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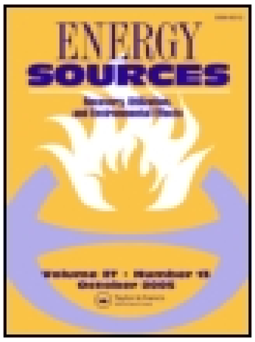

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Effect of color and nano film filters on the performance of solar photovoltaic module

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ABSTRACT

Solar intensity and surface temperatures have a major impact on the performance of solar photovoltaic modules. Light spectrum has different wavelengths, and energy levels where each of them can affect the solar panel differently. The goal of this study is to investigate the effect of color filters and thermal insulating Nano films on the solar panel output characteristics. Two indoor experiments were conducted where four color filters and three types of insulating Nano films were tested on a photovoltaic module. The results showed that red color filters and Nano films, with a blocking rate of 20%, generated more electrical power than other solar filters. The results also showed that the surface temperature of the photovoltaic module was significantly decreased by applying certain color and Nano film filters. This research aims to improve the overall performance of the solar cell by controlling the solar intensity and decreasing the surface temperature through applying color and Nano film filters.

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Photovoltaic; color filters; nano film filters; PV temperature

Introduction

Photovoltaic (PV) cells are made of semiconductor materials that convert sunlight into electricity by utilizing photons to eject a flow of electrons as a direct electric current. When a PV cell is exposed to a light source it generates a current and a voltage. The relationship between the absorbed irradiance and generated current is considered linear; however, the voltage is dependent on the type of material used in the cell and the operating temperature. When the cell is illuminated while not connected to a load, it operates at the open circuit voltage (Vos) while, the short-circuit current is the current through the PV cell when the voltage across the cell is zero.

There are many factors that impact the performance of a PV cell and one of these factors is temperature. As the temperature of a photovoltaic cell increases, the short circuit current increases partially whilst the open circuit voltage decrease substantially which generates a lower output power from the cell (Dinçer and Meral 2010). Studies have shown that elevated temperatures on solar panels can drastically decrease their shunt resistance values, and consequently, their efficiencies (Singh et al. 2008) (Suita and Tadakuma 2006). In contrast, decreasing the temperature close to the nominal operating temperatures leads to an increase in the efficiency of solar panels (Teo, Lee, and Hawlader 2012).

One solution to prevent the surface temperature of a solar panel from increasing is to apply photo-filters on it such that longer wavelengths, with less energy, are only allowed into the panel. This paper investigates the effect of different thermal insulating Nano films with several visible lights blocking rates, as well as different color filters on the parameters of solar panels. A set of indoor

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experiments were conducted to study the effect of these filters on the performance of solar panels. Indoor experiments of solar panels are important since they are conducted under controlled conditions, therefore, there is a repeatability of the testing conditions that permit the optimization of the solar panels. This study will help us gain a better understanding about the influence of color filters and thermal insulating Nano filters on a photovoltaic cell and its output efficiency.

Background

Many studies investigated the effects of surface and ambient temperatures on the performance of PV panels. For instance, Tonui and Tripanagnostopoulos showed that PV/T panels' performances can be improved by extracting heat via forced and natural convection (Tonui and Tripanagnostopoulos 2007). Teo et al. showed that actively cooling photovoltaic cells using airflow in an array of ducts attached to the back of the cells could improve the efficiency of the cell up to 14% (Teo, Lee, and Hawlader 2012). Other studies investigated utilizing water to improve the efficiency of solar panels (Moharram et al. 2013) (Irwan et al. 2015) (Smith et al. 2014). Odeh and Behnia used water to cool the upper surface of a PV panel to achieve an efficiency of 15% at peak radiation conditions (Odeh and Behnia 2009). Water, that is used for cleaning the surfaces of solar panels was also proven to increase the panels output performance by up to 8.7% (Mohsin et al. 2018). Furthermore, previous studies tested the use of a water heat exchanger on the back of a solar panel to significantly decrease its surface temperature, and consequently, increasing its efficiency by 9% (Bahaidarah et al. 2013). Researchers even investigated submerging the whole solar panel underwater as a cooling technique (Mehrotra et al. 2014). Moreover, studies also showed that there is a strong relationship between the ambient temperature and the efficiency of PV panels (Bhattacharya, Chakraborty, and Pal 2014) (Eldin, Abd-Elhady, and Kandil 2016).

