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Solar PV Panels-Self-Cleaning Coating Material for Egyptian Climatic Conditions

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Abstract: The electrical efficiency of photovoltaic panels is affected by many environmental parameters, which have a negative impact on system electrical efficiency and cost of energy, dust and increased panel temperatures being the most serious in the MENA region. In this work, a few organic-based self-cleaning coatings are developed, and their effects on PVs' electrical efficiency re assessed for polycrystalline panels exposed to natural soiling conditions outdoors at El-Sherouk City. The results show that monolithic hydrophobic-based coatings using paraffine and dimethyl-siloxane show up to 14.3% improvement in the electrical efficiency of the PV panels, but the role of nanoparticles TiO_2 and Al_2O_3 addition needs further investigation. Hydrophobic-based coatings using dimethyl-siloxane reduce the coated panels' surface temperature compared with the uncoated panel.

Keywords: solar energy; polycrystalline photovoltaic panels; dust; temperature; self-cleaning coating

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1. Introduction

The accumulation of dust and pollutants on a cell's surface is a serious weather condition that negatively affects the performance of PV cells and reduces light transmissivity through the solar panels. The impact of dust on PV electrical efficiency is one of the most important problems facing PV utilisation in dusty countries. Middle Eastern and North African countries are witnessing significant expansion in solar energy projects yet are challenged by environmental conditions that seriously affect the performance of photovoltaic solar energy. These environmental conditions include high summer temperature, wind, dust, clouds, and shade, which has motivated researchers to investigate techniques for overcoming the present challenges as well as taking advantage of the existing opportunities [1–18]. The reduction in PV electrical efficiency in desert areas ranges from 8.41% to 50% according to reported results [5,6,8–11]. The nature of dust (which is suspended in the air in the form of soil particles and particulate matter) follows the density of the type of land that passes through it, humidity, wind deviation, and air altitudes. The intensity of the dust increases as the sun's surface warms and wind speed increases. These factors are changeable with different locations and, thus, dust accumulation effects differ from place to place [3–5,12,13]. Studies have shown that most of the photovoltaic installations in desert areas suffer from loss in electrical efficiency due to the accumulation of dust, airborne dirt, and sand particles from sandstorms, as well as high temperature in the summer season.

The Egyptian energy sector has increased its electricity produced from renewable sources to be 25 TWh in 2020/2021 compared to 15.60 TWh in 2017/2018. Moreover, the installed capacities increased to be 6.05 GW in 2020/2021 compared to 3.79 GW in 2017/2018 [7,19]. Solar-powered systems, especially solar PV, represent the most rapidly growing capacity compared to other renewable energy technologies worldwide and in the Egyptian market. The Egyptian PV solar energy sector has increased its capacity from 172 MW in 2018 to 1623 MW in 2020 [19–24], as there has been a huge expansion in photovoltaic solar mega projects, such as the Benban solar park project which has a capacity of 1465 MW, roof top and off grid central plants with capacity 32 MW, roof top projects with capacity 100 MW, and the Kom Ompo PV plant with an initial capacity of 26 MW in 2020 [25]. Furthermore, photovoltaic solar technologies are the most common technologies used for domestic applications, such as solar streetlights recharging by day, pumping systems, commercial advertising, desalination, building integrated photovoltaic thermal systems, eco-friendly seaports, and powering farms [26–31]. Yet, the main challenge is that the electrical efficiency of the panels degrades due to weather and environmental conditions such as soiling, shadow, and high operation temperatures [20]. The amount of electrical efficiency degradation due to dust deposition depends on location and electrical efficiency drop in Alexandria, Egypt, which recorded a reduction in power of up to 51.12% as the electrical efficiency of the solar photovoltaic panel system was reduced from 15.9% to 7.88% for clean and unclean modules, respectively [32]. Therefore, overcoming electrical efficiency degradation due to dust deposition will maintain a reduction of CO_2, as large-scale photovoltaic plants up to 100 MW could result in a CO_2 reduction of 75,451.74 t/y [31]. Applying this for the Egypt 2020 PV installed capacity, the total CO_2 reduction by PV technology will be about 1,056,324.36 t/y, if the electrical efficiency degraded due to dust the amount of CO_2 reduction will be only 528,162.18 t/y.

The significant loss in the energy harvesting electrical efficiency of solar panels resulting from soiling requires regular cleaning; however, the traditional methods of manual cleaning are energy-, labour-, and time-consuming processes. Another disadvantage of manual cleaning is the introduction of cracks and scratches on the PV surface. Researchers and engineers around the globe have been developing new cleaning methods, namely electrostatic, mechanical, and coating methods. Cost-wise, the electrostatic and mechanical methods are more expensive than most coating methods. Therefore, developing low-cost coatings is an attractive goal for many researchers; in this context, hydrophobic or hydrophilic coatings are used to cover the glass surface. After applying those coatings, even if soiling occurs, the effort needed for cleaning is reduced, reducing cost significantly. However, the effect of sand erosion can cause the coating to deteriorate [14,15]. Similarly, increased summer temperatures result in measurable drops in PV efficiencies, due to heating the panels, which urges applying direct cooling by a variety of methods such as using nanofluids in the cooling application of PV/T systems [16,18].

Recent studies [33–35] have summarised previous efforts adopted for self-cleaning coatings such as superhydrophobic or hydrophilic materials to reduce dust deposition on solar PV panels and have evaluated the influences of antisoiling coatings on the energy produced by PV modules. They also reported work on preparing hydrophobic material for regions with a hot climate and high dust density and the effects of antisoiling on solar cells covering glass for different climate and surface properties, and their work investigated the performance of different self-cleaning coatings with and without micronanosurface structures. Most of the available studies focus on analysis of the effect of dust accumulation in reducing the electrical efficiency of PV modules or the transmission of the glass. Few studies evaluated the alternatives of antisoiling coatings by testing them in different environmental outdoor conditions, based on the modification of the module glass with a self-cleaning and/or easy-to-clean surface.

