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Full length article

Hydrophobic nanocoating impacts on the PV panels' current-voltage and power-voltage curves

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ABSTRACT

Numerous factors, such as dust accumulation and light reflection off photovoltaic (PV) panel surfaces, adversely affect the performance and efficiency of PV solar panels. On PV panels, dust accumulation increases with time. Irradiation losses caused by dust deposition have a negative impact on PV solar panels. Regular cleaning is necessary for PV panel maintenance, but when carried out manually, it is labor-intensive. The hand-cleaning techniques use a lot of water and energy. The automated cleaning methods initially cost a lot of money and need an electrical source to function. As a result, self-cleaning techniques like hydrophobic coatings are popular since they don't require power and don't leave scratches on panels during cleaning. Since the current-voltage curve, the power-voltage curve, and the fill factor are the most indicative factors of the efficiency and performance of photovoltaic panels, the impact of hydrophobic nanocoating and dust on these factors were investigated in the present study. Results showed that the nano coating was hydrophobic and had a self-cleaning effect. After 40 days of exposure to outdoor conditions, the dust densities on reference panel (RP) and prepared nano-coated panel (PNP) before water spraying (self-cleaning) were 10 and 4.30 g/m², while the dust densities after water spraying(self-cleaning) were 4.80 and 1.12 g/m², respectively. The I-V curve for a clean reference panel (RP) and a prepared-nanocoated panel (PNP) showed that the short circuit current Isc was 5.69 and 5.82 A, and the open circuit voltage Voc was 20.3 and 20.7 V, respectively. The fill factor for PNP (0.7) was higher than RP (0.68). For dusty panels, the short circuit current Isc was 4.80 and 5.65 A, and the open circuit voltage Voc was 20.0 and 20.2 V, respectively. The fill factor for PNP (0.69) was higher than RP's (0.63). Based on study results, the nano coating has a positive impact on the I-V curve, P-V curve, and fill factor. That's because of its anti-reflective and self-cleaning effect.

1. Introduction

Solar energy is the sun's radiant energy, which generates massive amounts of electromagnetic energy through the thermonuclear fusion of hydrogen gas. The total global solar energy absorption is approximately $1.8 * 10^{11}$ MW. This amount of ubiquitous and limitless energy is more than enough to meet all global power requirements. Middle Eastern regions are ideal for large-scale PV installations (Ahmed et al., 2020).

Solar radiation is divided into three major wavebands: UV radiation has wavelengths less than 400 nm

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(photons with an energy larger than 3.1 eV). Visible (VIS) radiation has wavelengths ranging from 400 to 760 nm (photon energy between 1.6 and 3.1 eV). For wavelengths greater than 760 nm, infrared (IR) radiation is used (photon energy below 1.6 eV). The near infrared (NIR) extends to 4 µm (Polo et al., 2019).

Solar energy is clean, efficient, non-polluting, and dependable. As a result, PV technology has a very promising future as a means of meeting the world's future energy needs. Solar PV electricity has grown in popularity over the last few decades. There is already a sizable market for PV panels, which have the ability to generate sustainable energy globally. Furthermore, PV-generated power is predicted to become the dominant global energy source by the end of the century (Xu et al., 2018).

PV module manufacturers supply parameters in STC. However, such conditions are uncommon in the field. As a result, estimating the electrical characteristics of a module or array necessitates transferring these attributes to outdoor conditions. The short-circuit current (Isc) and open-circuit voltage (Voc) are the two most important parameters of the I-V and P-V curves (Voc). The product of current and voltage at each point on the I-V curve represents the output power for that operating condition. The fill factor (FF) is defined as the ratio of Pm to the product Isc Voc. The higher the fill factor, the better the cell quality (Fig. 1). The use of a variable resistor, R, makes measuring the I-V curve of a PV generator quite straightforward. In order to capture the points of the I-V curve from short circuit to open circuit, the value of R will be adjusted in progressive stages from zero to infinity. Voltage and current will be measured at each step (Durán et al., 2012).

A photovoltaic system's output power is influenced by a variety of variables, including solar radiation, PV surface temperature, shadow, tilt angle, and dust accumulation. The design of a PV system should take into account a variety of variables, including but not limited to tilt angle, irradiation, and dust collection. The output power of the PV is significantly impacted by these variables. The effects of dust buildup on PV output power have been the subject of research (Abdeen et al., 2017).

