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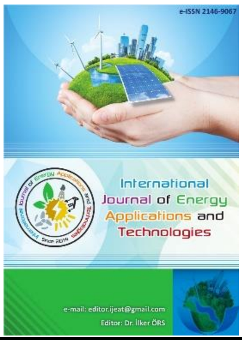

Original Research Article

Color filter effects on the performance of monocrystalline and polycrystalline photovoltaic solar panels

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ABSTRACT

We evaluated effect of different color filters on the electric production performance of monocrystalline and polycrystalline solar photovoltaic panels in real outdoor environment. In the experiment, we used four different color filters from blue to red on photovoltaic panels to observe energy and efficiency performance of the mono and polycrystalline solar photovoltaic panels as well as temperature of the panels measured with and without filters. We observed the wavelength dependence of monocrystalline photovoltaic panel is more effective than the polycrystalline photovoltaic panel one. For both panels we see that yellow color filtered produced the highest power value and have the lowest temperature value. This can be explained with that the spectrum of yellow color filter covers most of the radiation of solar but blocking infrared and ultraviolet side of the sun spectrum. This also causes the lower panel temperature. On the other hand, we observed that photovoltaic panels with blue color filter have the highest temperature value and the lowest power value. By the study we suggest that by optimizing the semiconductor band gaps in photovoltaic panels respect to solar wavelength, one can produce photovoltaic panels with higher efficiency by using filters, especially in hot climate regions. We expected that the results will also contribute to a better analysis of the points that need to be developed during the photovoltaic panel production stages.

Keywords: Efficiency; Filter effect; Photovoltaic; Solar energy; Wavelength

1. Introduction

A solar or photovoltaic cell converts sunlight into electricity directly using the photoelectric effect without any interface for conversion. Typically, photovoltaic panels are installed on the roofs of residential and commercial buildings. Utilities have also built large (over 100 MW) photovoltaic facilities. Photovoltaic plants have been established in different countries to meet energy needs [1-3]. Countries have also established solar energy policies and control measures to reduce dependence on fossil fuels and increase their domestic energy production with solar energy [4]. On the other hand, a lot of research is now undertaken to increase the efficiency of the solar industry in order to make the future world more efficient in terms of energy use [5]. The photovoltaic panel efficiency is determined by photovoltaic cell efficiency depending on silicon type and cell design and total panel efficiency depending on cell layout, configuration, and panel size. However, in the real environment use, the panel efficiency and performance are also dependent on the external factors such as received solar radiation intensity, wavelength of solar radiation, cloud and other shading effects, dust, cell temperature, inverter efficiency, panel orientation, geographical location, weather conditions etc. In literature, there are many studies related to solar energy and a lot of studies presents that energy efficiency of photovoltaic panels based on material type, solar irradiation, temperature coefficient etc. [6-19]. Overall electrical power generation using a-Si, polycrystalline and monocrystalline panels was investigated focusing on outdoor performance [20]. The efficiency analyses of various photovoltaic panel technologies such as using crystalline, multi crystalline, and cadmium–telluride were studied in similar weather situations including same orientation angle [21]. The optimal orientations and tilt angles of photovoltaic solar panels were evaluated by proposing increase of months from September to December by changes optimum monthly various tilt angles from 35 to 61 in degree [22]. Theoretical performance of monocrystalline silicon type photovoltaic modules were studied according to various angles of inclination and directions [23]. The impact of dust collection was investigated in power output in photovoltaic panels [24, 25]. As can be seen from literature, there are many studies including analysis of photovoltaic panels based on tilt angle, used materials to manufacture photovoltaic panels, dust collection etc. However, in our study, we experimentally evaluated the light color effects on the electric production performance of solar photovoltaic panels in outdoor environment. We used four different filters from blue to red on photovoltaic panels to observe energy and efficiency performance of the solar photovoltaic panels as well as temperature of the panels measured with and without filters. We aimed to determine the filter effect that produces lower temperature, higher power, and efficiency on the end user. We expect that the results of the study will contribute to a better analysis of the points that need to be developed during the panel production stages.

