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Experimental Investigation to Improve the Energy Efficiency of Solar PV Panels Using Hydrophobic SiO_2 Nanomaterial

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Received: 27 April 2020; Accepted: 22 May 2020; Published: 24 May 2020

Abstract: This research aims to experimentally improve the overall efficiency of solar photovoltaic (PV) panels by coating them with hydrophobic SiO_2 nanomaterial. Also, an accurate mathematical model was used to estimate the parameters of the PV panel, which is a non-linear optimization problem. Based on the experimental data and using the particle swarm optimization (PSO) algorithm, the optimal five parameters of a single diode model of a PV panel were determined in this study. This experimental work was conducted and carried out in the Renewable Energy Laboratory of Assiut University, Egypt. A comparative analysis was completed for three identical solar PV panels; the first panel was coated with hydrophobic SiO_2 nanomaterial, so it was considered to be a self-cleaning panel; the second panel was uncoated and cleaned manually on a daily basis; and the third panel was kept dusty all the time through the experimental investigation, and was used as a reference. Experimentally, the output power of the PV panels was monitored for each panel in this study. Also, the anti-static and anti-reflection effects of coating solar PV panels with hydrophobic SiO_2 nanomaterial were investigated experimentally. According to the obtained experimental results, it was found that the use of SiO_2 coating for PV panels results in the better performance of the PV panels. The overall efficiency of the coated panel increased by 15% and 5%, compared to the dusty panel and the uncoated panel which was manually cleaned daily, respectively.

Keywords: improve energy efficiency; hydrophobic; SiO_2; nanomaterial; coating; self-cleaning; dust; PV panels

1. Introduction

Global Warming is one of the greatest challenges facing people on earth these days. Fossil fuel contributes significantly to global CO_2 emissions. For this reason, using fossil fuel to generate electricity should be minimized, if not eliminated. On the other hand, there should be more penetration of clean energy sources to meet the global electricity demand to mitigate the effect of Global Warming [1]. Nowadays, the use of renewable energy sources, mainly from solar and wind, is growing very fast and competing with fossil fuel technologies with level costs. These renewable energy sources are sustainable, have great potential to be converted to useful energy forms and are more ecofriendly compared to than fossil fuels [2]. At minimum cost, heat and electricity can be provided from solar energy, which is normally required for all daily life applications. Also, it is environment-friendly, with zero CO_2 emissions [3]. Solar photovoltaic (PV) panels suffer from losing their efficiency due to depositions of snowfall, dust and airborne dirt from factories, which results in a degradation in PV performance. Light transmission from the outer surfaces of PV panels is reduced as a result of dust accumulation, leading to less photon absorption, which lowers the overall efficiency of the PV system. The situation is worse in the Middle East and North Africa (MENA) region, where dust is prevalent and rainfall is scarce. In such weather conditions, more frequent cleaning for PV panels is required to maintain the efficiency of the system. Accordingly, solar PV energy is considered a very attractive, mature, cost effective and sustainable energy source. However, there are some limitations when using solar PV energy, such as its low efficiency, dust, and the effect of temperature and pollen, which reduce its overall efficiency up to 30% in desert areas due to high quantities of dust or pollen accumulating over the panels [4]. Dust accumulation on solar panels depends on the slope of the PV panel, its orientation, the roughness of the surface, whether it is coated or not, ambient temperature and wind speed [5,6]. Also, the chemical, biological and electrostatic properties of dust affect dust accumulation on the surface of PV panels, as summarized in Figure 1. Dust shields the solar panels from sunlight and photons cannot exist free from electrons and reduce the output power of the panel [7].

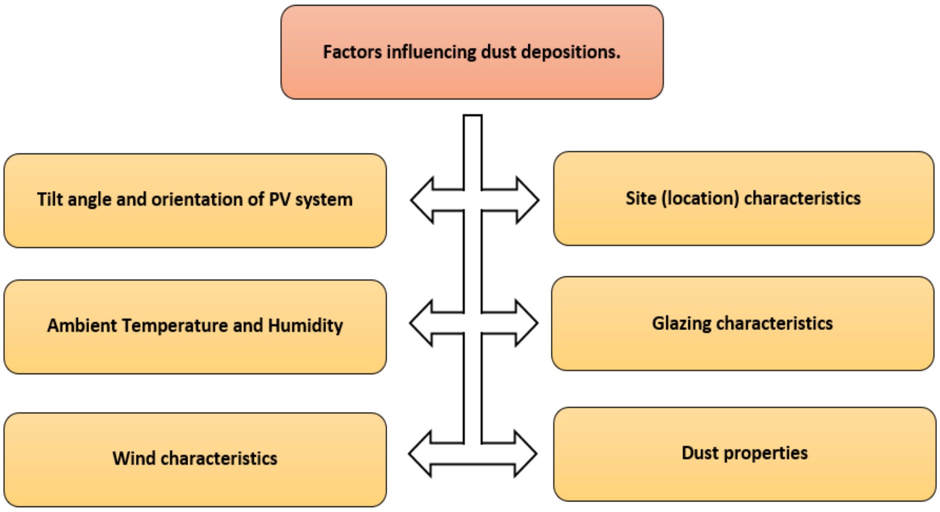

Figure 1. Factors influencing dust depositions on the surface of PV panels.