New ideas have been proposed for developing easy-to-clean, hydrophobic, and antireflective coatings by colocating water-repellent functional groups alongside active functional groups on nanostructured particles which bond to the resin matrix, cementing the silica nanoparticles into the resin, giving a tough, durable, and transparent coating [36–40]. A range of materials and compositions are reported in the literature [37,38] for superhydrophobic surfaces based on aluminium oxide coatings on glass substrates via solution-based approaches for solar panel cover glass applications and have demonstrated that metallic oxides can be readily used in mimicking the lotus leaf using physical and chemical techniques such as in sol films or as nanoadditives combined with polymeric materials. The development of self-cleaning coatings for protecting the surface of the panels is based on the desired wettability. The surface can be modified to become hydrophobic and repel the water which will carry the dust on its way, or the surface can be modified to become hydrophilic and disperse the water, preventing the soils from sticking. Hydrophilic self-cleaning may be integrated with a photo catalysis effect. In general, the fabrication of the self-cleaning coating requires two main components: (a) a matrix material with low surface energy in the case of superhydrophobic coating or with a high surface energy in the case of superhydrophilic coating and (b) the addition of nanoparticles to make a controlled rough surface. The selection of the nanoadditives should consider their optical properties (surface transmission and/or absorbance) so that the radiation absorbance is not impaired. In this context, the role of nanoparticles integration in other applications (e.g., the enhanced absorbance of TiO_2 and Al_2O_3 nanoparticles in selective solar applications, good heat storage capacity observed in polymeric-based materials used for phase change materials, and/or the improved thermal conductivity of nanoparticles) should be considered. A recent review article has illustrated that coating cover glass with antireflective and self-cleaning coatings offers good solutions for PV efficiency. SiO_2, MgF_2, TiO_2, Si_3N_4, and ZrO_2 materials were shown to be widely used in antireflection coatings, using different application methods. The study emphasised that superhydrophobic surfaces stand out among other methods for self-cleaning applications, in which Al_2O_3, TiO_2, and Si_3N_4 are successfully used for their surface adhesion and durability [41].

Therefore, this work is based on some scientific concepts [15,38,41] for tailoring a new range of materials far beyond those reported in the literature which are based on organic matrices holding nano- and micro-oxides. Previous works [42,43] by the authors have investigated a new formula for self-cleaning coatings and have shown that different nanomaterials with different thermal properties and concentrations need to be studied in the future to decide how to boost panel performance while reducing cleaning requirements. This work compares different formulas based on hydrophilic (glycerol) and hydrophobic (dimethyl-siloxane and paraffine wax) polymeric coatings loaded with different nanoparticles (silicon oxide, aluminium oxide, and titanium dioxide). Each material of the host matrix selected in this work has some advantages. Glycerol is a low-cost hydrophilic polymer of low refractive index, which is the same as that of glass, and high specific heat compared to air. Paraffine is a hydrophobic, coloured, crystalline solid with low density and melting point and, when it melts, it turns into an odourless, colourless substance which is nonsoluble in water. Dimethyl-siloxane is the simplest member of the silicone polymer family, which is optically transparent and hydrophobic. It exists in a liquid form (low molecular weight) or as a soft rubber or resin form (high molecular weight). Its properties have made it very popular in biomedical and microfluid device applications, whereas its adoption in coating solid surfaces for resisting soiling is not yet adopted. The nano-oxides are selected to acquire a photocatalytic property with a reduced band gap. The photocatalytic self-cleaning property is activated once the light beams hit the solar panel surface, initiating a photochemical reaction which works through degrading the organic waste adhered to the panel surface into water and carbon dioxide [44]. This work investigates the changes in the electrical efficiency of coated PV panels by different combinations of polymeric matrix (glycerine, paraffine wax, and dimethyl-siloxane) with different nanoparticles (silicon oxide, aluminium oxide, and titanium dioxide). The work was conducted in two stages, where the first stage investigated the PVs' electrical efficiency under natural outdoor conditions (natural radiation conditions). In the second stage, the electrical efficiency of the PV panels was measured under laboratory-controlled radiation conditions (simulated solar radiation).

2. Materials and Experimental Construction Methods

2.1. Material Preparation

In the first stage of work, three different types of nanoparticles—silicon dioxide (SiO_2), titanium dioxide (TiO_2), and aluminium dioxide (Al_2O_3)—were mixed with two different polymeric coatings as the matrix (paraffin wax and glycerol). The electrical efficiency measurements were conducted under natural outdoor radiation conditions. In the second stage, dimethyl-siloxane and glycerol as the host matrix with Al_2O_3 and TiO_2 nanoparticles were used, and the electrical efficiency measurements were conducted under controlled simulated radiation conditions. The nanoparticles were supplied by Nano Tech and their specifications are described in Table 1.

Table 1. Materials used in the work.

Material	Description
Dimethyl-siloxane	Inexpensive, colourless, odourless, liquid, hydrophobic polymers with density of 0.965 g/cm^3 at 20 °C that can be coated as thin films on solid surfaces to make them highly water-resistant.
Paraffine	Coloured, crystalline solid that has a density of 0.77 g/cm^3 and melting point of 50 °C; when it melts, it turns into an odourless, colourless substance, nonsoluble in water.
Glycerol	Glycerol 98% with density of 1.26 g/cm^3 at 20 °C was purchased from LOBA CHEMIE, India. Acetic acid glacial of 1.048 g/cm^3 at 20 °C was purchased from LOBA CHEMIE, India, with melting point of 20 °C and boiling point of 290 °C.
Silicon dioxide (SiO_2)	Density of 2.4 g/cm^3, melting point of 1600 °C, boiling point of 2230 °C, and size less than 50 nm.
Titanium dioxide (TiO_2)	A total of 25 nm 99.9% purity, density of 4.23 gm/cm^3, melting point of 1843 °C, boiling point of 2972 °C, and size less than 15 nm.
Aluminium dioxide (Al_2O_3)	A total of 25 nm 98% purity, density of 3.9 gm/cm^3, melting point of 2040 °C, boiling point of 2977 °C, and size less than 30 nm.