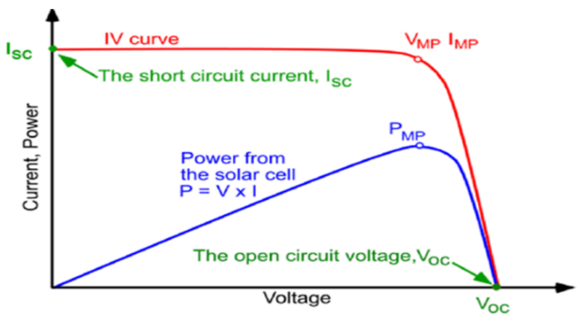

Fig. 1. I-V and P-V curves for solar panel (Alzahrani et al., 2020).

High temperatures and dusty environments have a significant impact on the performance of PV systems. This study examined how soiling affected the operation of a 2.0 MWp solar system installed in a car park in the north of Oman. According to the results, soiling caused a 4.8%, 18.1%, and 38.1% decrease in power generation after one week, three weeks, and five weeks of operation, respectively. Additionally, it was shown that soiling percentages of 7.5% and 12.5% could result in monthly power production dropping from 307.2 MWh to 289.7 MWh and 274.0 MWh, respectively (Al Siyabi et al., 2021).

The short circuit current, open circuit voltage, and output power of the PV are all decreased when the dust density rises. The maximum output of the PV can be reduced by approximately 34% by dust with a density of 10 g/m^2 (Chen et al., 2019).

To maintain their functionality, PV panels should be cleaned frequently. There are a number of manual, automated, or self-cleaning PV panel cleaning techniques available. The excessive use of water and power in the manual cleaning method is its main drawback. The initial investment in automated processes is quite high and they too require power to operate. As a result, self-cleaning innovations like hydrophobic coatings are well-liked maintenance options for PV panels. The coating approach is more trustworthy and economical because it doesn't require power to operate and doesn't scratch panels during cleaning (Shenouda et al., 2022).

Nanoparticles are created via a variety of processes, which are classified as bottom-up or top-down. Fig. 2 depicts a simplified representation of the procedure. Sol-gel is one of the most extensively utilized ways for creating hydrophobic nanocoating's. A colloidal solution of particles suspended in a liquid phase is referred to as a sol. A gel is a solid macromolecule that is submerged in a solvent. Because of its simplicity and the fact that most nanoparticles can be synthesized using this process, sol-gel is the most used bottom-up method. It is a wet chemical technique that employs a chemical solution as a precursor to an integrated system of discrete particles. In the sol-gel process, metal oxides and chlorides are commonly utilized as precursors. Shaking, stirring, or sonication are then used to disperse the precursor in a host liquid, resulting in a system with a liquid and a solid phase. To recover the nanoparticles, several processes such as sedimentation, filtration, and centrifugation are used, and the moisture is removed further by drying (Ealia and Saravanakumar, 2017).

The main objective of this study is to investigate hydrophobic nano coating impacts on the PV panels' current-voltage, power-voltage curves, and fill factor.

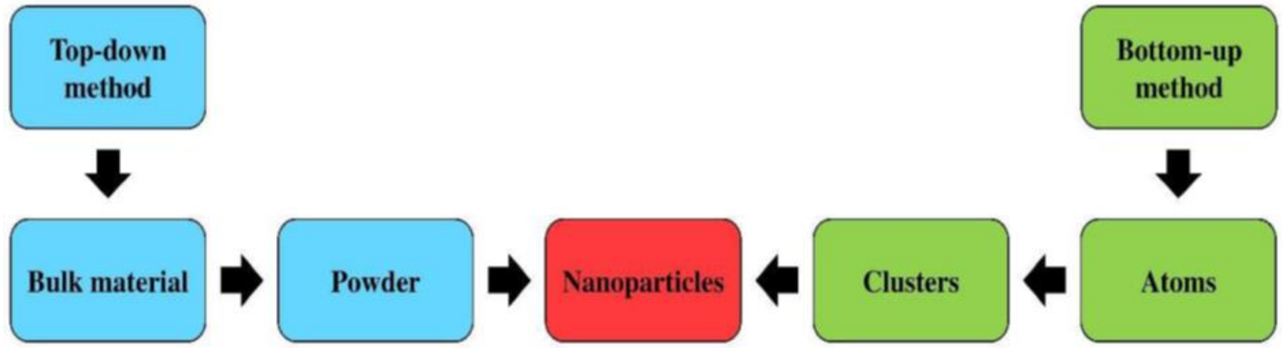

Fig. 2: The nanoparticles synthesis process.