There are several methods of cleaning PV panels, which might be categorized into two approaches, mainly: (1) traditional manual cleaning methods and (2) self or automated cleaning methods. The traditional manual cleaning approach has many limitations, as it is time consuming and the process may result in panel surface cracks with time, as a result of brushing. In addition to this, the traditional approach might not remove the small particles totally. On the other hand, the self or automated cleaning approach applies different methods for cleaning, such as electrostatic methods, mechanical methods and coating methods. While electrostatic methods and mechanically automated methods consume additional energy from the solar PV systems, hence more cost, the use of coating methods for panel cleaning does not consume any energy. To improve the overall efficiency of solar PV panels, it is required that they be cleaned more frequently, which is costly, and energy and time consuming [8]. Therefore, there is a need to come up with novel innovative cleaning methods that are not time and energy consuming. Figure 2 lists several cleaning strategies for solar PV panels; automatic, passive self-treatment, natural and self-cleaning methods. Self-cleaning methods include electrostatic, mechanical and coating methods. Mechanical methods apply robotic, air-blowing, water-blowing and ultrasonic vibration techniques. Coating methods use hydrophobic material that covers the panel's glass, which carry away the dust from panel surfaces [9,10].

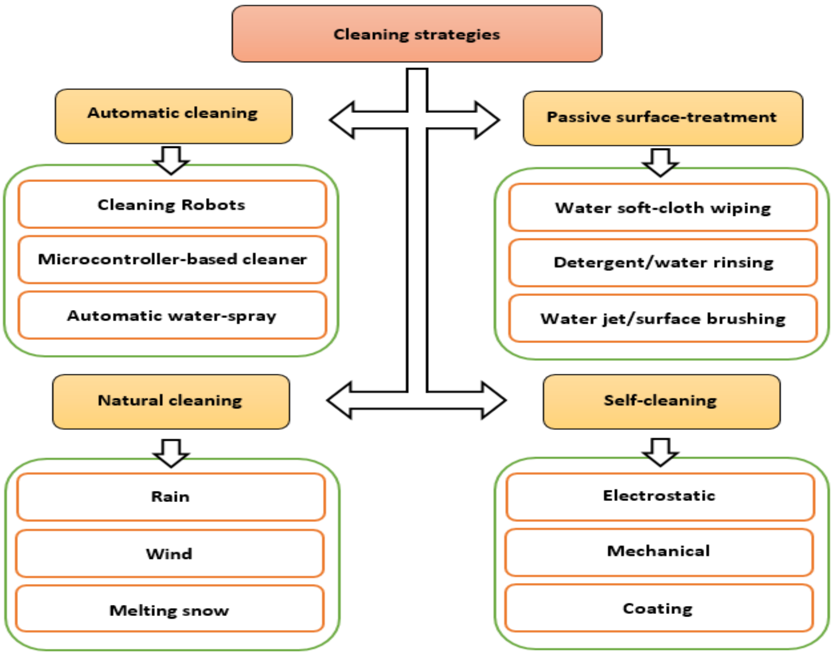

Figure 2. Different cleaning strategies for removing dust from solar PV panels.

In the large scale of solar PV panels, using hydrophobic coating materials is most economic for PV panel cleaning, as this method does not consume energy for cleaning and does not cause scratches on PV surfaces, which will maintain the power output of the panels [11]. Using self-cleaning hydrophobic nanomaterials to coat the surface of solar PV panels is an efficient method to increase the overall efficiency of the panels over a long lifetime, as illustrated in Figure 3.

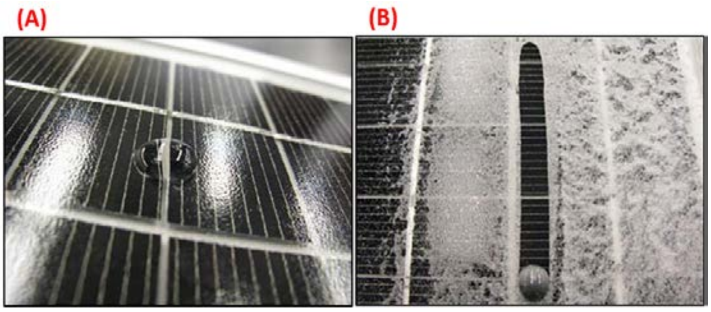

Figure 3. Self-cleaning hydrophobic coatings; (**A**) nanomaterial coated solar PV panel, and (**B**) water rolls off the surface like a sphere rolling down a slide.

The main working principle of using hydrophobic coating nanomaterials is that the layer forms a barrier so that water accumulates in a spherical shape, and when the solar panels are installed at a tilted angle, water rolls off the panel surface as a sphere rolling down [12,13], as depicted in Figure 3. Table 1 summarizes a literature review of self-cleaning strategies for removing dust from solar PV panels, focusing on coating materials and water contact angles over a sliding angle CA/SA. The contact angle (CA) measuring the surface wettability on flat surfaces, and a small sliding angle (SA) of 1–5° will increase the water sliding of coated PV surfaces.

Table 1. Summary of a literature review of self-cleaning strategies.

Authors	Year	Nano-Coating Materials	Water CA/SA
Alam et al. [14]	2019	SiO_2	168.5/2
Zhang et al. [15]	2017	Hybrid soot/SiO_2	166/1
Yuan et al. [16]	2017	Al_2O_3-ZnO	168.9/1
Qu et al. [17]	2017	Kaolin/PVC	155/5
Li et al. [18]	2016	PTMS-SiO_2	158.5
Tang et al. [19]	2015	HFTES	166/4
Li et al. [20]	2014	SiO_2	163.6/1.4
Schaeffer et al. [21]	2014	Functionalized-SiO_2	160/2.5
Zhan et al. [22]	2014	SiO_2-P(BA-Co-EFOA)	170.3/3
Xu et al. [23]	2012	F-SiO_2	150/5
Deng et al. [24]	2012	Hybrid carbon/SiO_2	165 ± 1/1
He et al. [25]	2011	ZnO-FAS	165.8/1
Li et al. [26]	2009	SiO_2	157/1
Xu et al. [27]	2009	PS/FAS	160/0
Ling et al. [28]	2009	SiO_2-APTS	162.3 ± 1/4 ± 1
Manca et al. [29]	2009	TMS-SiO_2	168/3
Wang et al. [30]	2007	$CaCO_3$-polyacrylate	155/2