2. Theoretical background

The sun radiation comes to the earth is over a wide extent of wavelengths at different intensities. The solar radiation reaching on the atmosphere is 1.367 W/m² (the Solar Constant). Atmospheric gases filter some wavelengths of incoming solar energy. The Sun's beam rays are reduced by passing through the atmosphere. The maximum radiation at roughly 1000 W/m^{2}reaches on the earth sea level with clear weather conditions. The solar radiation spectrum at the Earth is generally in the range from the visible and near-IR ranges with a small part in the near-UV [26]. The energy of photons is defined by the frequency as $\boldsymbol{E} = \boldsymbol{h}\nu$. Here E is the energy of photon, h is the Planck constant as h = 6.663 x10^{-34}Js, $\nu = \mathbf{c}/\boldsymbol{\lambda}$ is its frequency, c is the speed of light 299,792,458 m/s, λ is the wavelength. Since the light energy depends on the frequency, one can change the energy by changing the light frequency that is coming. For example, for the red (λ=665nm), yellow (600nm), green (550nm), and blue (470nm) photons, light frequencies are ν=4.5082Hz, 4.9965Hz, ν=5.4508Hz, and ν=6.3786Hz and energies are E=1.8644eV, 2.0664eV, 2.2543eV, and 2.6380eV, respectively. The lowest energy is from the red photons and the blue photons have the highest energy. This means that the amount of radiation falling on the photovoltaic panel increasingly affects its electric production performance respect to the light wavelength. Currently, available photovoltaic solar modules respond to a few frequencies. With the growing interest in creating productive cells over a wide frequency range, extensive work has been done on photovoltaic solar cells. Because frequency is intercorrelated to wavelength by $\nu = c/\lambda$, if you change the wavelength of the light spectrum, you can also change the energy. The color filter can only let frequencies in corresponding to its color, so when they are used on a panel, only that light color will respond as if it was coming.

3. Materials and Methods

The experimental setup and location are depicted in Figure 1. In the experiment, we used four photovoltaic solar panels, two polycrystalline with the max power of 105W (LEXRON36 SP poly lxr105) and the other two monocrystalline with the max power of 95W (LEXRON36 SP mono lxr95). The photovoltaic panels were placed on angle adjustable tables to operate the angles of inclination of each photovoltaic panel. Electric energy generated from the photovoltaic solar panels was transmitted to an inverter using Maximum Power Point Tracking (MPPT) charge controllers (VICTRON MPPT 75/15) which has Bluetooth device connection to monitor the operation system. The load output of each MPPT charge controller was 15 A. Electric energy come from the MPPT was transmitted to the solar gel battery (MUTLU FD.225.110.B) using a pure sine wave inverter (LINETECH 60S-12E).

Experiments were performed on June 23-25 and 28, 2021 with the average perceived temperature 24.16°C, 26.38°C, 27.4°C, 26.6°C, humidity 79%, 69.5%, 66.6%, 63% and wind 37 km/h, 24 km/h, 11 km/h, 26 km/h in north-northeast, respectively. Experimental study was located at the coordinates of 40°12'02.66"N, 26°42'15.84"E in the parking lot of Canakkale 18 Mart University as seen in Fig. 1 (a) and (b). Fig 1 (b) shows the computation path of the sun for the selected location at the coordinates of 40°12'02.66"N, 26°42'15.84"E [27]. In the Fig 1(c), we imaged experimental setup with polycrystalline and monocrystalline photovoltaic panels with MPPT charge controllers, Bluetooth connection, full sine inverter, gel battery in protective box. In Figure 2 (a-d), we imaged the photovoltaic modules without filter and with colored filters red, blue, yellow, and green filters on the photovoltaic panel. The monocrystalline and polycrystalline photovoltaic solar panels were filtered, and the efficiency and power of photovoltaic solar panels and temperatures of the panels were measured with and without the filter every day. Measurements were recorded from 10:00am to 4:00pm for 1-hour intervals. To compare the obtained data from different days, we used unfiltered photovoltaic panels as reference values, so it has been proportionally normalized by considering the sun radiation values on different days.