2. Materials and methods

The metal oxide nano-coating was prepared at the Egyptian Petroleum Research Institute, Nasr City, Cairo, Egypt. The outdoor experiments were carried out on Pv station, located in Itay al Barud, Beheira Governorate, Egypt, located at latitude 30.529264° N, longitude 30.4213071° E, and 6 m above sea level. The nano-coating characteristics (chemical and physical) analyses were carried out in the National Center for Research, the Egyptian Petroleum Research Institute, and the Faculty of Science, Alexandria University's electronic microscope unit.

2.1. Photovoltaic panels

A photovoltaic (PV) panel can directly convert solar radiation into electricity and send it to a load. PV panels are the primary components of any PV system, and they can be placed in arrays to maximize electric energy generation. The PV panels are mounted on a metal structure, the angle of which can be adjusted manually. Two panels were used to generate power: a reference uncoated panel (RP) and a prepared nanocoated panel (PNP). Each panel has a rated power of 100 watts (Fig. 3).

Fig. 3: The 100 W PV panel.

2.2. The PV system diagram

Every PV panel is connected to a 12 V solar charge controller. The solar charge controller is connected to a 9 Ah battery. The PV system block diagram for PV system and the connections of its components are illustrated in Fig. 4.

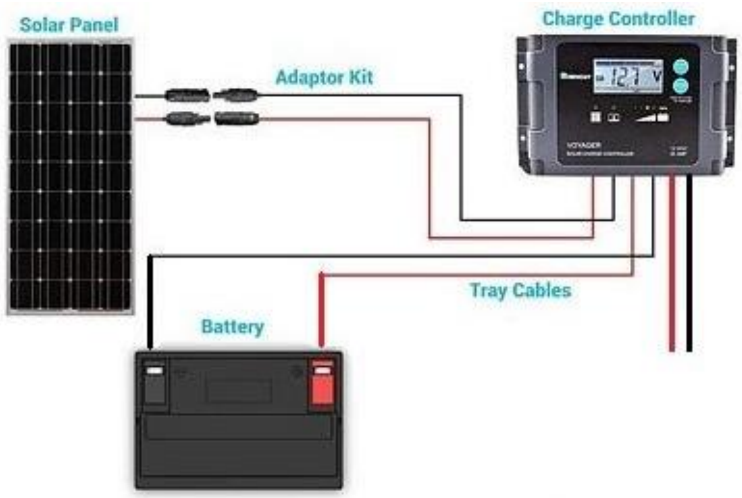

Fig. 4. PV system diagram.

2.3. Power resistors

By managing current flow and voltage, power resistors are designed to withstand and dissipate huge quantities of power. Power resistors are composed of high thermal conductivity materials, to permit for effective cooling. A resistor's power rating specifies how much power it can safely handle before it begins to suffer irreparable harm. They typically have a power rating of at least 5 Watts. A combination of power resistors that have a resistance rating of 0.10, 0.22, 0.5, 1, 2, and 4 ohms and each resistor has a power rating of 10 watts was used to make many resistance values ranging from 0.22 to 24 ohms. A wire wound power resistor of 10W is shown in Fig. 5.

Fig. 5. The power resistors.

2.4. Measurement devices

The ISM 400 solar radiation meter provides a real-time irradiance reading on the LCD that determines the radiation incident on a planar surface (Range 2000 W/m^2, Resolution 0.1 W/m^2, and dimension110(L) × 64 (W) × 34(H) mm) (Fig. 6a).

The digital multimeter can be used to measure DC voltages and currents, AC voltages and currents, and frequencies, as well as capacities, resistances, and temperatures (DC Voltage from 1mV to 1000V, AC Voltage from 1mV to 750V, DC Current from 1mA to 20A, and AC Current from1mA to 20A) (Fig. 6b).

A digital clamp meter is a type of electrical gadget that has jaws that can be opened to clamp around an electrical conductor. This allows for the measuring of current in a conductor without making physical contact with it or disconnecting it for insertion into the probe (AC 600A ± (2%+5), DC 600A ± (2%+5), AC voltage 600V ± (0.8%+5), and DC voltage 600V ± (0.5%+2)) (Fig. 6c).

A digital infrared thermometer (DT8011T) is a device that determines temperature by measuring a fraction of the thermal radiation emitted by the object being measured (Temperature Range -50 ~ 1100°C, Accuracy ±2% or 2°C, Dist. to Spot Ratio12:1) (Fig. 6d).

Fig. 6. Measurement tools.