The coating mixes were prepared in two beakers, where a 25 mL beaker was used for measuring the polymer and the other was used for weighing the nanoadditive particles. The coating was prepared by mixing the two beakers and the mix was prepared by heating and stirring for 1 h or sonicating for 20 min by a sonication device. Table 2 shows the amount of material and preparation conditions used for preparing the coating materials. After the preparation stage, the coating was applied on the panels' surfaces by brushing one layer.

2.2. Experimental Setup and Methods

Figure 1 shows the setup of the panels used in this work. Two types of polycrystalline panels were used through the work. The experimental work was conducted in three stages, where in the first and second stages small-sized panels were used for proof of concept with less material consumption, and the measurements were conducted outdoors subject to natural environment with uncontrolled radiation conditions (for the first stage) and indoors under controlled radiation conditions of 520 W/m^2 (in the second stage). In the third stage, larger-sized panels were used, and the measurements were conducted indoors under controlled radiation conditions of 850 W/m^2, for improving the accuracy of the measurements. The first type used for stage 1 employed polycrystalline solar panels (ReneSola RS-SL5TU-18P- polycrystalline-260 mm × 220 mm × 18 mm) of 0.0572 m^2 area with maximum power 5W with open circuit voltage of 22V and max current power of 0.27A. The second type (used for stage 2) employed polycrystalline solar panels of 0.09065 m^2 area (x- polycrystalline-370 × 245 × 17) with maximum power 10 W with open circuit voltage of 22 V and max current power of 0.57 A. For outdoors testing conditions, the panels were held directed to the south direction at 30°, for all conditions. The panels were installed outdoors at the university premises at El-Sherouk City located at the northeast of Cairo and characterised by its desert hot climate with latitude 30.144212 and longitude 31.639718. The electrical efficiency measurements were conducted under natural outdoor radiation conditions for the first set of experiments and under indoor controlled conditions for the second set of experiments. The controlled radiation conditions were made by subjecting the panels to lamps for about 15 min, which resulted in simulated solar radiation of 520 and 850 W/m^2 (representing average winter and summer radiation conditions). For all testing conditions, the panels' exposure took place outdoors to resemble natural dusting conditions. After conducting the measurements, the panels were returned to their natural outdoor exposure conditions. Table 2 shows all testing conditions.

Table 2. Preparation conditions.

Stage/Coating No.	Matrix	Volume, mL	Nanoparticle	Weight, gm/(%)	Preparation
Stage 1/1 5W small-sized panels/outdoor measurements	Paraffine wax	25	SiO_2	0.385 gm (2%)	Heating and stirring for 1 h
Stage 1/2 5W small-sized panels/outdoor measurements	Glycerol	25	Al_2O_3 + TiO_2	0.63 gm (both) (2%)	Heating and stirring for 1 h
Stage 1/3 5W small-sized panels/outdoor measurements	Paraffine wax	25	Al_2O_3 + TiO_2	0.38 gm (both) (2%)	Heating and stirring for 1 h
Stage 2/1 5W small-sized panels/indoor (520 W/m^2) measurements	Glycerol	2 mL of glycerol dissolved in 8 mL of solvent ethanol and magnetic stirring	Al_2O_3 + TiO_2	0 + 0.04, 0.02 + 0,02, and 0.03 + 0.01, respectively	1.5 mL of acetic acid glacial was added as a surfactant for the TiO_2 and magnetic stirring for 20 min at 25 °C. After adding the nanoparticles, each beaker was sonicated for 10 min at 70 Hz.
Stage 3/1 10W sized panels/indoor (850 W/m^2) measurements	Dimethyl-siloxane	25	Non		
Stage 3/2 10W sized panels/indoor (850 W/m^2) measurements	**Dimethyl-siloxane**	**25**	**Al_2O_3 TiO_2**	1.20625 gm for each alone	Sonication device was used for 20 min