Based on Table 1, authors can conclude that the use of nano-coated material based on SiO_2 is more efficient in solar PV panels, due to its high contact angles (CA). Therefore, the authors preferred to use SiO_2 in this research, which is suitable for the MENA region. Typically, for untreated, flat surfaces with contact angles greater than 90°, an increase in surface roughness leads to a decrease in surface energy, resulting in larger static contact angles (CA). The coated material increases the surface of the PV panel's contact angle (CA) more than 90°, which mean that the surface becomes more hydrophobic, as shown in Figure 4A. The behavior of a water droplet based on Wenzel's and Cassie/Baxter models [31,32] is illustrated in Figure 4B. Water slightly imparts the asperities based on Wenzel's assumption. In Cassie/Baxter's regime, water is suspended above the asperities because of the air fraction between the pillars, as shown in Figure 4B.

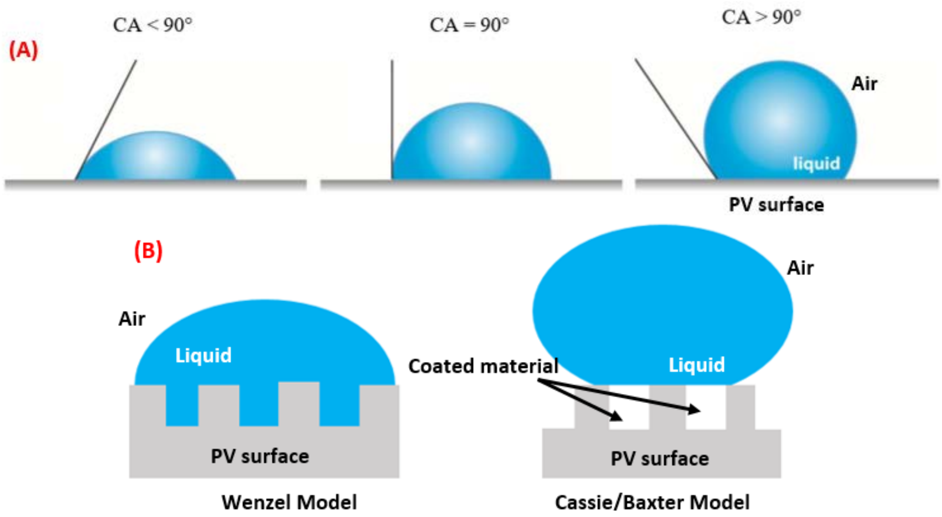

Figure 4. Behavior of a water droplet on a hydrophobic surface. (**A**) Water contact angles (CA) and (**B**) Wenzel and Cassie/Baxter models.

In this study, a comparative analysis was performed for three identical solar PV panels: the first panel was coated with hydrophobic SiO_2 nanomaterial, and was therefore considered to be a self-cleaning panel; the second panel was uncoated and cleaned manually on a daily basis; and the third panel was kept dusty all the time through the experimental investigation, and was used as a reference. The main contributions of the current research work can be summarized as following:

- Improving experimentally the overall efficiency of solar PV panels by coating them with hydrophobic SiO_2 nanomaterial to reduce the dust composition on the PV panels.
- Estimating the parameters of a PV panel, the optimal five parameters of a single diode model, which is a non-linear optimization problem, by using an accurate mathematic model, a particle swarm optimization (PSO) algorithm and experimental data of *I-V* characteristics of PV panel.
- Experimental measurement of the output power of the PV panels for 45 days, measured every hour per day.
- Also, the anti-static and anti-reflection effects of coating solar PV panel with hydrophobic SiO_2 nanomaterial were investigated experimentally.

This paper is organized as follows. In Section 2, a mathematical model of a solar PV panel is explained. In Section 3, the description of the experimental set-up is explained in detail. Results of the theoretical and experimental work, with its discussions, are presented in Section 4. In Section 5, the output of this work is concluded and key findings are listed.

2. Mathematical Model of the PV Panel

To estimate the parameters of the PV panel, which is a non-linear optimization problem, mathematically, the single diode model (SDM) was used to model the PV. Figure 5 depicts the electrical equivalent circuit modeling of the PV panel.

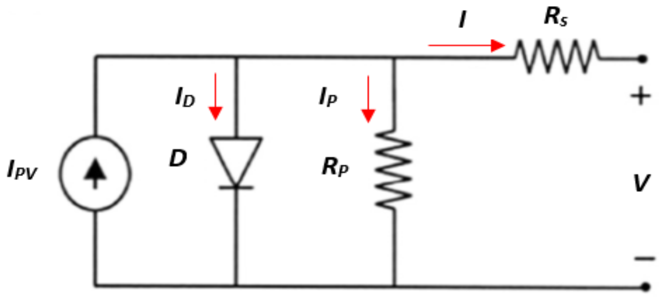

Figure 5. Equivalent circuit of the single diode model (SDM).

By applying Kirchhoff's law to the top node, the following equation can be obtained easily:

$$I = I_{pv} - I_D - \left(\frac{V + I \times R_s}{R_p}\right) \tag{1}$$

where I_{pv} and I_D represent the photo-generated current and the diode current in ampere (A), respectively.
R_s and R_p indicate the series and shunt resistance in ohms (Ω).