2.5. Methodology

The outdoor experiments were carried out between May and July of 2022. The measurements were taken every hour from 8 a.m. to 4 p.m. Solar radiation, PV panel surface temperature, PV panel output (DC current, DC voltage), dust accumulation density g/m^2, and I-V curve variables were all measured (Voc, Isc). The nanocoating characteristics, chemical and physical analyses were conducted by Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), Energy dispersive X-ray (EDX), Uv-Vis Microscopy, water contact angle and Fourier transform infrared (FTIR).

2.5.1. Preparation of hydrophobic nanocoating

Synthesis of PDMS/SiO2 nanocomposites: The PDMS precursor Part-A (Sylgard184 elastomer base, 3 gm) has been combined with toluene and anhydrous ethanol. Then, add 20 ml of sodium silicate 5% (w/v) mixed with PDMS, 80 ml of ethanol absolute, and 2 ml of ammonium hydroxide NH4OH, and stir for 2 hours at 30-35 C° using a magnetic stirrer. The sample was left for 24 hours. After thoroughly washing with double distilled water to remove all ions, the pale white solid product obtained was centrifuged at 4000 rpm for 10 minutes and dried at 70 °C for 2 hours.

Preparation of transparent hydrophobic nanocoating: The following processes were used to prepare samples: The PDMS/SiO2 nanocomposites were combined with ethanol, isopropanol, and the curing agent (for samples, the weight ratio of PDMS/SiO2 nanocomposites to curing agent was 10:1). The mixture was then homogeneously dissolved for around 30 minutes using an ultrasonic washer (29 kHz, 150 W). The produced nanocoating was then spray coated onto the PV panel.

2.5.2. Solar radiation (W/m^2)

The intensity of solar radiation (irradiance W/m^2) was monitored with a digital solar radiation meter and recorded every hour. The irradiance meter was slanted at the same angle as the solar panels (15̊).

2.5.3. The PV panel's surface temperature

The solar panel's surface temperature was measured every hour from sunrise to sunset using infrared and thermocouple thermometers directly in centigrade unit.

2.5.4. I-V and P-V curves

These curves can yield many characteristics and values such as Voc, Isc, Vmp, Imp, Pmp (V*I), and FF (Vmp*Imp / Voc*Isc). The properties of the PV panel can be altered by adjusting the load resistance linked to the PV panel (Duran et al., 2008). By increasing the load resistance, the module's output voltage and current were adjusted from 0 V to Voc and Isc to 0, respectively (Willoughby et al., 2014). Plotting voltage and current yields the I-V curve, while plotting calculated power and voltage yields the P-V curve. A combination of power resistors with different resistance values from 0.10 ohm to 24 ohm with a 0.5 ohm increase in every measurement was used as a variable resistance (Fig. 5).

3. Results and discussions

Scanning electron microscopy (SEM): The SEM reveals the nano-surface coating's roughness, which plays a crucial role in increasing hydrophobicity and, consequently, the contact angle. Energy Dispersive X-ray (EDX) data clearly demonstrate the presence of Si and O, indicating good dispersion of silica nanoparticles throughout the coating. Additionally, the presence of C and O, together with Si, provides an explanation for the functionalizing chemicals used. The weight percentages for O, Si, and C were 41.99, 40.66, and 17.35%, respectively. According to transmission electron microscopy (TEM), the nanoparticles had an average size of 11 nm. The clusters' average size was 80 nm. The magnification of all TEM images was set to 100 nm. According to the Uv-Vis spectroscopy, the nanocoating displayed a high transmittance in visible light. The average transmittance in the visible light range (400-800nm) was 91%, and the nanocoating was UV (200-390nm) radiation resistant. Fourier transform infrared spectroscopy (FTIR) measures the absorbance of a sample to an incoming infrared spectrum in the 400 to 4000 cm-1 regions. The primary functional groups of the spectral bands are Si-CH3, O-H, Si-C, Si-O-Si, C-H, Si-C, and C=C. Surface wettability of nanocoating (WCA): The produced nano coating had a water contact angle of 123 degrees, indicating that the PDMS/SiO2 nanocoating is hydrophobic.

3.1. Current-voltage curve for clean RP and PNP panels (I-V curve)

The I-V curves for a clean reference panel (RP) and a prepared-nanocoated panel (PNP) are shown in Fig. 7. The short circuit current Isc was 5.69, 5.7, and 5.82 A, respectively, and the open circuit voltage Voc was 20.3 and 20.7 V, respectively, at solar radiation of 960W/m^2 and a PV panel surface area of 0.6 m^2. The characteristics and efficiency of the prepared nano-coated panel were higher than the reference uncoated panel.