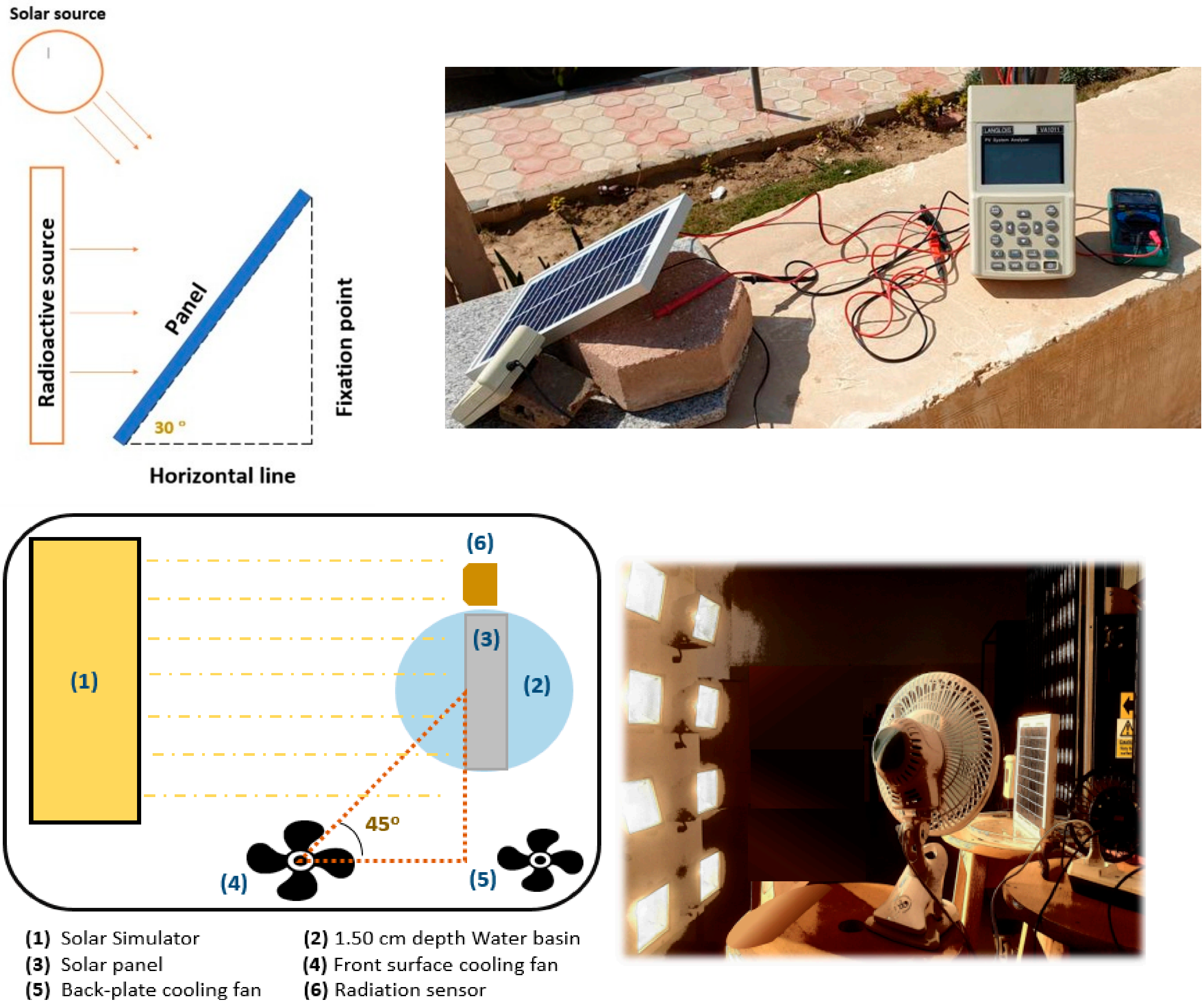

Figure 1. Experimental testing setup.

A PV solar analyser PROVA 1011 was used to measure the panels' solar radiation and electrical efficiency and develop the I–V characterisation curves. The wire sensor measured the temperature on the surface of the panels. The measurements were taken through a specified number of days for each stage of work (2 weeks for stage 1 and one month for stage 2 for each coating) twice per week. The measured parameters are the short circuit current, the maximum current, the open voltage, the output power, the weather parameters, the solar radiation, and the panels' surface temperature. Each coating was evaluated by comparing the electrical efficiency of two polycrystalline panels, where one panel was coated and the other was not coated and both panels were exposed to identical radiation and time conditions.

3. Results and Discussion

3.1. The Combined Role of Polymer Matrix/Nanoparticles in Uncontrolled Radiation Conditions

At this stage, both hydrophilic and hydrophobic host matrix coating materials were used. Finally, an overall comparison for all conditions was made. Figure 2 shows a summary of the results obtained for all tested groups during that stage, where the x-axis presents the time intervals and the y-axis presents the measured electrical efficiency. As mentioned before, the comparison was based on the electrical efficiency of coated and uncoated panels exposed to identical radiation and time conditions. The exposure conditions were selected to cover both winter and mild/hot summer conditions. The main observations resulting from stage 1 showed the enhancement in electrical efficiency brought about by both paraffine and glycerol coating, through all testing conditions.