A current supply I_{pv} is linked to a parallel diode D with (*I-V*) a characteristic curve, which is defined by the Shockley formula, which is expressed as [33,34]:

$$I_D = I_0\left(\text{Exp}\left(\frac{V + I \times R_s}{n \times V_t}\right) - 1\right) \tag{2}$$

The ideality factor of such a diode is denoted by n, selected according to the sort of semiconductor material and the fabrication design.

V_t represents the thermal voltage in voltage (V), which expressed as follows [33,34]:

$$V_t = (N_s \times \text{k} \times T)/q \tag{3}$$

k is the Boltzmann constant and it is equal to 1.380649×10^{-23} (joule/kelvin).

T indicates the PV panel temperature, expressed in kelvin.

N_s and q represent the number of PV panels which are connected in series, and the charge of the electron is $1.602176634 \times 10^{-19}$ coulomb.

The circuit model presented in Figure 5 is characterized by five variables, expressed as follows: $\alpha = \left(I_{pv}, I_o, n, R_s, R_P\right)$, and can be identified analytically or numerically. In the current case study, an ESP-160 PPW solar panel is considered. The electrical specification of the solar PV panel is listed in Table 2.

Table 2. Solar PV panels data.

Module Type	ESP-160 PPW
Maximum Power P_{max} (W)	160
Maximum Voltage V_{max} (V)	12
Maximum current I_{max} (A)	13.3
Module Efficiency (%)	15.4

To build an accurate PV mathematical model, the (I-V) characteristic of the PV panels is needed. The non-linear aspect of this equation leads to a non-linear mathematical model, governed by several unknown variables. Therefore, the estimation process of these parameters $\alpha = \left(I_{pv}, I_o, n, R_s, R_P\right)$, for the SDM, is reformulated as a non-linear optimization problem.

To effectively resolve such a hard optimization problem, several optimization algorithms were investigated. In this work, authors used a PSO algorithm to obtain the solar PV parameters. The performance requirements in terms of accuracy identification should be achieved through the appropriate design of an objective function, which should be minimized. The implementation cost function is described by Equation (5), which is adopted as the root mean square error criteria.

The difference equation between the detected current I_{det} and the predicted current I_{pre}, which can be quantified through several performance indexes, is defined as follows [33]:

$$J(\alpha) = I_{\text{det}} - I_{pre}(V_{\text{det}}, \alpha) \tag{4}$$

The appropriate cost function can be provided as:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N} (J_i(\alpha))^2} \tag{5}$$

where N is the set of empirically detected points (I_i, V_i).

The predicted current value is obtained by means of Equations (1) and (4) of the SDM as a measure of the detected voltage (V_{det}) and the estimated variables, respectively.

3. Experimental Set-Up

This work aims to study and investigate the effect of dust on the performance of solar PV panels. Experimentally, the panel's performance, under dusty conditions, was evaluated for uncoated and coated panels. In this study, different factors were considered, including: dust density, dust size, the type of dust particles, tilt angle, wind speed, wind direction, the exposure period and the climatic conditions of the site. The study was conducted in the Renewable Energy Laboratory at Assiut University, Egypt. The PV panels have been installed on the roof top of the laboratory, with a tilt angle of 30°, facing south, as per the latitude of the site, to ensure maximum energy production around the year. The PV panels were kept without cleaning at all for six months. Data readings were recorded for a period of 45 days between 1 July and 15 August 2019. Three identical PV panels were used. The first panel was coated with hydrophobic SiO_2 nanomaterial, and was considered as a self-cleaning panel; the second panel was uncoated and was cleaned manually every day; and the third panel was kept dusty for all of the experiment as a reference. Experimentally, the PV characteristics, output power, solar radiation, ambient temperature and efficiency of the solar PV panels were recorded every day for 45 days. Figure 6 demonstrates the experimental setup.

Figure 6. Picture of experimental set-up during measuring work. (**A**) Self-cleaning panel coated with SiO_2 hydrophobic nanomaterial, (**B**) uncoated panel—manual cleaning, (**C**) dusty panel, over all the time of the experiment (reference), (**D**) load (variable resistance) and (**E**) measuring devices.

The hydrophobic SiO_2 nano-coating material, which used to coat the solar PV panel, is a concentrate for impregnation which forms a transparent film protecting the treated surfaces from dust, oil, dirt, etc. The authors used a commercial type of nano-coating material [35] which is mainly formed from SiO_2 material. The authors used 5 to 10 milliliters of the hydrophobic nano-coating material per square meter of the panel, with the thickness of the coated material being 1–2 mm (measured in the laboratory). It was spread uniformly over the surface of the PV panel using a microfiber cloth. After that, it was left for more than 60 min to complete the drying process. At higher humidity values, this process takes up to a couple of hours. All three PV panels were kept on the roof top in the open air for six months to let dust accumulate naturally on top of their surfaces. After that, one of the three panels was cleaned with normal tap water in a free flow of fresh-water (like rain) without any mechanical aid, to confirm the hydrophobic effect on the panels. The process of surface self-cleaning with nano-coated material is illustrated in Figure 7. Secondly, a PV panel was cleaned manually by using a soft brush with distilled water and dish soap, Figure 8A, or using a soft brush, as shown in Figure 8B. In addition, the anti-reflection and anti-static properties were tested in a laboratory. After PV panel coating, the surface becomes a little bit rougher, water is not allowed to settle after treatment, and a rainbow-like light appears when looking at an angle of inclination. Commercial panels are produced with an expected lifetime of 20–25 years, and the coating's lifetime is only three years. Therefore, after three years (coating lifetime), the coating layer will have to be removed from the PV panels' surface due to environmental effects, and a new coating surface will be needed.

