 (2023) with 70.27 W output and minimum PV power output was on July 17 (2023) with 67.60 W output. Fig. 3 presents PV power output and average daily meteorological parameters. Maximum daily average reduction in electrical efficiency corresponds to the warmest day for the whole period of measurement on July 17, 2023 with reduction of 8%.

Minimum daily average reduction is on July 15 (2023) with reduction of 7.13%. On Figs. 4, 5 and 6 are given graphical representation of measured parameters during whole three days of measurement.

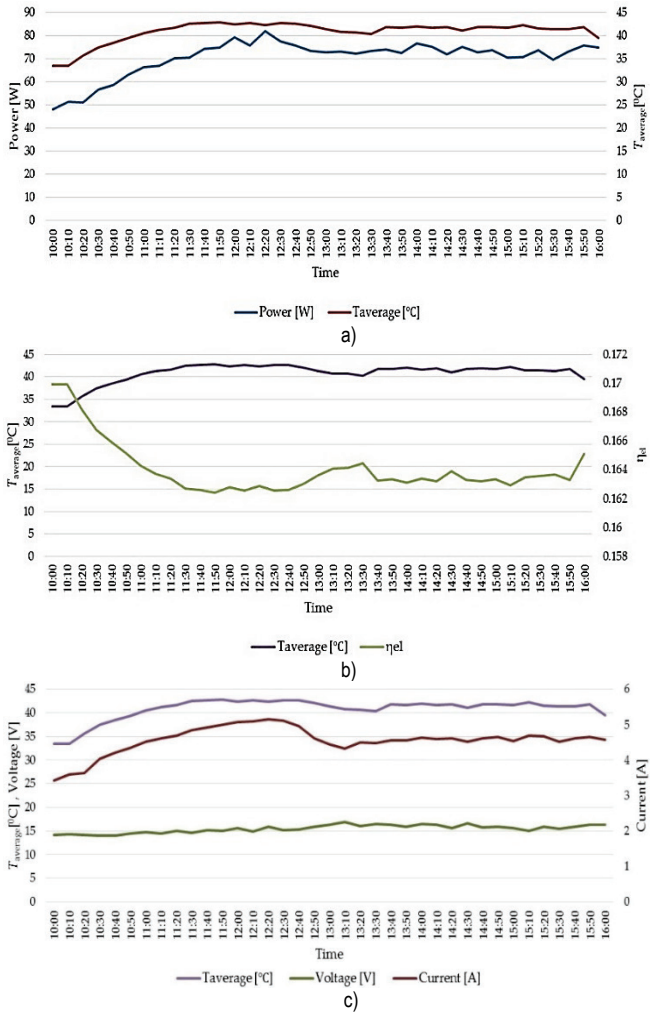


Figure 4 a) Dependence of power on PV module temperature; b) Dependence electrical efficiency on PV module temperature; c) Dependence of voltage and current on PV module temperature (measured on July 15, 2023)

4 DISCUSSION

Analyzing results in Tab. 6 and Figs. 4, 5 and 6, it can be seen that when air temperature increase also increases PV module temperature. Maximum and minimum average daily PV module temperature correspond with the maximum and minimum average daily air temperature. Increasing PV module temperature average daily PV voltage decrease as well as average daily current and power output. Maximum PV power output for the whole period of measurement correspond to the day with minimum average daily air temperature and PV module temperature but also maximum daily average solar irradiance. In addition, on that day, maximum value of PV electrical efficiency for the entire measurement period was recorded. Minimum PV power output correspond to the warmest day for the whole period of measurement with also maximum PV module temperature on the same day. It can be concluded that PV power output is reduced with PV module temperature increase. The same is for PV electrical efficiency. Increasing PV module temperature leads to the PV electrical efficiency decrease as expected.



Figure 5 a) Dependence of power on PV module temperature; b) Dependence electrical efficiency on PV module temperature; c) Dependence of voltage and current on PV module temperature (measured on July 16, 2023)

It is shown that an increase in the PV module temperature above 25 °C leads to a 0.455 - 0.449% reduction in electrical efficiency for each 1°C rise. In Figs. 4, 5, 6, a), it can be seen that with increasing PV module temperature, PV power output is reduced. Drops in PV module temperature corresponds to increases in PV power output. Analyzing influence of PV module temperature on electrical efficiency it can be concluded that with increasing PV module temperature PV electrical efficiency decrease (Figs. 4, 5, 6, b). Measurements over three days show a positive correlation between PV module temperature and current. As it can be seen on Figs. 4, 5, 6, c) current curve had a similar distribution as PV module temperature. With increasing PV module temperature voltage decrease. Maximum values of voltage correspond to the drops of PV module temperature (Figs. 4, 5, 6, c).