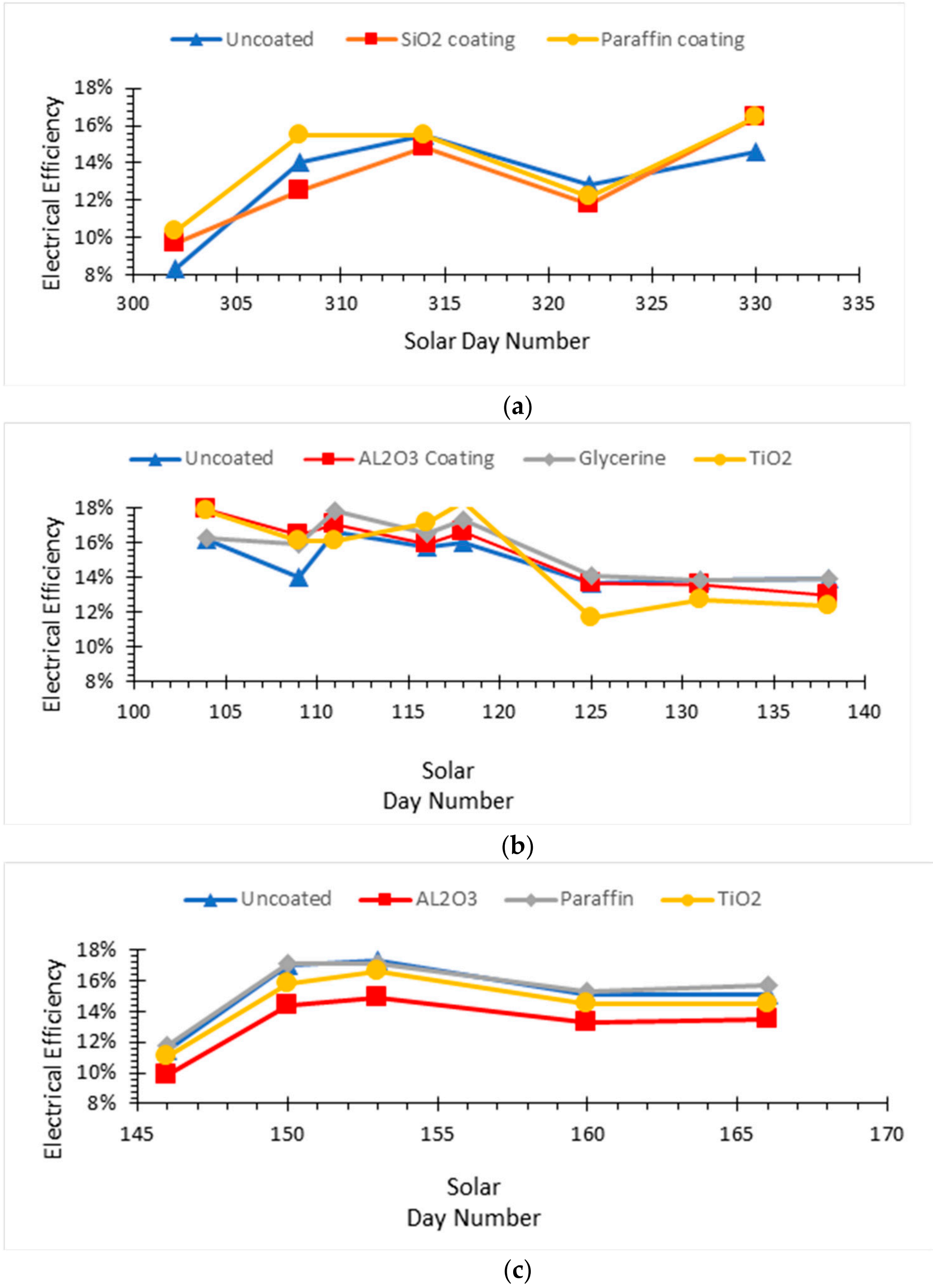

Figure 2. Electrical efficiency of stage 1 experiments. (**a**) Paraffine and SiO_2, November; (**b**) glycerine and Al_2O_3/TiO_2, April/May; (**c**) paraffine and Al_2O_3/TiO_2, June.

The addition of silicon oxide nanoparticles to paraffin resulted in higher panel electrical efficiency through the first days of application (from 14 to 16%); however, a deterioration in electrical efficiency was observed afterwards, followed by an enhancement for both panels coated with paraffine alone and paraffine with SiO_2, compared to the uncoated panel. However, since this sudden drop in electrical efficiency occurred for all three panels, it may be attributed to a drop in solar radiation during the measurement day (729 w/m^2 compared to 819 w/m^2).

The addition of aluminium oxide nanoparticles to glycerine showed improvement in the electrical efficiency during the first days (from 14 to 16%), but the electrical efficiency dropped afterwards. The same effect was observed for the titanium oxide nanoparticles when added to glycerine, but the electrical efficiency dropped even below the uncoated panel. Again, since the drop was observed for all tested panels, it is worth noticing that the solar radiation reached 822 w/m^2, compared to 900 w/m^2 during the earlier days. The glycerine with TiO_2 exhibited the highest electrical efficiency when the radiation was the highest (956 w/m^2).

The paraffine-based coatings showed slightly higher efficiencies (16–17%), and the addition of TiO_2 nanoparticles showed improved performance compared to Al_2O_3 nanoparticles, unlike the case of glycerine, where the addition of Al_2O_3 nanoparticles showed higher efficiencies. During the relevant testing period, the solar radiation was high and stable (in the range of 890 w/m^2 to 920 w/m^2). The effects brought about by using paraffine and the higher electrical efficiency of coated panels may be explained due to its heat energy storage capacity. The addition of nanoparticles could improve its low heat transfer. However, the results obtained in this work show the limited impact of adding nanoparticles on the improvement of the panels' electrical efficiency. A previous study has reported a maximum of 13% thermal conductivity enhancement in paraffine loaded by 2 wt.% MWCNT-wax sample at 35 °C. The insignificant overall improvement of thermal conductivity was attributed to the particle agglomeration and settlement associated with poor dispersion quality, and mechanical dispersion methods were reported as not sufficient to achieve the long-term stability of MWCNT-dispersed wax.

The most important observation at this stage was the interrelation between panels' electrical efficiency before and after coating with the solar radiation, which made it difficult to obtain a mere analysis of the effects of the coating materials. The work during stage 1 has also shown that using an either monolithic hydrophobic or hydrophilic coating as the hosting matrix results in an improvement in the electrical efficiency, but the role of nanoparticles TiO_2 and Al_2O_3 addition needs further investigation, due to the obtained discrepancies in the efficiencies. The observed fluctuation in results is linked to outdoor weather conditions that are variant between stable weather conditions, sandstorms, and rain. It was also observed that the paraffine-based coatings showed higher efficiencies all through, compared to the glycerine-based coatings, especially at higher solar radiations.

3.2. The Combined Role of Glycerol Matrix/Nanoparticles in Controlled Radiation Conditions

Glycerol was used as the host matrix for this stage with Al_2O_3 and TiO_2 nanoparticles. Four different panels were installed outdoors fixed at a tilt angle of 30° in a location with a latitude of 30.144212 and a longitude of 31.639718. The experiments were conducted throughout the 2 months of November and December, which only affected the dusting conditions, as the measurements were made indoors under controlled radiation conditions. The panels were left outdoors in natural environmental soiling conditions. In these experiments, the electrical efficiency was measured under controlled simulated radiation conditions equivalent to 520 W/m^2. The results are shown in Figure 3. The results show that the changes in the measured efficiencies were limited at the beginning of the experiments (when the coating was newly applied), probably because of a decline in the light transmittance after coating. However, when the panel became soiled over time, the coated panels showed slightly higher efficiencies (rise from 10 to 11%). The lowest electrical efficiency was observed when TiO_2 was used alone (coating 1), while the highest electrical efficiency was measured when Al_2O_3 and TiO_2 were used (coating 3). This may be owed to the high optical band gap of TiO_2 in the ultraviolet region, which reduces its ability to capture enough energy required to activate the photocatalytic effect that could later degrade the organic dust. Improvement was achieved when alumina Al_2O_3 with high composition was added to the TiO_2, as it reduced the optical band gap, which resulted in a good photocatalytic effect [45–47].