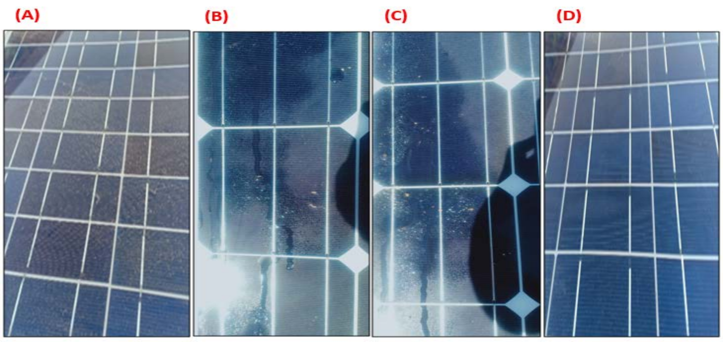

Figure 7. Process of surface self-cleaning with nano-coated material; starting from (**A**) dirty panel throughout (**B**) partially cleaned panel, then (**C**) almost cleaned panel, and finally (**D**) totally cleaned panel.

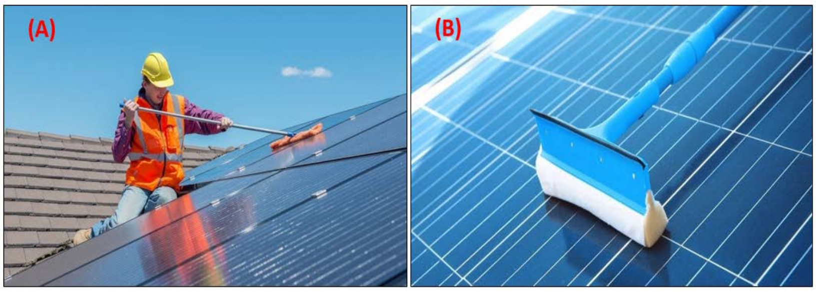

Figure 8. Manual cleaning process of the PV panels. (**A**) Using a soft brush with distilled water and dish soap, (**B**) using a soft brush.

Measuring the output power of the three solar panels during the daytime indicated the anti-reflection effect of the hydrophobic nanomaterial coating. The anti-static effect of hydrophobic nanomaterial was investigated by allowing natural dust to deposit itself on the panels' surface. All readings of the voltage, current, ambient temperature and solar irradiation were recorded on every hour of every day during the 45 days for all the three panels. At the end, the daily average values were obtained.

4. Results and Discussion

Figure 9 shows the hourly measured solar radiation of the location where the study was conducted during the experimental time. In Figure 10, the total values of the daily solar radiation are presented. According to this figure, it was found that the daily solar radiation at the site varied from 6.5 to 8.4 kW/m^2. This indicates high potential energy for the experiment site for the PV installation.

The overall efficiency of a PV panel is linearly proportional to its output power. So, with the output power increase, the overall efficiency is increased as well. Figure 11 presents the maximum output power of the three panels under study over the 45 days of experiment. The output power was reduced due to dust depositions, which reduced light penetration through the outer protective surface of the panel. This resulted in the minimization of the photon absorption, which degraded the overall efficiency of the PV system. The uncoated panel, which was cleaned manually, increased its output power by 10% compared dusty panel (reference one). The manual cleaning process is time-consuming, costly, hazardous and might result in corrosion of the panel frame. On the other hand, using the self-cleaning hydrophobic SiO_2 nanomaterial coating increases the output power by 15% compared to the dusty panel (reference one) and by 5% more than the uncoated manually cleaned panel, as shown in Figure 11. The maximum output power of the panels was measured at the maximum solar radiation per day.

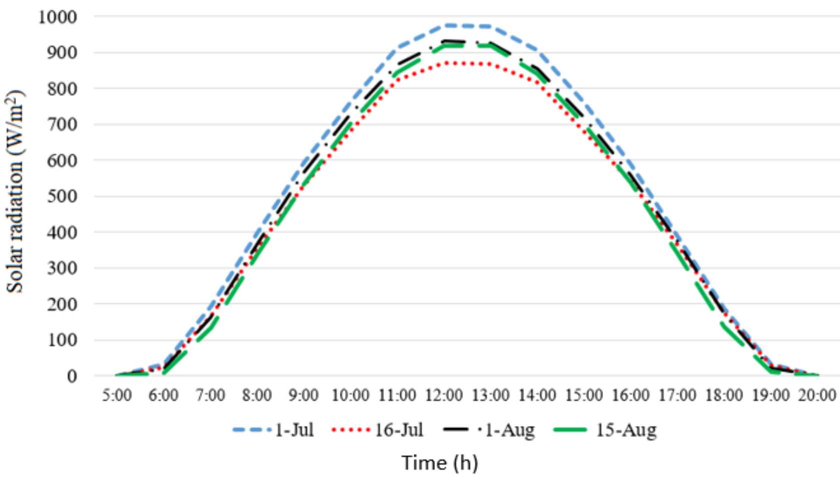

Figure 9. Hourly solar radiation in W/m^2 of different days of the site under study (during 2019).