There are, however, other techniques and methods that are used to enhance the electrical characteristics of solar panels by decreasing their surface temperatures. One of these techniques is utilizing phase change materials (PCMs). Biwole et al. used a PCM on the back of a solar panel to maintain its surface temperature below 40□ at peak radiation conditions (Biwole, Eclache, and Kuznik 2013). Other researches showed that passive cooling, utilizing PCMs, can significantly increase the efficiency of solar panels (Stritih 2016) (Su et al. 2017) (Osueke, Onyekachi, and Nwabueze 2011).

Other methods that are used include applying color filters on the solar panel to control its surface temperature by allowing certain wavelengths of the visible light to enter the cell while, at the same time, reflecting others. Previous studies showed that portions of the visible light entering the PV cell can affect its performance (Sudhakar, Jain, and Bagga 2013) (Ogherohwo, Barnabas, and Alafiatayo 2015). Kazem and Chaichan experimented with several color filters and found that purple colored filters produced higher performance compared to other colored filters (Kazem and Chaichan 2016). Other investigations studied down-shifting materials, like Zinc Oxide nanoparticles, to reduce the energy of photons absorbed by photovoltaic cells and, hence, improving their performances (Znajdek et al. 2017).

The method presented here focuses on the effect of color filters and thermal insulating Nano films on the surface temperature of the solar panel and its output characteristics. In this study, the panels were tested indoors with controlled room temperature and under fixed radiant flux with a light that is normal to the surface of the panel.

Method

Two indoor experiments were conducted in this investigation to study the output performance of a solar panel using different colors and thermal insulating Nano films as light spectrum filters. The first experiment investigated the effect of three thermal insulating Nano films, with visible light blocking rates of 20%, 60%, and 80%, on the temperature and performance of the solar panel. The Nano films used in this study are coated with a mixture of ceramic and carbon particles 25 to 50 nm in diameter with 99% IR and UV blocking rates according to the manufacturer's datasheets. In the second experiment, three color filters were used for the same purpose: red, green, and blue. This type of color filters is made of thin transparent plastic with color coatings and is mainly used in photography.

Both experiments were conducted using the Photovoltaic Performance Simulator (PVPS) device, illustrated in Figure 1, that is located at the Alternative Energy Department at Al-Zaytoonah University of Jordan. The device is equipped with 24 light bulbs which allows the user to control the amount of radiant flux that is transferred to the panel as well as the distance from the light source and the angle of light hitting the panel. A radiant flux sensor was placed between the panels to control the flux at 500 W/m^2 during the experiments. Normally, the Standard Test Conditions (STC) are held under 1000 W/m^2. However, the radiant flux was reduced in this experimental setup due to the excessive ambient temperatures generated by the lightbulbs at 1000 W/m^2. Both experiments were conducted in a darkroom with a controlled ambient temperature at 24°C.

In the first experiment, four 20 × 30 cm solar panels, with the characteristics shown in Table 1, were used to study the effect of thermal insulating Nano films on the output performance and temperature of the panels. Three Nano films (with visible light blocking rates of 20%, 60%, and 80%) were installed on 1 mm thick clear glass sheets that have the same dimensions as the solar panels. The glass sheets, with the Nano films installed, were then placed on top of three solar panels. Another clear glass sheet, without filters installed, was placed on top of the fourth solar panel. All four solar panels were connected to a datalogger to record their open circuit voltages and short-circuit currents. Another four k-type thermocouples were attached to the back of each solar panel and connected to the same datalogger to record their temperatures during the experiment. The four solar panels were placed flat in the PVPS 40 cm away from the lights so that the light hits the panels at 90 degrees as illustrated in the schematic diagram in Figure 2. The experiment lasted 60 min and the logger recorded data every 5 min.

In the second experiment, the same procedure was followed. Three color filters (red, green, and blue) were placed on top of three solar panels only this time the glass sheets were not used. The fourth panel was left without any filters. All four panels were placed in the PVPS at the same distance and angle from

Figure 1. The Photovoltaic Performance Simulator (PVPS) device.