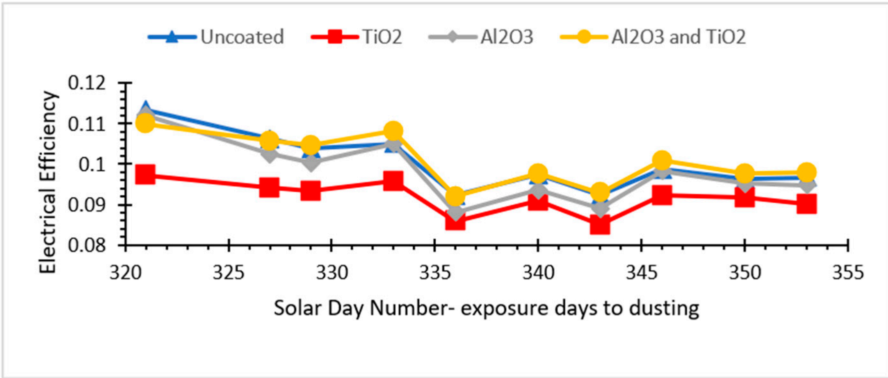

Figure 3. A comparison of the electrical efficiency of glycerol matrix/nanoparticles.

3.3. The Combined Role of Dimethyl-Siloxane Matrix/Nanoparticles in Controlled Radiation Conditions

To avoid the negative impacts on solar absorbance brought about by nanoparticles, dimethyl-siloxane (due to its optical transparency) was used as the host matrix for this stage. Figure 4 shows the results obtained during this stage of the work for the comparison of the electrical efficiency of uncoated and coated panels and the surface temperature variations for both panels. An overall enhancement in electrical efficiency (in the range 11.96–14.49% for the coated vs. 12–14% for the uncoated) was observed for the panels coated with monolithic dimethyl-siloxane.

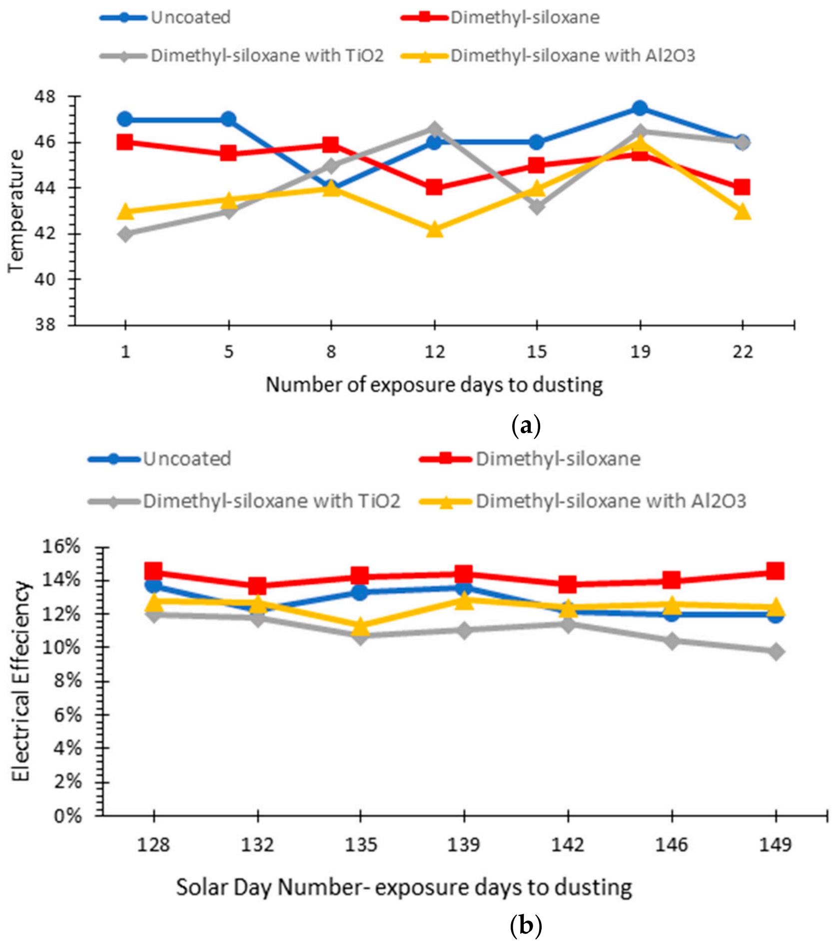

Figure 4. (**a**) Temperature for uncoated and coated panels with dimethyl-siloxane. (**b**) Electrical efficiency.

The experiments presented in Figure 4 were conducted through May and June, which only affected the dusting conditions, as the measurements were indoors under controlled radiation conditions. The experiments included four panels (uncoated and coated with dimethyl-siloxane with and without additions). The results revealed a slight change in the electrical efficiency of the panels coated with nanoadditions (in the range 12.3–13.7%) throughout the testing period under a fixed radiation of 850 W/m^2. The addition of Al_2O_3 and TiO_2 nanoparticles to the dimethyl-siloxane did not result in any significant improvement in the overall electrical efficiency of the panels. It is also worth observing the effect of the dimethyl-siloxane coating on reducing the temperature of the panel surface.

Finally, the surface temperature measurements revealed that the coated panels showed lower surface temperatures than the uncoated panels, in agreement with the electrical efficiency. The results indicate the correlation between surface temperature and electrical efficiency. The higher electrical efficiency after coating can be attributed to the hydrophobic nature of the siloxane functional group that repels water, expelling the dust through the formed water droplets [47,48].