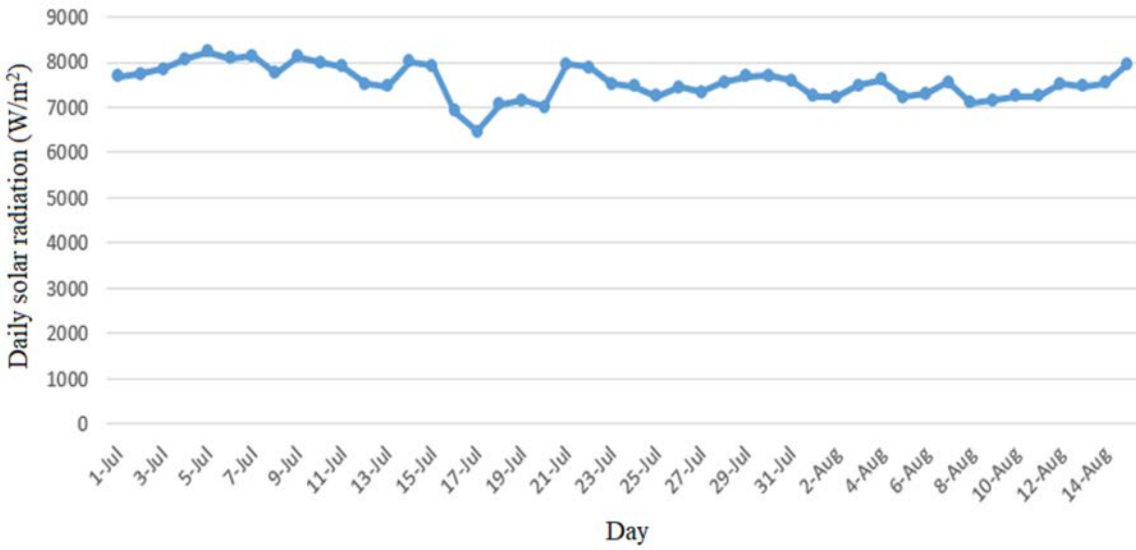

Figure 10. Daily solar radiation in W/m^2 of the site under study (during 2019).

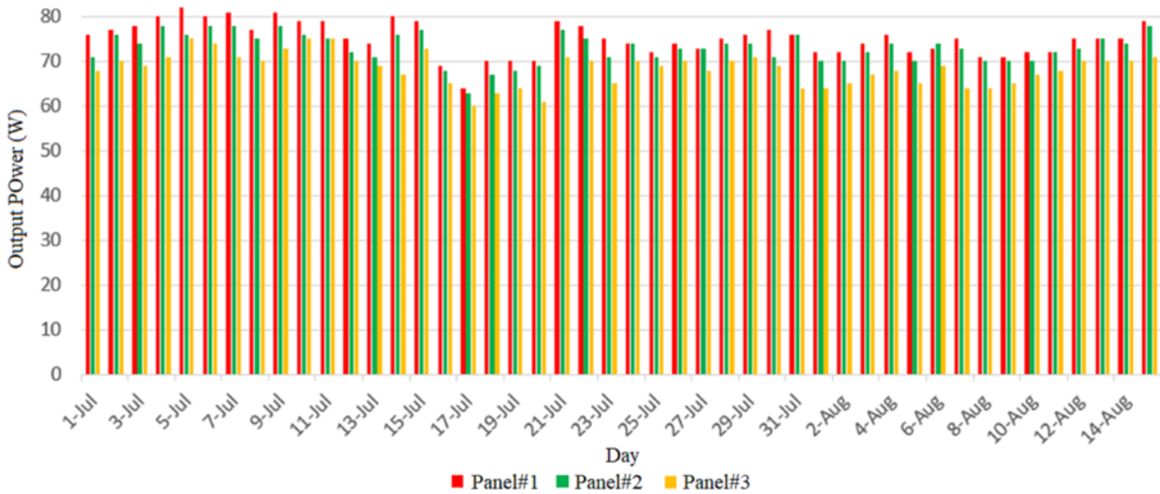

Figure 11. The average power generated by the three panels (during 2019); panel 1: SiO_2 nano-coated panel; panel 2: manual cleaning panel without a coating of any material; panel 3: dusty panel.

Based on this experimental analysis, the use of SiO_2 hydrophobic nanomaterial coating will increase the total efficiency of the solar PV panels as demonstrated in Figure 11. This is due to the ability of the coated panel to remove dust with no efforts or any external act. In the case of coated panel, it was found that the natural flow air on its surface is enough for cleaning and removing the dust particles.

The anti-static effect of the hydrophobic SiO_2 nanomaterial coating can spread away from the water droplets and produce a thin layer with less resistance for photons. The small water droplets join and run easily off the surface of the panel, as shown in Figure 6. The flow of the water on the surface will cause dust to fall, unlike the other non-coated panel, in which the flow of water might produce a layer of mud on top of the panel's surface, as shown in Figure 12. Also, at high wind speeds, the self-cleaning process is improved, and increases the overall efficiency of the SiO_2 coated PV.

Figure 13 shows the measured wind speed at the maximum solar radiation per day. According to Figures 11 and 13, it can be observed that, during the days with high wind speed, the output power of PV panel 1 is high when compared to days with low wind speed.

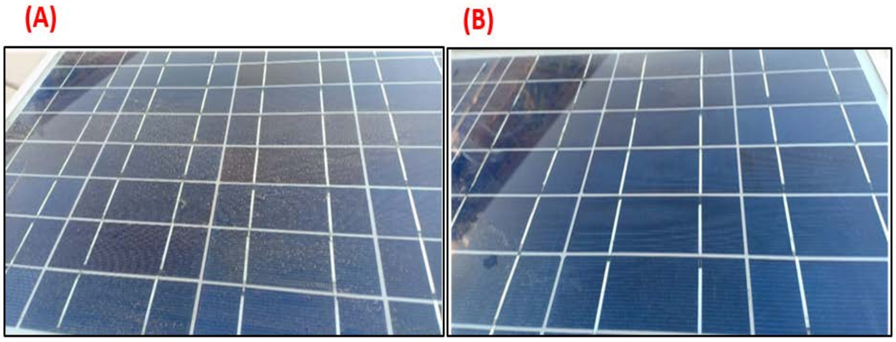

Figure 12. Anti-static effect of the solar PV panels. (**A**) non-coated panel (reference panel) (**B**) hydrophobic nano-coating SiO_2 material on the PV panel.