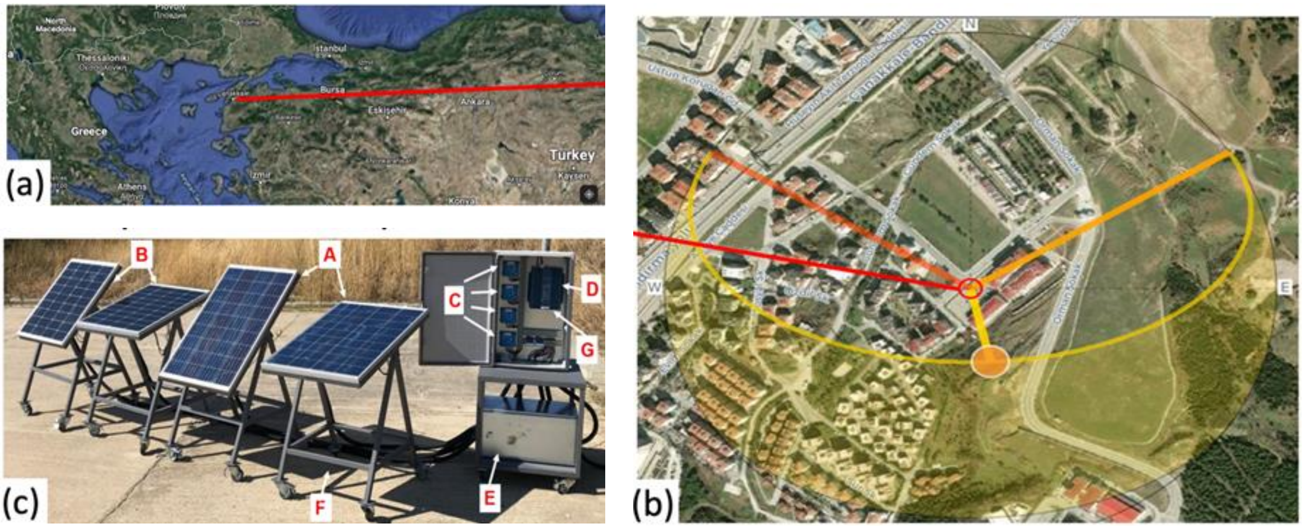

Fig. 1. (a) A partial location map of Canakkale province, Turkey, (b) Computation path of the sun for the selected location at the coordinates of 40°12'02.66"N, 26°42'15.84"E in the parking lot of Canakkale 18 Mart University [26], (c) Experimental setup: A. Polycrystalline photovoltaic panel, B. Monocrystalline photovoltaic panel, C. MPPT charge controllers with Bluetooth connection, D. Full sine inverter, E. Gel battery in protective box, F. Panel orientation angle adjustment, G. System power output