4. Discussion

This work presents experimental results for different strategies for developing hybrid active/passive coatings with self-cleaning actions for PVs based on hydrophobic/hydrophilic polymeric matrices reinforced with ceramic nanoparticles. The strategy behind this hybridisation is to develop coatings that can hold soiling material and result in a drop in the surface temperature of the panels, simultaneously. The polymeric host materials investigated through this study include hydrophobic-based coatings using paraffine and dimethyl-siloxane and monolithic hydrophilic-based coatings using glycerol. The different investigated coatings were selected based on their good heat storage capacity due to their polymeric nature which allows them to store heat. However, to result in the aimed drop in the surface temperature of the PVs, the thermal conductivity of the polymeric host material should be improved. The addition of the nanoparticles was made to verify this requirement.

Both hydrophobic and hydrophilic polymeric coatings have the capacity for integrating the soiling particles, depending on the climatic conditions and the cleaning methods adopted later [48]. Thus, it is foreseen that different ranges of materials need to be investigated and presented to the market. The selection of the mating nanoparticles should be made to meet the final aim of the coatings. It cannot be taken for granted that all nanoparticles are suitable for different coatings, even though they have the same physical properties, especially when the wide variation in soiling particles is considered in different parts of the world [2,6,12,20]. The surface can be modified to become hydrophobic and repel the water which will carry the dust on its way, or the surface can be modified to become hydrophilic and disperse the water, preventing the soils from sticking. In general, the fabrication of the self-cleaning coating requires two main components: (a) choosing a matrix material with a low surface energy in the case of superhydrophobic coating or with a high surface energy in the case of superhydrophilic coating and (b) the addition of nanoparticles to make a controlled rough surface [15].

Among nanoparticles, TiO_2 is characterised by its photocatalytic property. This property is activated once the light beams hit the solar panel surface, initiating a photochemical reaction. Due to its wide band gap, titanium dioxide can be used as a photocatalyst under ultraviolet radiation only. The best photocatalyst is one that can be used under visible light as well as ultraviolet light because sunlight is mainly composed of visible light. It has wide application value in many fields due to its excellent structural, optical, and chemical properties. The nanoparticles of titanium dioxide (TiO_2) are commonly used in sunscreens as protection against ultraviolet radiation. Partly because the particles are so small, nanoscale TiO_2 does not reflect visible light and absorbs UV light, allowing for a transparent barrier that shields the skin from harmful solar rays. Moreover, nanometre-sized titanium dioxide (TiO_2) is an environmentally friendly optical semiconductor material.

Al_2O_3 is characterised by its high thermal conductivity and its transparency in the visible light spectrum.

This work has shown that monolithic hydrophilic-based coatings using glycerol reinforced with Al_2O_3 and TiO_2 show insignificant improvement in the electrical efficiency of PV panels, where their combination with TiO_2 and Al_2O_3 nanoparticles provided higher electrical efficiency. Whereas monolithic hydrophobic-based coatings using paraffine and dimethyl-siloxane showed higher improvement in the electrical efficiency of PV panels, the effect remained through the 30 measuring days. The role of the addition of TiO_2 and Al_2O_3 nanoparticles was not proven through this work, due to the obtained discrepancies in the efficiencies found in this work. Compared with the uncoated panel, a reduction in the surface temperature of the coated panel was found for hydrophobic-based coating using dimethyl-siloxane. The results also show measurable variations in the obtained results with solar radiation and natural soiling exposure period.

5. Conclusions

In this work, PV passive coatings based on hydrophobic/hydrophilic polymeric matrices reinforced with ceramic nanoparticles are investigated. The obtained results show the following conclusions:

1. Monolithic hydrophobic-based coatings using paraffine with TiO_2 nanoparticles addition showed 14–17% PV electrical efficiency and 11.4–14.3% using paraffin with SiO_2 additions. The effect remained through the 30 measuring days. The role of nanoparticles TiO_2 and Al_2O_3 addition needs further investigation, due to the obtained discrepancies in the efficiencies.
2. Monolithic hydrophilic-based coatings using glycerol reinforced with Al_2O_3 or TiO_2 show insignificant improvement in the electrical efficiency of PV panels, where the combined addition of TiO_2 and Al_2O_3 nanoparticles provided higher electrical efficiency maintained at about 9.3–10.8%.
3. Hydrophobic-based coatings using dimethyl-siloxane maintained the PVs' electrical efficiency at about 14–15% and resulted in a reduction in the surface temperature of the coated panel compared with the uncoated panel.
4. The results open the door for more investigations, leading to modifications in the industry of the glass panels to integrate the coating materials.