3.2. Power-voltage curve for clean panels (P-V curve)

The maximum power Pmax for a clean reference panel (RP) and a prepared nano-coated panel (PNP) was 78.5 and 84.4 W, respectively, as shown in Fig. 7.

3.3. Fill factor for clean panels (FF)

The fill factors for RP and PNP were 0.68 and 0.7, respectively (Fig. 8). Therefore, the PNP has higher output power and better efficiency.

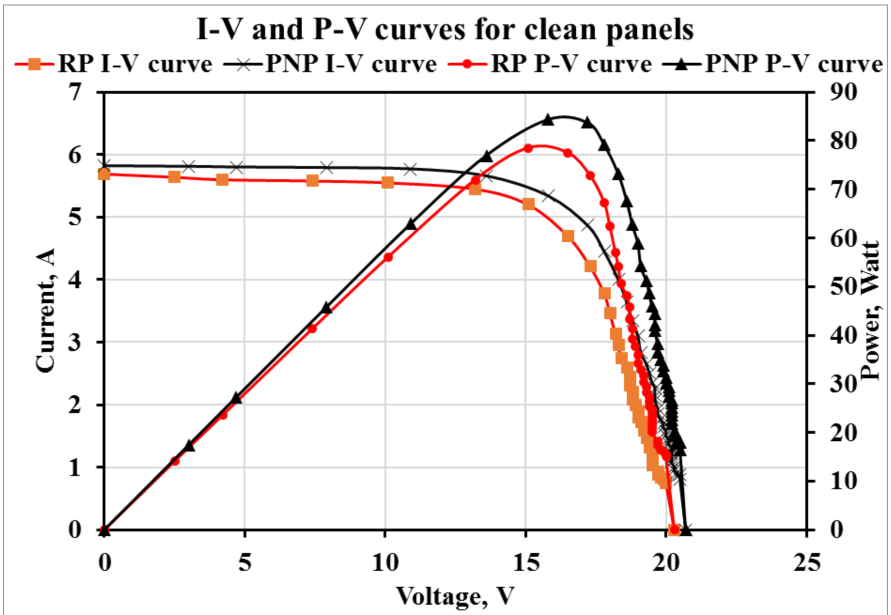

Fig. 7. The I-V and P-V curves for clean RP and PNP.

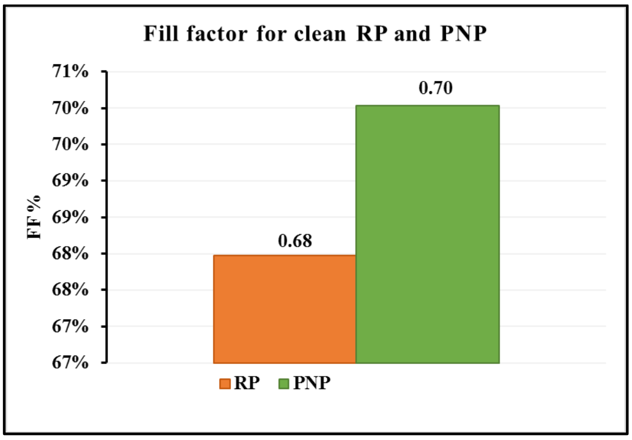

Fig. 8: Fill factor for clean RP and PNP.

3.4. Performance of loaded clean RP and PNP.

Clean RP and PNP had average DC powers of 65.2 and 69.3 W, respectively (Fig. 9). The average efficiency was 14% and 14.8% respectively (Fig. 10). The panel's temperature was 46.4, and 45.3 °C, respectively (Fig. 11). The PNP has higher efficiency and the lowest temperature.

3.5. I-V and P-V curves after self-cleaning

After 40 days of exposure to weather conditions and dust, a volume of 4 liters of water was sprayed onto the surface of each panel in 2 minutes, through orifices with a 0.5 mm diameter, to test the self-cleaning property. The dust density on RP and PNP before water spray was 10 and 4.30 g/m^2, while the dust densities after water spraying were 4.80 and 1.12 g/m^2 respectively.

3.6. Current-Voltage curve after self-cleaning

The I-V curve after self -cleaning for reference panel (RP), and prepared-nanocoated panel (PNP), are shown in Fig. 12. The short circuit current Isc values were 4.80 and 5.65A, and the open circuit voltage Voc values were 20.0 and 20.2 V, respectively. The panels efficiency was 10.5% and 13.7%, respectively, at solar radiation of 960 W/m^2 and a PV panel surface area of 0.6 m^2. The characteristics and efficiency of the prepared nano-coated panel were higher than those of the reference panel.