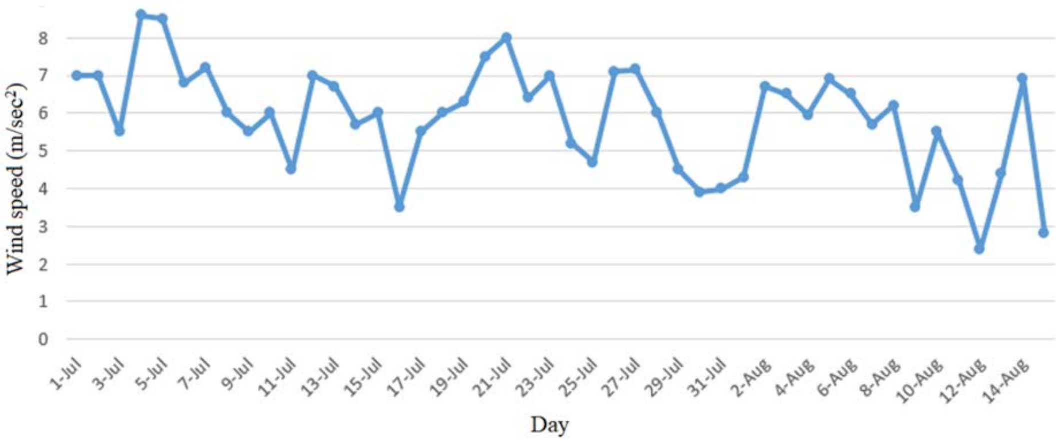

Figure 13. Measured wind speed at the site under study (Assiut University, Egypt) at the maximum solar radiation per day.

In Figure 14, the effect of coating with SiO_2 nanomaterial was studied with respect to PV panel temperature. The study found that the anti-reflection effect of hydrophobic solar PV can reduce the temperature of the panel by about 10% compared to the dusty uncoated panel, and by 5% compared to the manually cleaned uncoated panel at the maximum solar radiation per day.

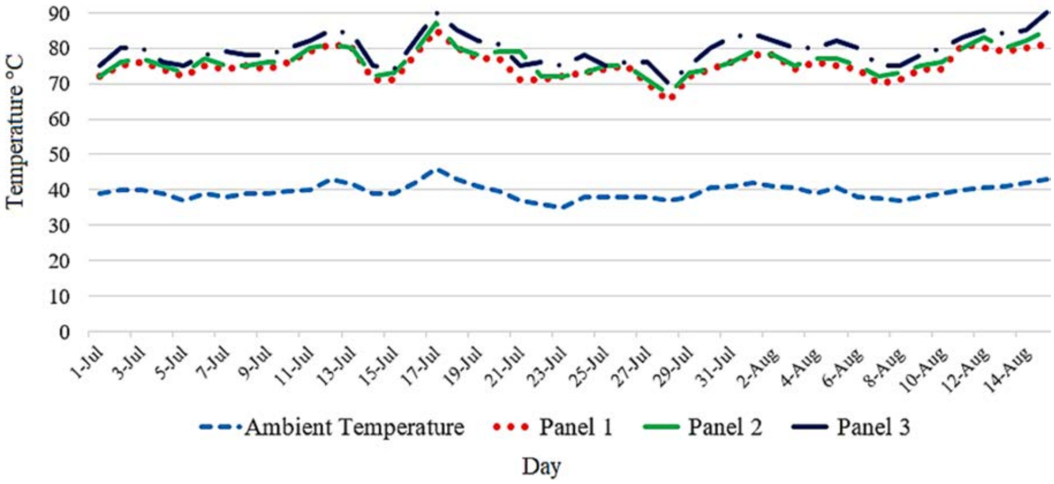

Figure 14. Average daily temperature; ambient and the three panels' temperatures at the maximum solar radiation per day.

For the purpose of estimating the PV panel parameters of the PV panel which was coated with SiO_2 nanomaterial, experimental work was done to measure the current and voltage of the PV panel at different loadings, as shown in Figure 5. Based on the experimental data, and using the particle swarm optimization (PSO) algorithm, the optimal five parameters of a single diode model of the PV panel was determined. During the optimization process, five parameters (short circuit current, diode saturation current, ideality factor, series resistance and shunt resistance) were used as the decision variables in order to minimize the cost function. The cost function is represented by the root mean square error between the actual current and estimated current. The minimum, maximum and optimal values of the five parameters of a single diode model of PV panel are shown in Table 3. A comparison between the experimental and estimated *I-V* data of the PV panel which coated with SiO_2 nanomaterial is shown in Figure 15. From this figure, it can be noted that there is good matching between the experimental data and the estimated data. The minimum value of the root means square error between the actual current and the estimated current is 0.052. The cost function variation during the optimization process is illustrated in Figure 16.

Table 3. Minimum, maximum and optimal values of five parameters of a single diode model of a PV panel.