Table 1. Electrical characteristics of the solar panels.

V_{mp} (V)	I_{mp} (A)	$V_{o.c}$ (V)	I_{sc} (A)	P (W)	F.F %	η %
8.9	0.72	10.8	0.67	5	88.6	12.06

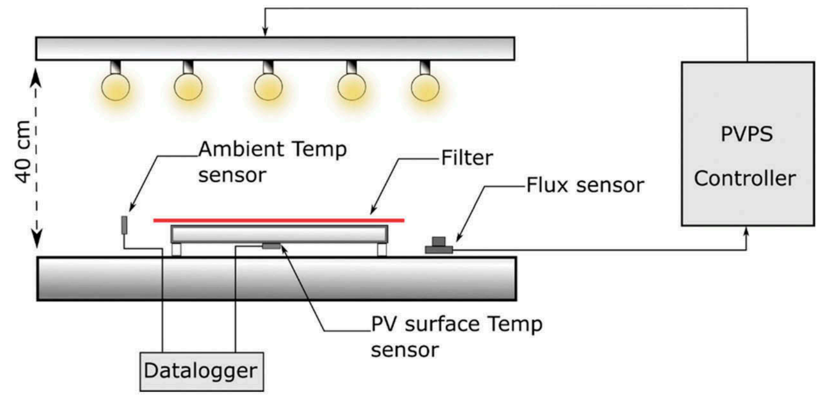

Figure 2. A schematic diagram showing the equipment used in the experimental setup.

the light as the first experiment. Four thermocouples were also attached to the panels and connected to the datalogger to record the temperatures. The second experiment lasted 60 min with 5-min data recording interval. Figure 3 shows the complete setup of the second experiment.

Results and discussion

Results acquired from both experimental sets, demonstrate that there is a direct proportionality between a light source, output current, output voltage and energy of the PV cell. The results of the experiments show the impact of the color filters and thermal insulating Nano films on the surface temperature of the PV as well as its output characteristics.

Effect of thermal insulating nano films

In the first experiment, three thermal insulating Nano films were tested. The experimental results of the maximum output power and maximum efficiency of the solar PV panel were compared, with and without filters as given in Table 2.

Figure 3. The second experimental set with color filters.

Table 2. Experiment results summary.

Filter type	Current (A)	Voltage (V)	Power (W)	Efficiency %	Average Surface Temperature (°C)
No filter	0.41	9.97	4.09	14.0%	59
Nano 20%	0.67	9.14	6.129	21.0%	54.3
Nano 60%	0.49	9.02	4.42	15.2%	54.0
Nano 80%	0.64	9.22	5.90	20.3%	49.0

The voltage, current, and power variation of the module with different Nano film filters are illustrated in Figure 4. When the filters were applied, the module's power was significantly increased in comparison with the module without filters. A greater amount of current was generated when the 20% Nano film filter was applied. Consequently, the maximum output power was obtained from the latter filter. In contrast, the minimum power was obtained from the module that had no filters. Yet, the maximum voltage was obtained from the module that had no filters. Additionally, the minimum voltage was obtained when the 60% Nano film filter was applied.

The efficiency of the photovoltaic module with different thermal insulating Nano film filters was obtained as illustrated in Figure 5. The best efficiency was obtained when the 20% Nano film filter was applied. The lowest efficiency was obtained when no filters were added. This variation in the output power and efficiencies is due to the relatively higher light transmittance of the 20% Nano filter compared to the 60% and 80% filters. A previous study showed that conventional nanoparticle filters have lower efficiencies, compared to thin-film filters, due to their low performance in the high-transmittance spectrum region on the PV cell (Otanicar, Taylor, and Telang 2013). On the other hand, the efficiency of the 80% Nano filter was higher than the 60% filter. This is mainly due to the significant decrease in the surface temperature between the modules as illustrated in Table 2. Studies have shown that elevated surface temperatures on the solar panels affect the voltage parameters and output powers of the PV cells (Karki 2015). There are, however, other studies that investigated non-conventional Nano fluid filters, utilizing different solvent materials, which had a significant impact on the efficiency of solar panels (Galleano et al. 2015) (Choubineh, Jannesari, and Kasaeian 2019) (DeJarnette et al. 2016).