3.7. Power-Voltage curve after self-cleaning

The PV panels' maximum power point (MPP) Pmax is attained at a location on the characteristic where the product I-V is at its highest. It represents the maximum amount of power that the PV panel connected to the load can produce. The maximum power (Pmax) for Rp and PNP was 60.56 and 78.82 W, respectively.

3.8. Fill factor after self-cleaning

The fill factor is the relationship between the maximum power the panel can deliver under normal operating conditions and the result of multiplying the open-circuit voltage by the short-circuit current (VOC x ISC). The higher the fill factor, the more power the array can produce. This fill factor value represents curve squareness and gives an idea of the PV panel's quality. Normal values range from 0.7 to 0.8. For RP and PNP, the fill factors were 0.63, and 0.69, respectively (Fig. 13). The PNP has a greater output power and greater efficiency as a result.

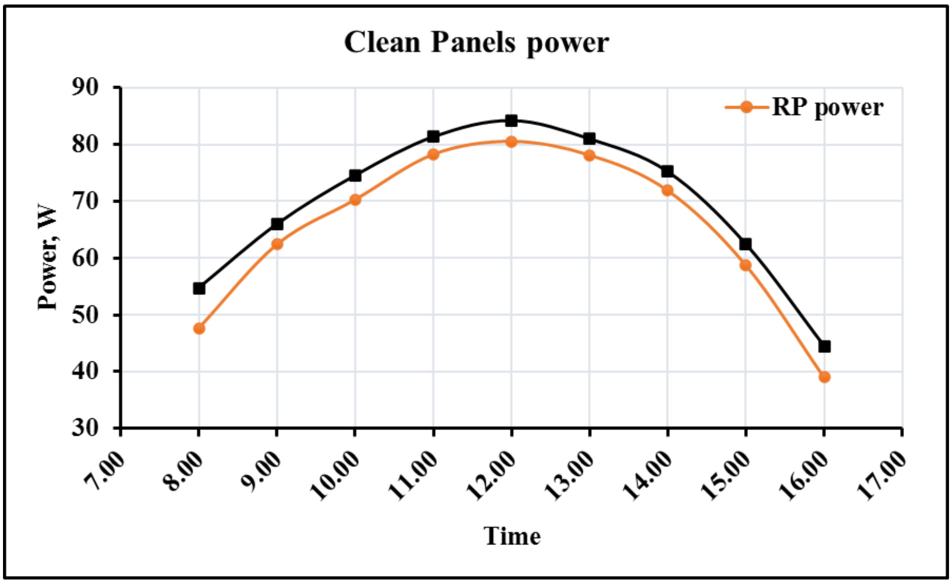

Fig. 9. The power of clean RP and PNP.

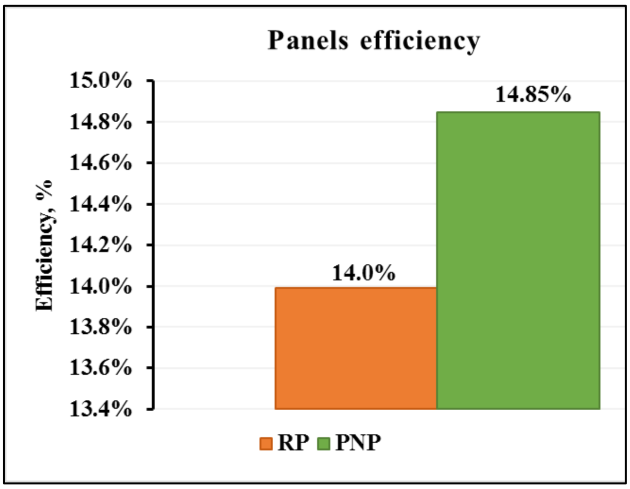

Fig. 10. The RP and PNP efficiency.

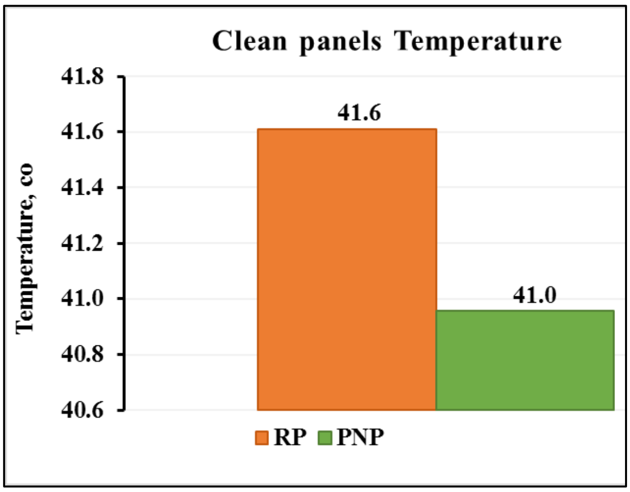

Fig. 11: The clean panels temperature.