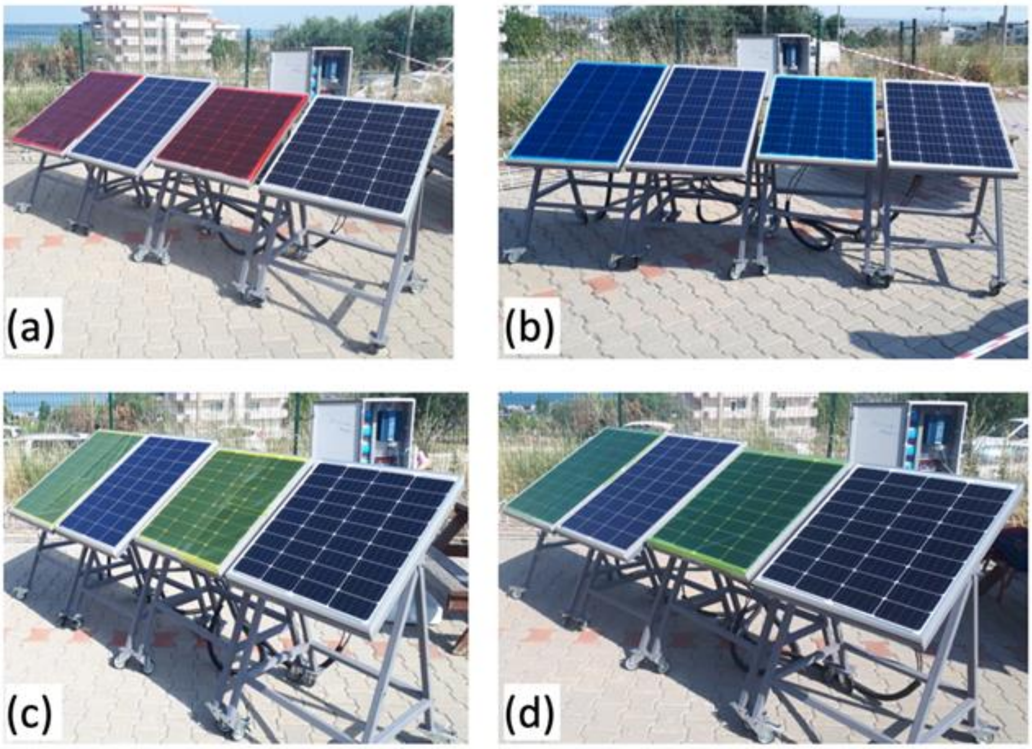

Fig. 2. Photovoltaic module without filter and with colored filters a) red, b) blue, c) yellow and d) green filters on the photovoltaic panels

4. Results and Discussion

Figure 3 shows the power values of photovoltaic solar panels with the same tilt angles at different hour of the day measured with and without the filters compared to the average power values of unfiltered monocrystalline and polycrystalline photovoltaic panels. We observed that the wavelength dependence of monocrystalline photovoltaic panel is more effective than the polycrystalline photovoltaic panel one by seeing the variation of power values. Both photovoltaic panels filtered with yellow filter showed the highest power value, while panels filtered with blue filter showed the lowest power value. It has been observed that there is an increase in power values between 11:00 and 14:00. The reason for this is that the intensity of the sun's rays and the angle of inclination increase between these hours as expected. There

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is a sharp power drops were observed in the polycrystalline photovoltaic panel with all filters at 16:00. This can be explained by the color diffraction on the polycrystalline photovoltaic panel at the angle of incidence of the sun but why there is the difference between panel types is needed to investigate further.

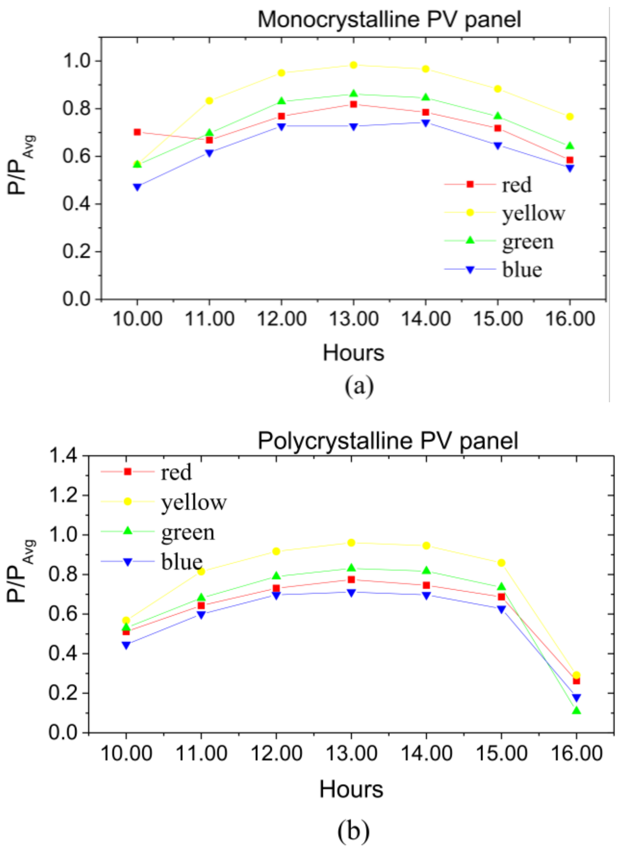

Fig. 3. Time variation of the power ratio of red, yellow, green, and blue filtered monocrystalline photovoltaic panel compared to the average power values of unfiltered monocrystalline (a) and polycrystalline (b) photovoltaic panels