The surface temperature of the photovoltaic module with different Nano film filters was measured and shown in Figure 6. Using the Nano film filters, in general, has decreased the surface temperatures of the solar panels by at least 5 °C. The lowest temperature was measured when using 80% Nano film, whilst the highest surface temperature was measured when no filters were added. The film filters that were used are dark colored and closer to the longer wavelength in the visible light spectrum. Previous studies showed that filters with longer wavelengths can be efficient for the PV cell (Sudhakar, Jain, and Bagga 2013) (Taylor, Otanicar, and Rosengarten 2012).

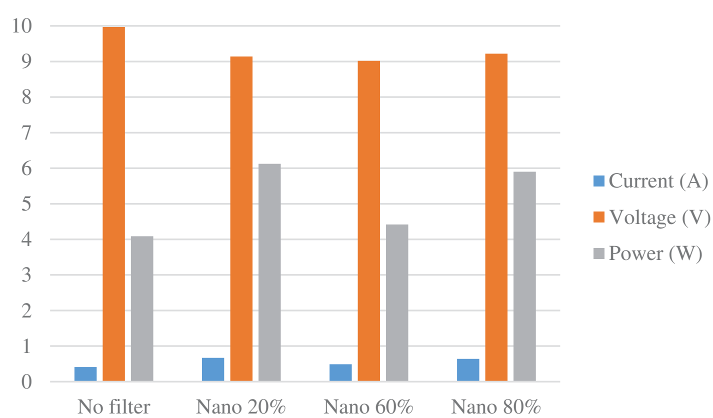

Figure 4. Variation of Voltage, Current and power output of solar cell with Nano film filters.

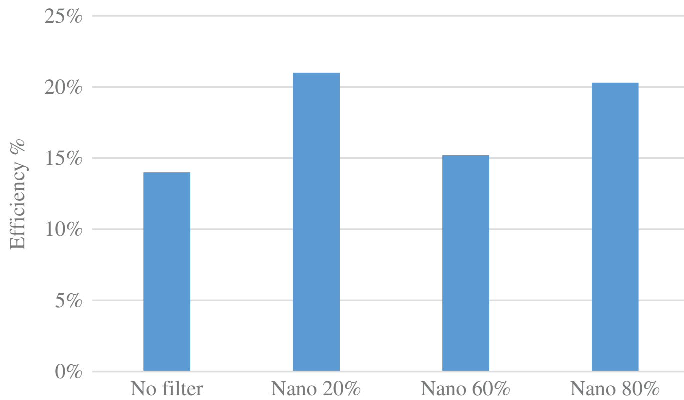

Figure 5. Variation of efficiency of solar cell with Nano film filters.

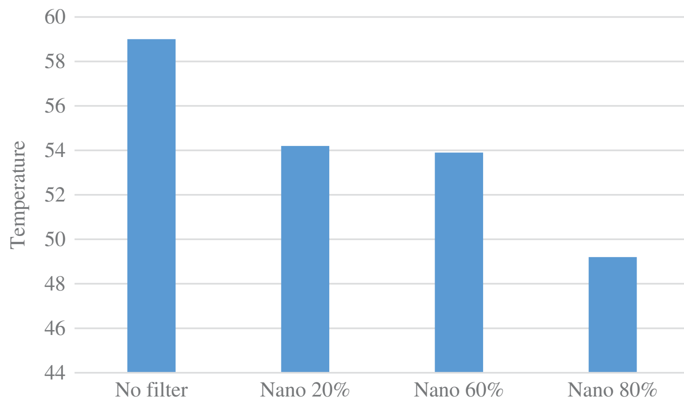

Figure 6. Variation of surface Temperature of a solar cell with Nano film filters.

Effect of using color filter

In the second experiment, colored filters were tested. The experimental results of the maximum output power and maximum efficiency of the solar PV panel were compared, with and without filters as given in Table 3.