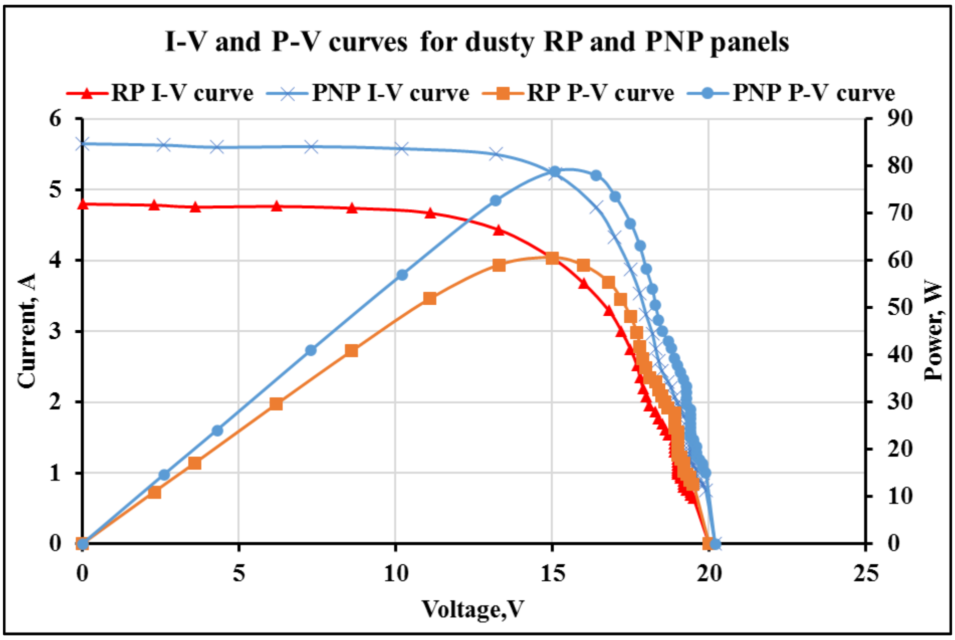

Fig. 12. The I-V and P-V curves for dusty RP and PNP.

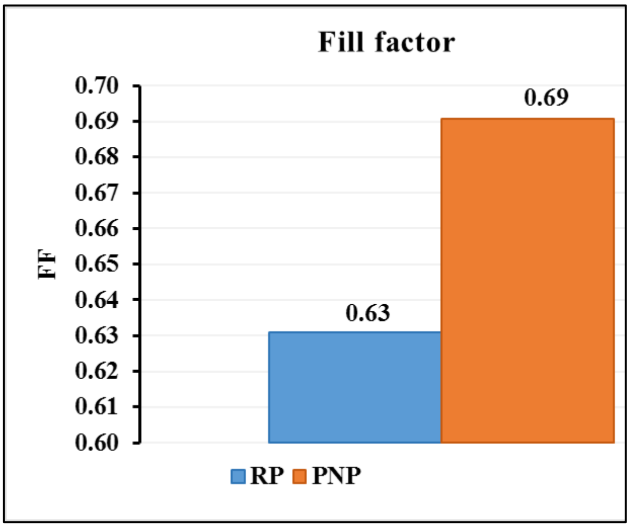

Fig. 13. The fill factor for dusty RP and PNP.

4. Conclusions

This study was conducted to investigate the effect of the nano coating and dust accumulation on the I-V curve, P-V curves, and the fill factor of PV solar panels. Based on the results of this study, the following conclusions were obtained: SEM analyses showed the surface roughness of the nano-coating, which is an important factor in increasing the hydrophobicity and thus the self-cleaning property. The weight percentages of O, Si, and C were 41.99, 40.66, and 17.35%, respectively. TEM showed that the average nanoparticle size was 11 nm. The average cluster size was 80 nm. The water contact angle was 123 degrees, so the nanocoating shows hydrophobic properties. The average transmittance for the prepared nano coating was 91% in the visible light range (400-800nm). After 40 days of exposure to outdoor conditions, the dust densities on RP and PNP before water spray were 10 and 4.30 g/m2, while the dust densities after water spraying was 4.80 and 1.12 g/m2, respectively. For clean panels, the short circuit current Isc values were 5.69, 5.7, and 5.82 A, and the open circuit voltage Voc values were 20.3 and 20.7 V respectively. The fill factor for PNP (0.7) was higher than RP (0.68). Therefore, the PNP power (84.4 W) was higher than the RP power (78.5 W). For dusty panels, the short circuit current Isc values were 4.80 and 5.65 A, and the open circuit voltage Voc values were 20.0 and 20.2 V, respectively. The fill factor for PNP (0.69) was higher than RP's (0.63). Therefore, the PNP power (78.82 W) was higher than RP power (60.56). The average efficiency for RP and PNP was 10.5% and 13.7%, respectively. As a result, the nano coating has a positive impact on the I-V curve, P-V curve, and fill factor. That's because of its anti-reflective and self-cleaning effect.