Figure 4 shows variation of temperature values of red, yellow, green and blue filtered monocrystalline and polycrystalline photovoltaic panels compared to the average temperature values of unfiltered monocrystalline and polycrystalline photovoltaic panels depending on time. It was observed that the temperatures of both filtered photovoltaic panels were increased between 11:00 and 13:00. The panels filtered with the blue filter showed the highest temperature whereas the panels filtered with the yellow filter showed the lowest temperature value. It is possible to say that the blue filter with higher energy density shows more deviation in temperature value than other filters. The effect of the filters on the panel temperature was similar for both monocrystalline and polycrystalline panels. However, it was observed that the filter effect in temperature change was higher in monocrystalline panels than in polycrystalline panels. We can conclude that monocrystalline panel temperature responding filters' effect was more effective than polycrystalline panels.

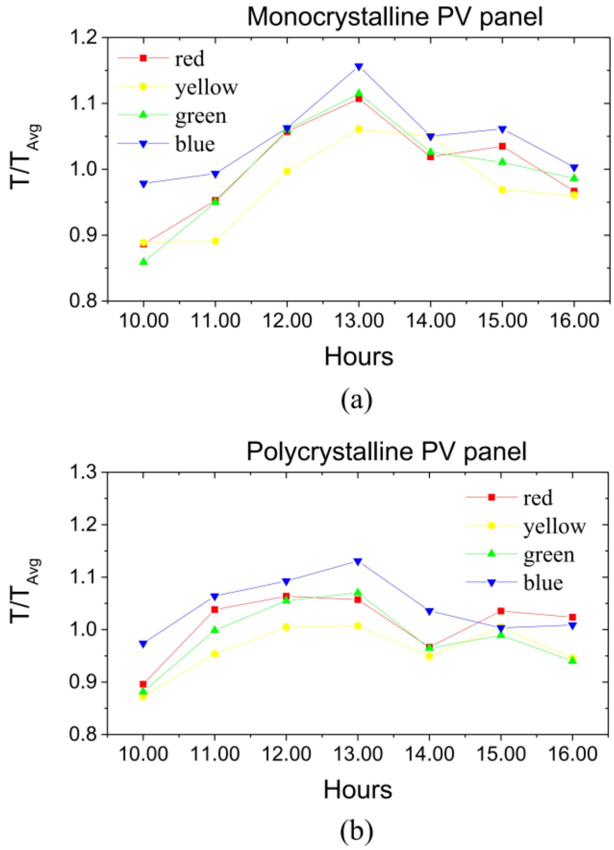

Fig. 4. Variation of temperature values of red, yellow, green, and blue filtered monocrystalline and polycrystalline photovoltaic panels compared to the average temperature values of unfiltered monocrystalline (a) and polycrystalline (b) photovoltaic panels versus time

From the power and temperature measurements in Figure 3 and Figure 4, there is an inverse relation between power values and temperature values. It was observed that the panels filtered with the yellow filters produced more power than the panels filtered with the blue filter, but the temperature values express reverse relation. Therefore, by using the filters we can produce lower temperature and higher power in the photovoltaic panels. This result is similar to Ref. [28] which the efficiency decreased with the increase of cell temperature.

We also evaluated the changes in voltage and current values in the monocrystalline and polycrystalline photovoltaic panels. Figure 5 presents variation of voltage and current values of red, yellow, green, and blue filtered monocrystalline photovoltaic panel compared to the average voltage and current values of unfiltered monocrystalline and polycrystalline photovoltaic panels. When compared to others, the panel with the yellow filter produces maximum peak currents among all the filters while the blue filter's one creates minimum currents. We can see that these results support the literature [29]. The yellow filter letting the light

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pass on the panel can produce more current when compared to other filters. This means that photon energies in the wavelength range corresponding to the yellow color has more energy content for more electricity production.