For a crystalline solar cell, the electrical output voltage is a function of the temperature, intensity, and color of the incident light (Su et al. 2017). The voltage, current and power variation of the module with different filters were shown in Figure 7. By applying the colored filters, the module power was significantly increased in comparison with the module that had no filters. A greater amount of current, voltage, and output power were obtained when the red color filter was applied. On the other hand, the minimum voltage and output power were obtained with the blue color filter. These results agree with previous investigations regarding the effect of color filters on solar panels (Sudhakar, Jain, and Bagga 2013).

Table 3. Experiment results summary.

Filter type	Current (A)	Voltage (V)	Power (W)	Efficiency %	Surface Temperature (°C)
No filter	0.41	9.97	4.0877	14.0%	59
Red	0.62	9.94	6.1628	20.5%	58.2
Green	0.6	9.88	5.928	19.8%	46
Blue	0.39	9.84	3.8376	12.8%	59.4

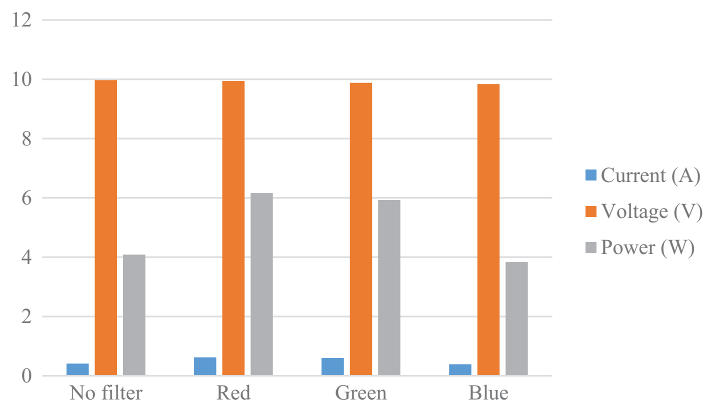

Figure 7. Variation of Voltage, Current and power output of solar cell with color filters.

The efficiency of the photovoltaic module with different color filters was obtained as illustrated in Figure 8. The best efficiency was obtained when the red color filter was applied. The lowest efficiency was obtained when the blue filter was applied. Previous studies that tested color filters on solar panels outdoors showed very similar results where the red color filter produced the maximum voltage, current, and power (Ogherohwo, Barnabas, and Alafiatayo 2015) (Yingwei et al. 2012).

The surface temperature of the photovoltaic module with different color filters was measured and shown in Figure 9. Surprisingly, the solar panel with the green filter had the lowest surface temperature. In contrast, the highest surface temperature was measured when using the blue filter. Perhaps this is due to the fact that green is a secondary color, a combination between blue and yellow, while blue is a primary color on its own.

Based on the above figures and measured data, it was noticed that the best performance solar photovoltaic module could be obtained by using a red color filter or a Nano film with a visible light blocking rates of 20%.

Uncertainty analysis

To measure the uncertainty in this study, the two previously discussed set of experiments were repeated three times under the same conditions. The voltage and current of the solar panels were

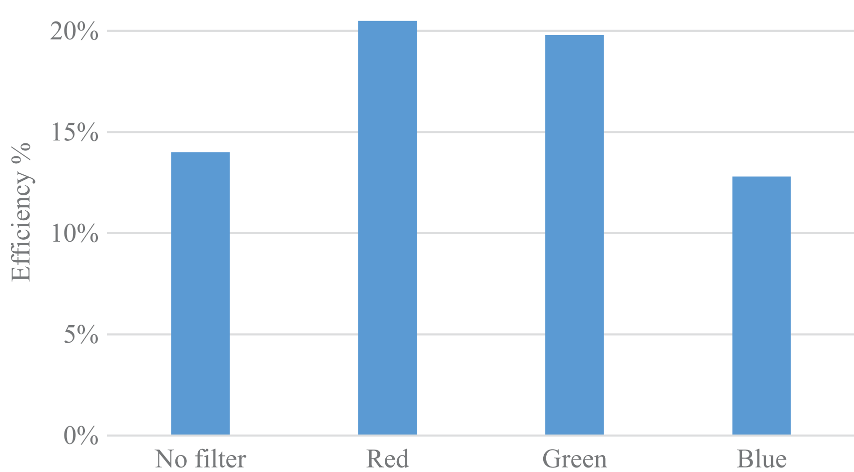

Figure 8. Variation of efficiency of a solar cell with color filters.