Parameter	Minimum Value	Maximum Value	Optimal Value
Short circuit current (A)	1	10	5.53
Diode saturation current (A)	1×10^{-8}	1×10^{-4}	8.86×10^{-7}
Ideality factor n	0.1	3	0.69
Series resistance (Ω)	0.05	0.5	0.21
Shunt resistance (Ω)	10	1000	76.58

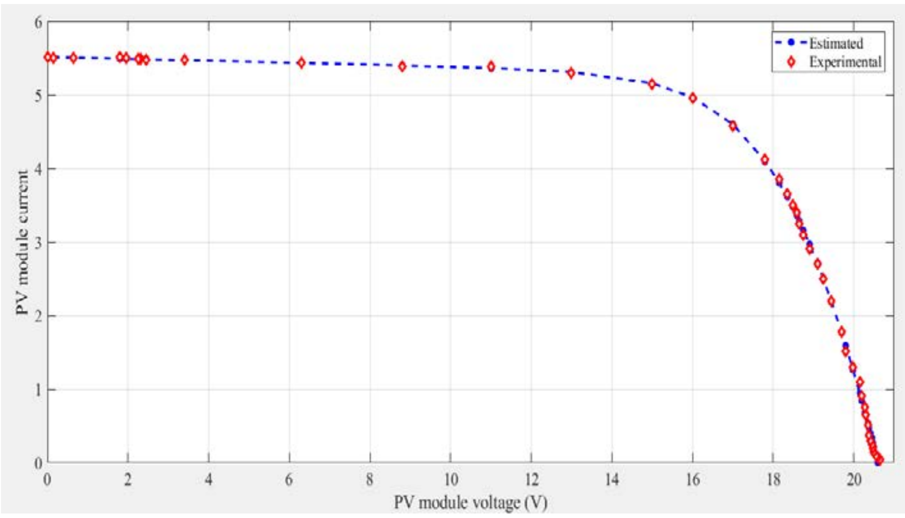

Figure 15. Comparison between the experimental and estimated *I-V* data of PV panel which was coated with SiO_2 nanomaterial.

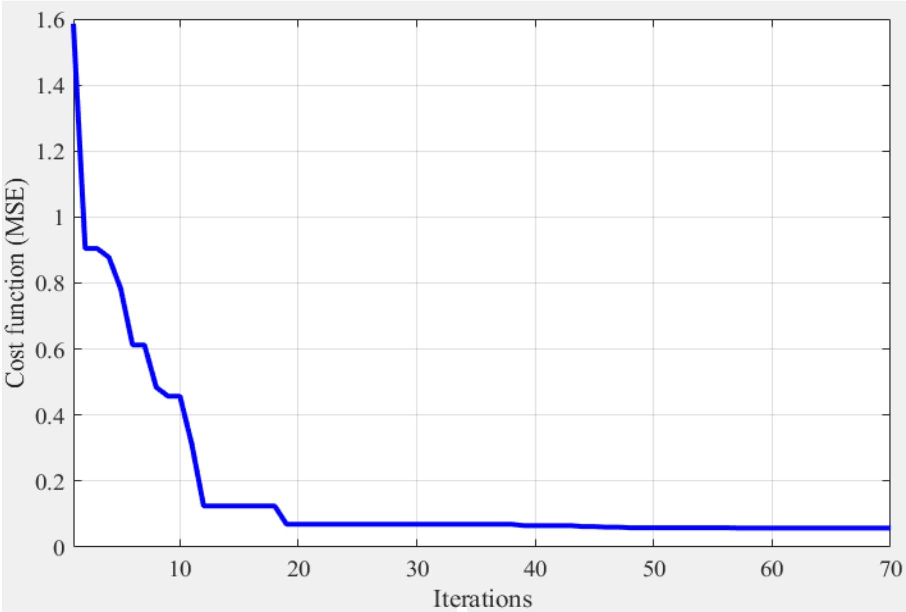

Figure 16. Cost function variation during the optimization process.

5. Conclusions

In this research, the effect of the coating on the performance of the PV panel was investigated. The output power, which indicates the overall efficiency of the three solar PV panels under three different conditions, was evaluated. The first solar panel was coated with SiO_2 hydrophobic nanomaterial, and was used for the self-cleaning process. The second solar PV panel was cleaned manually every day, without a coating of any material. The last solar panel was kept during the period of the experiment without a coating and without cleaning; this was used as a reference for all measuring processes. Using hydrophobic SiO_2 coating nanomaterial improved the total performance of the solar PV panels in the following ways:

- The output power, which indicates the overall efficiency of the solar PV system, was increased by 15% more than the dusty panels and 5% more than the uncoated panels which were cleaned manually every day.
- The anti-static effect was improved due to the water droplets spreading away and producing a thin layer with less resistance for photons. The small water droplets joined and ran easily off the surface of the panel. The flow of the water on the surface caused dust to fall, unlike the other non-coated panel, on which the flow of water produced a mud layer on the surface of the panel.
- Due to the anti-reflection effect, the temperature of the panels was reduced by about 10% compared to the dusty panel and 5% compared to the manual cleaning panel without the coating.
- The overall efficiency of the solar PV panels increased due to their ability to remove dust without using any energy source or human aid.

Based on the experimental data and using the particle swarm optimization algorithm, the optimal five parameters of a single diode model of a PV panel were determined. There was good matching between the experimental data and estimated data. The minimum value of the root means square error between the actual current and estimated current was 0.052. The cost function variation during the optimization process was illustrated in this study.

Author Contributions: Conceptualization, A.E., H.A.Z. and H.A.-E.; methodology, H.A.Z., H.R. and H.R.A.; software, H.R. and H.A.-E.; validation, A.E., H.A.Z. and H.A.-E.; formal analysis, H.R. and H.R.A.; investigation, H.A.Z. and H.A.-E.; resources, H.R.A., H.R., H.A.-E., H.A.Z. and A.E.; data curation, A.E.; mathematical modeling, H.R. and H.A.Z.; experimental work, H.A.-E., A.E and H.R.A.; writing—original draft preparation, H.R.A., H.R.,

H.A.-E., H.A.Z. and A.E.; writing—review and editing, H.A.Z. and H.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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