The performance losses of the filtered photovoltaic module are mainly due to a smaller number of photons delivered to the solar cells. The losses also depend on a particular color due to a specific reflection spectrum of each color. The electric production efficiency of photovoltaic panels is described on standard testing conditions specifying solar cell temperature at 25°C, solar irradiance at 1000 Watts per square meter, and air mass at 1.5. Thus, efficiency is calculated according to the equation: $\eta = \frac{P_{max}}{GA_{PV}}$ where P_{max} is max. power generated by panel, G is the solar radiation (1000W/m^2) and A_{PV} is the area of the panel. In Figure 6. We compared filtered and unfiltered monocrystalline and polycrystalline photovoltaic panel efficiencies over time.

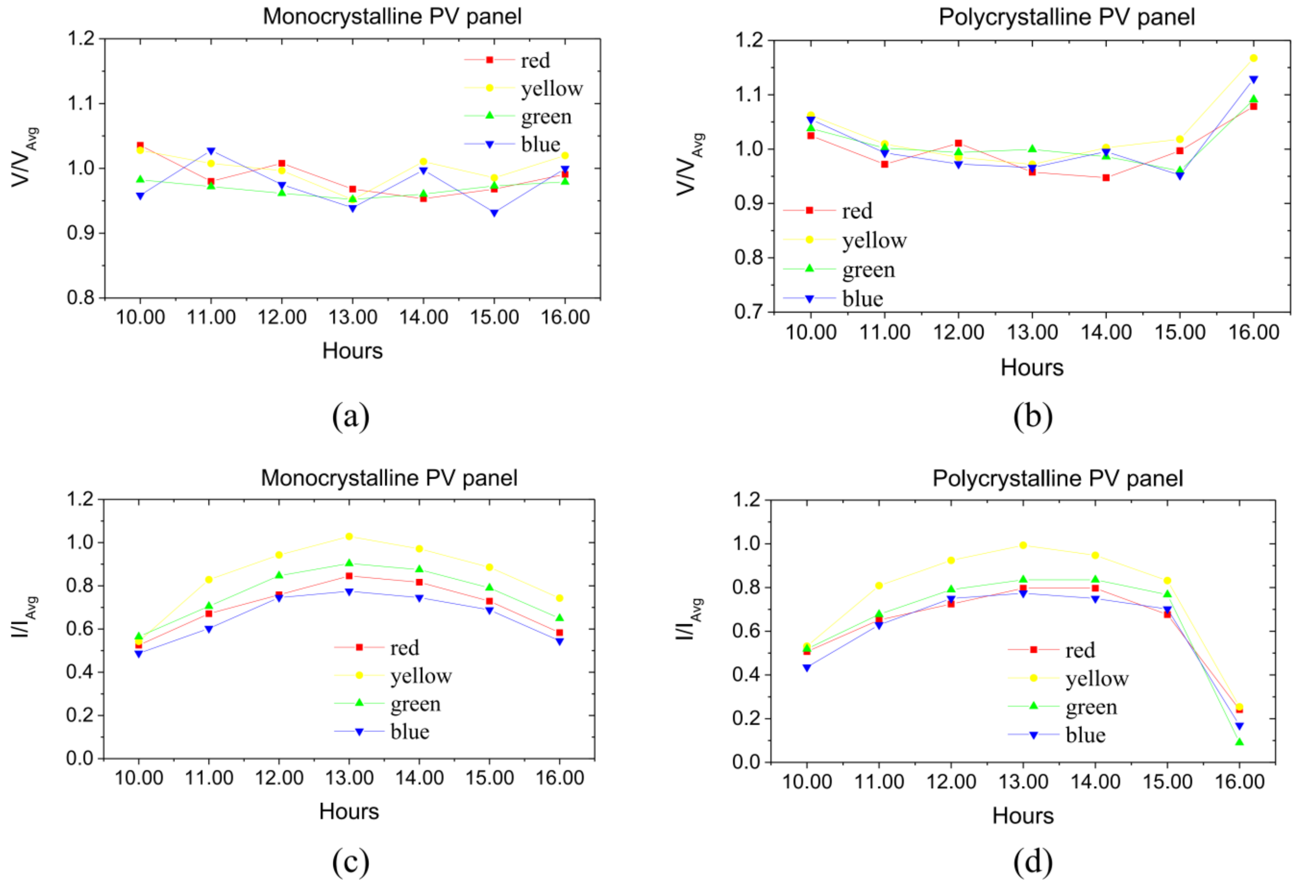

Fig. 5. Variation of voltage (a, b) and current (c, d) values of red, yellow, green, and blue filtered monocrystalline photovoltaic panel compared to the average voltage and current values of unfiltered monocrystalline and polycrystalline photovoltaic panel versus time