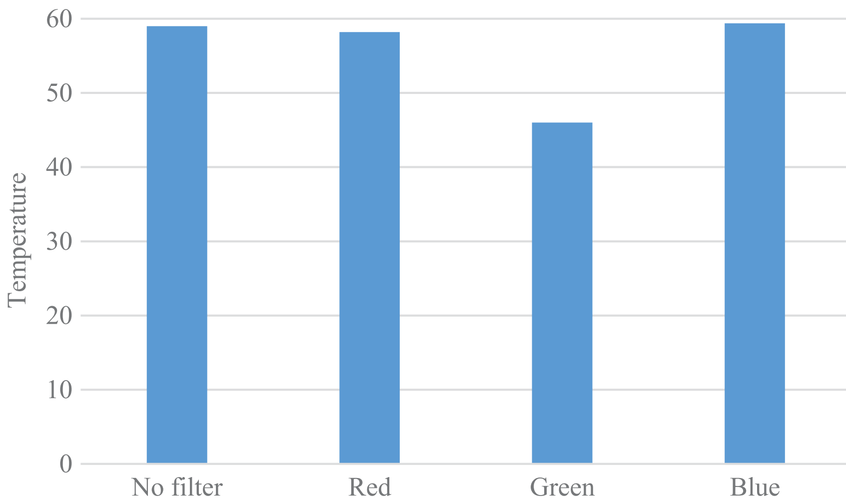

Figure 9. Variation of surface Temperature of solar cell with color filters.

recorded every minute for 30 min using a data acquisition. An uncertainty analysis was conducted using four factors, as outlined in (Yingwei et al. 2012), which include uncertainties caused by: the solar panels, the distance of the light source, irradiance, and data acquisition.

Uncertainty component caused by instability of current u_1

A stable performance of the solar panels is essential to perform uniformity measurements. A highly stable light source (SVPS) was used directly above the solar panels to test their stability as was illustrated in Figure 2. The maximum and minimum readings of current were taken, as shown in Table 4, and then the uncertainty (u_1) was calculated for each filter as shown in the following equation:

$$u_1 = \frac{(I_{max} - I_{min})}{(I_{max} + I_{min})} \times 100\%$$

Uncertainty component caused by open circuit voltage u_2

The same procedure was followed to calculate the uncertainty of the output voltage in the solar panels. The voltage was recorded every minute for 30 min using data acquisition. The maximum two readings of open circuit voltages were used to calculate the uncertainty (u_2) as shown in Table 5.

Uncertainty component caused by the position repeatability u_3

The distance between the light source and the solar cells was measured 10 times in several places on the surface of the PVPS to calculate the uncertainty. The uncertainty caused by the distance repeatability, u_3, can be taken as 0.5%.

Table 4. Maximum current and its uncertainty (u_1).

Used Filters	Red	Green	Blue	No filter	Nano 20%	Nano 60%	Nano 80%
Current (A)	0.62	0.61	0.37	0.415	0.61	0.45	0.6
	0.612	0.618	0.375	0.41	0.62	0.458	0.61
u_1	**0.65%**	**0.65%**	**0.67%**	**0.61%**	**0.81%**	**0.88%**	**0.83%**

Table 5. Maximum voltage and its uncertainty (u_2).

Used Filters	Red	Green	Blue	No filter	Nano 20%	Nano 60%	Nano 80%
Current (A)	9.94	9.88	9.84	9.97	9.14	9.02	9.22
	9.61	9.53	9.52	9.66	8.84	8.72	8.9
u_2	**1.7%**	**1.80%**	**1.65%**	**1.58%**	**1.67%**	**1.69%**	**1.77%**

Uncertainty component caused by irradiance unrepeatability of solar simulator u_4

Irradiance unrepeatability of solar simulator indicates the variations of irradiance between each flash of the light source (Yingwei et al. 2012). The flux sensors, which is installed on the test plane as shown in Figure 2, measured the irradiance of the light source 10 times during the light flashes which lasted 60 s. The curve of the data is shown in Figure 10.