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تأثير طلاء النانو المقاوم للماء على منحنيات التيار-جهد والقدرة-جهد للألواح الشمسية الكهروضوئية

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الملخص العربي

تؤثر العديد من العوامل مثل تراكم الغبار وانعكاس الضوء عن أسطح الألواح الكهروضوئية، على أداء وكفاءة الألواح الشمسية الكهروضوئية. يزداد تراكم الغبار بمرور الوقت على أسطح الألواح الشمسية الكهروضوئية. نتيجة لتراكم الأتربة المتزايد يحدث انهيار في أداء الألواح الكهروضوئية نتيجة للإشعاع المفقود بسبب طبقة الأتربة على سطح الألواح والتي تعمل كعازل بين الضوء وبين الخلايا الكهروضوئية.

يعد التنظيف المنتظم ضروريًا لصيانة الألواح الكهروضوئية وتفادي التأثير الضار للأتربة، ولكن عند تنفيذه يدويًا، فإنه يتطلب عمالة كثيفة، وأيضا تستهلك تقنيات التنظيف اليدوي الكثير من الماء والطاقة. تكلف طرق التنظيف الآلي في البداية الكثير من المال وتحتاج إلى مصدر كهربائي لكي تعمل. ونتيجة لذلك، تبرز أهمية تقنيات التنظيف الذاتي مثل الطلاءات النانوية المقاومة للماء لأنها لا تتطلب طاقة ولا تترك خدوشًا على سطح الألواح أثناء التنظيف.

نظرًا لأن منحنى التيار والجهد (I-V)، ومنحنى القدرة والجهد (P-V)، وعامل الملء (FF) هي أكثر العوامل الدالة على كفاءة وأداء الألواح الكهروضوئية، لذلك فقد تم دراسة تأثير الطلاء النانوي الكاره للماء والغبار على هذه العوامل.

أظهرت الدراسة أن طلاء النانو كان كارهًا للماء وله تأثير التنظيف الذاتي. بعد ٤٠ يومًا من التعرض للظروف الخارجية، كانت كثافة الغبار على اللوح المرجعي غير المطلي بالنانو RP واللوح المعامل بطلاء النانو المحضر PNP قبل الغسيل بالماء (التنظيف الذاتي) ١٠ و٤,٣٠ جم / م^2، بينما كانت كثافة الغبار بعد الغسيل بالماء (التنظيف الذاتي) ٤,٨٠ و١,١٢ جم / م^2 على التوالي.

أظهر منحنى التيار والجهد للوح المرجعي النظيف RP واللوح المعامل بالنانو النظيف PNP أن تيار دائرة القصر I_{SC} كان ٥٫٦٩ و٥٫٨٢ أمبير، وأن جهد الدائرة المفتوحة V_{OC} كان ٢٠٫٣ و٢٠٫٧ فولت على التوالي. كان عامل التعبئة FF للوح المعامل بالنانو PNP (٠٫٧) أعلى من معامل التعبئة للوح المرجعي النظيف RP (٠٫٦٨).

بالنسبة للألواح المغبرة، كان تيار دائرة القصر ISC ٤٫٨٠و ٥٫٦٥ أمبير، وكان جهد الدائرة المفتوحة ٢٠ و٢٠٫٢ فولت على التوالي. كان معامل التعبئة FF للوح المعامل بالنانو PNP (٠٫٦٩) أعلى من معامل التعبئة للوح المرجعي النظيف RP (٠٫٦٣).

يتضح مما سبق أن طلاء النانو الشفاف له تأثير إيجابي على منحنى I-V ومنحنى P-V وعامل التعبئة FF، بسبب تأثيره المضاد لانعكاس الضوء وخاصية التنظيف الذاتي التي خفضت كمية الأتربة المتراكمة على اللوح الذي تمت معاملته بالطلاء النانوي الشفاف.