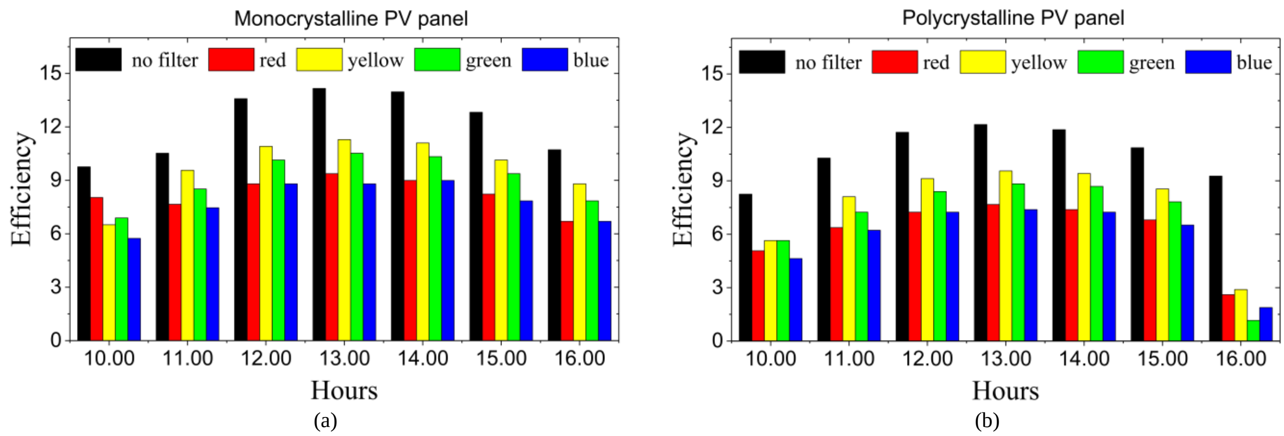

Fig. 6. Comparison of filtered and unfiltered monocrystalline (a) and polycrystalline (b) PV panel efficiencies over time

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In experiments for monocrystalline photovoltaic panel, the yellow color filter performs better in the electrical production efficiency (9.76% on average), followed by green (9.09%). It has been observed that red and blue colors generate less electricity and provide lower conversion efficiency than other colors. These values are on average 8.25% and 7.76%, respectively. Therefore, it is best to apply the filter on the solar panel. This reduces the effect of overheating on the panel and provides better production efficiency. Similar filter effects were observed in the experiments performed for the polycrystalline PV panel. The yellow color performed better in the electrical production efficiency (5.94% on average). Green color (5.53%) comes after yellow color. Red and blue produced less electricity than the other colors (5.02% and 4.72% on average, respectively) and resulting in lower production efficiency.

5. Conclusion

The wavelength dependence of monocrystalline photovoltaic panel is more effective than the polycrystalline photovoltaic panel one. For both panels we see that yellow color filtered produced the highest power value and have the lowest temperature value. This can be explained with that the spectrum of yellow color filter covers most of the radiation of solar but blocking IR and UV side of the spectrum. This causes lower panel temperature. On the other hand, we observed that PV panels coated with blue color have the highest temperature value and the lowest power value. In conclusion, by optimizing the semiconductor band gaps in photovoltaic panels respect to solar wavelength, one can produce PV panels with higher efficiency, especially in hot climate regions, by using filters.

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Authorship contribution statement for Contributor Roles Taxonomy

Sündüz Gökçen: Investigation, writing, experiment. **Necati Kaya:** Investigation, Review & editing, writing.

Conflict of interest

The author(s) declares that he has no conflict of interest.

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