From this figure, the uncertainty component caused by unrepeatability of the solar simulator (u_4) is calculated to be 0.2% using the same principle shown in 4.3.1.

Uncertainty component caused by the data acquisition card's effective number of bits

The minimum range and resolution of the data acquisition card are 200mv and 16bit, respectively, according to its user's manual. It is enough level of accuracy for the requirement of solar voltaic output measurement. Hence, the Uncertainty component caused u_5 by an effective number of bits can be ignored (Yingwei et al. 2012).

Uncertainty calculation

Based on the above measurements, the uncertainty combination of the solar panel outputs, irradiance, and the simulator can be calculated using the following equation (Yingwei et al. 2012):

$$Uncertainty\ Combination\ (u_c) = \sqrt{u_1^2 + u_2^2 + u_3^2 + u_4^2}$$

The coverage factor k was taken to be 2, hence, the expand measurement uncertainty of the solar simulator irradiance non-uniformity is shown in Table 6.

Conclusion

The purpose of this study is to determine the effect of color filters and thermal insulating Nano films on the solar panel surface temperature and output characteristics using Photovoltaic Performance Simulator (PVPS). In this study, the panels were tested indoors with controlled room temperature and under fixed radiant flux with a light that is normal to the surface of the panel.

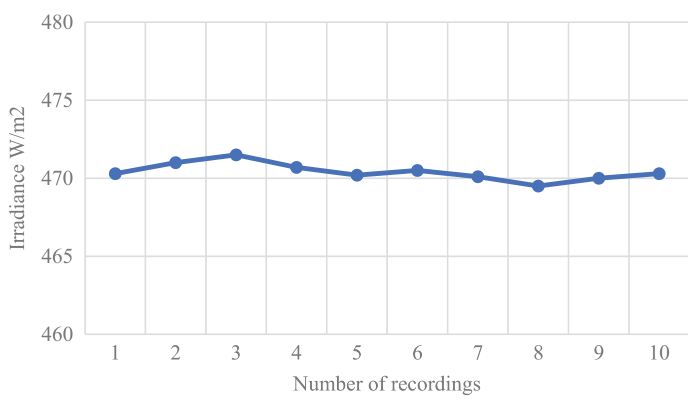

Figure 10. Data of the unrepeatability of the solar simulator.

Table 6. Uncertainty Combination.

Used Filters	Red	Green	Blue	No filter	Nano 20%	Nano 60%	Nano 80%
u_c	**1.69%**	**1.72%**	**1.63%**	**1.69%**	**1.98%**	**2.00%**	**2.06%**

Two indoor experiments were conducted. The first experiment investigated the effect of three thermal insulating Nano films with a visible light blocking rates of 20%, 60% and 80% on the surface temperature and performance of the solar panel. In the second experiment, three color filters were used for the same purpose: red, green, and blue.

The results showed that the red color filter and the Nano film filter with the blocking rate of 20% generated more electricity than the other filters whilst the green color filter and the Nano film filter with 80% blocking rate produced the lowest surface temperatures on the PV modules. The efficiency of solar panels, in general, could be improved by using red color filters or Nano films with 20% visible light blocking rate.

This paper also demonstrated a series of measurements conducted to test the performance of the solar panels. These measurements were done to ensure achieving the optimum uniformity and intensity distribution on the test plane. The repeated measurements were used to calculate the uncertainty in the experiments. The results showed that the uncertainty was between 1.63% and 2.06% for all six filters during the experiments.

Notes on contributors

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Eman Abdelhafez is currently an Lecturer in Alternative Energy Technology Department at Al Zaytoonah University of Jordan. She received the M.Sc. in Mechanical engineering from the University of Jordan (2009). Her research interests include microelectromechanical systems (MEMS), microfluid, water disinfection and renewable energy. She has published twenty articles most of them in the fields of renewable energy and Artificial intelligence. She was a member of a research team working of four funded projects in the areas of solar energy, hydrogen production and Hybrid Fuel-Cell/Battery system.

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