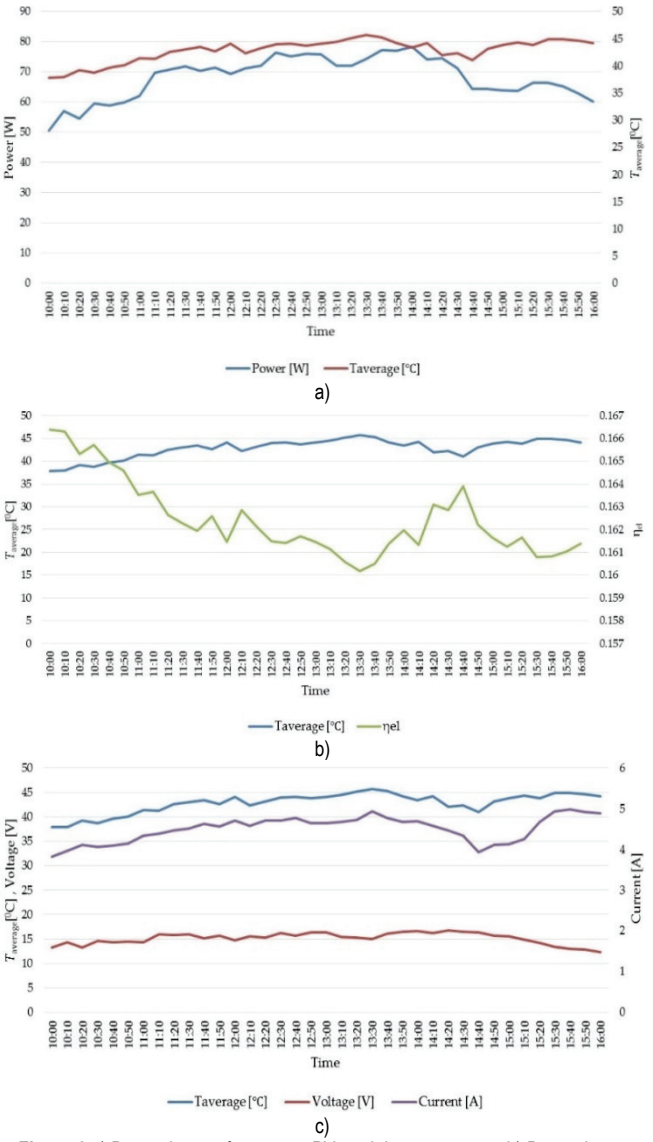


Figure 6 a) Dependence of power on PV module temperature; b) Dependence electrical efficiency on PV module temperature; c) Dependence of voltage and current on PV module temperature (measured on July 17, 2023)

5 CONCLUSION

Solar radiation that reaches the surface of the photovoltaic (PV) module is partly transformed into electrical energy. The most of radiation is transformed into heat. The temperature of the photovoltaic module increases which causes a decrease in their electrical efficiency particularly at temperature above 25 °C. In this study, an evaluation of PV output taking into account real weather conditions and PV module temperature is presented. Experimental investigation was performed in summer time, in July in period of three days. Considering all the analyses, it can be concluded that weather conditions—such as sunlight exposure, air temperature, and wind speed—greatly affect the temperature of PV modules and, as a result, their performance. Maximum and minimum average daily PV module temperature correspond with the maximum and minimum average daily air temperature for the whole period of measurement. Measurement analysis shows that higher PV

module temperatures correlate with lower PV voltage, average power, and efficiency. It was shown that an increase in PV module temperature in range 2.199 - 2.224 °C above 25 °C leads to an approximately 1% reduction in electrical efficiency. These results are significant because they showed how the real operating conditions influence on the PV module. In addition, these results contribute to evaluating energy yield considering the climatic parameters. This is very important for some further strategic energy planning in the field of solar energy. Extremely high air temperatures and solar radiation, causes increase of the temperature of the PV module and it can be expected to exceed 25 °C for almost half of the year in analysed geographical area. Accordingly, it is necessary to analyse the cooling possibilities of the PV modules duo to decrease PV module temperature.

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