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References

1. Al-Maamary, H.M.S.; Kasem, H.A.; Chaichan, M.T. The impact of oil price fluctuations on common renewable energies in GCC countries. *Renew. Sustain. Energy Rev.* **2013**, *75*, 989–1007. [CrossRef]
2. Darwish, Z.A.; Kasem, H.A.; Sophian, K.; Alghoul, M.A.; Chaischan, M.T. Effect of Dust on Photovoltaic Performance: Review and Research Status. In Proceedings of the Latest Trends in Renewable Energy and Environmental Informatics, Kuala Lumpur, Malaysia, 2–4 April 2013; pp. 152–159. [CrossRef]
3. Fan, S.; Wang, X.; Cao, S.; Wang, Y.; Zhang, Y.; Liu, B. A novel model to determine the relationship between dust concentration and energy conversion efficiency of photovoltaic (PV) panels. *Energy* **2022**, *252*, 123927. [CrossRef]
4. Fan, S.; Liang, W.; Wang, G.; Zhang, Y.; Cao, S. A novel water-free cleaning robot for dust removal from distributed photovoltaic (PV) in water-scarce areas. *Sol. Energy* **2022**, *241*, 553–563. [CrossRef]
5. Adinoyi, M.J.; Said, S.A.M. Effect of dust accumulation on the power outputs of solar photovoltaic modules. *Renew. Energy* **2013**, *60*, 633–636. [CrossRef]
6. Chanchangi, Y.N.; Ghosh, A.; Sundaram, S.; Mallick, T.K. Dust and PV Performance in Nigeria. *Renew. Sustain. Energy Rev.* **2020**, *121*, 109–787. [CrossRef]
7. IRENA. Renewable Energy Statistics. 2020. Available online: https://irena.org/publications/2020/Jul/Renewable-energy-statistics-2020 (accessed on 16 June 2022).
8. Dida, M.; Boughali, S.; Bechki, D.; Bouguettai, H. Output power loss of crystalline silicon photovoltaic modules due to dust accumulation in Saharan environment. *Renew. Sustain. Energy* **2020**, *124*, 109–787. [CrossRef]
9. Dorobanţu, L.; Popescu, M.; Popescu, C.; Craciunescu, A. The effect of surface impurities on photovoltaic panels. *Renew. Energy Power Qual.* **2017**, *11*, 622–626. [CrossRef]
10. Elminir, H.K.; Hamid, A.E.G.R.H.; El-Hussainy, F.; Beheary, M.M.; Abdel-Moneim, K.M. Effect of dust on the transparent cover of solar collectors. *Energy Convers. Manag.* **2006**, *47*, 3192–3203. [CrossRef]
11. Essalaimeh, S.; Al-Salaymeh, A.; Abdullat, Y. Electrical production for domestic and industrial applications using hybrid PV-wind system. *Energy Convers. Manag.* **2013**, *65*, 736–743. [CrossRef]
12. Guo, B.; Javed, W.; Figgis, B.W.; Mirza, T. Effect of dust and weather conditions on photovoltaic performance in Doha, Qatar. In Proceedings of the First Workshop on Smart Grid and Renewable Energy (SGRE), Doha, Qatar, 22–23 March 2015; pp. 1–6.
13. Sweelem, E.A.; Shenawy, E.T.; Nafeh, A.E.A. Effect of Different Dust Accumulation on the Performance of PV Module in Egypt. *Int. J. Adv. Inf. Sci. Technol. (IJAIST)* **2015**, *44*, 44.
14. He, G.; Zhou, C.; Li, Z. Review of Self-Cleaning Method for Solar Cell Array. *Procedia Eng.* **2011**, *16*, 640–645. [CrossRef]
15. Kobrin, B. *Self-Cleaning Technologies for Solar Panels*; n-tech Research Publication: Glen Allen, VA, USA, 2018; p. 15.
16. Chaichan, M.T.; Kazem, H.A. Experimental analysis of solar intensity on photovoltaic in hot and humid weather conditions. *Int. J. Sci. Eng.* **2016**, *7*, 91–96.
17. Al-Waeli, A.H.A.; Chaichan, M.T.; Kazem, H.A.; Sopian, K.; Ibrahim, A.; Mat, S.; Ruslan, M.H. Comparison study of indoor/outdoor experiments of a photovoltaic thermal PV/T system containing SiC nanofluid as a coolant. *Energy* **2018**, *151*, 33–34. [CrossRef]
18. Bayoumi, A.; Nosier, M.A.; Abdelatiff, O.E.; Mahmoud, N.A.; Khalil, A.S.G. Modeling and simulation of a photovoltaic/thermal hybrid system using different back-pipe structures. In Proceedings of the 11th International Conference on Computer Engineering & Systems (ICCES), Cairo, Egypt, 20–21 December 2016; pp. 489–494.
19. NREA. *12th NREA Meter*; New and Renewable Energy Authority: Cairo, Egypt, 2022.
20. Alami, A.H.; Rabaia, M.K.H.; Sayed, E.T.; Ramadan, M.; Abdelkareem, M.A.; Alasad, S.; Olabi, A.-G. Management of potential challenges of PV technology proliferation. *Sustain. Energy Technol. Assess.* **2022**, *51*, 101942. [CrossRef]
21. IRENA. *Renewable Energy Statistics 2021*; International Renewable Energy Agency: Abu Dhabi, The United Arab Emirates, 2021.
22. IRENA. *Renewable Energy Outlook*; Egypt International Renewable Energy Agency: Abu Dhabi, The United Arab Emirates, 2018.
23. NREA. *Annual Report 2020*; New and Renewable Energy Authority: Cairo, Egypt, 2020.
24. NREA. *Annual Report 2018*; New and Renewable Energy Authority: Cairo, Egypt, 2018.
25. NREA. *Annual Report 2021*; New and Renewable Energy Authority: Cairo, Egypt, 2021.
26. RCREEE. *Market Assessment Study of Socio-Economic Impacts for Solar Pumping Systems in Terms of Local Job and Value Creation in Egypt*; Regional Center for Renewable Energy and Energy Efficiency: Cairo, Egypt, 2017.
27. Abdelkareem, M.; Assad, M.E.; Sayed, E.; Soudan, B. Recent progress in the use of renewable energy sources to power water desalination plants. *Desalination* **2018**, *435*, 97–113. [CrossRef]
28. Maghrabie, H.; Elsaid, K.; Sayed, E.; Abdelkareem, M.; Wilberforce, T.; Olabi, A. Building-integrated photovoltaic/thermal (BIPVT) systems: Applications and challenges. *Sustain. Energy Technol. Assess.* **2021**, *45*, 101151. [CrossRef]
29. Boghdady, T.; Alamer, A.; Yousef, M.; Elshafee, A.; Hassan, M.; Seif, A. Technical and Economic Study of Powering Poultry Farm in Egypt Using PV-Biomass on-grid Energy Generation System: Case Study. *Environ. Sci.* **2021**, *16*, 67–77. [CrossRef]
30. Seddiek, I. Application of renewable energy technologies for eco-friendly sea ports. *Ships Offshore Struct.* **2019**, *15*, 953–962. [CrossRef]
31. Salah, S.; Eltaweel, M.; Abeykoon, C. Towards a sustainable energy future for Egypt: A systematic review of renewable energy sources, technologies, challenges, and recommendations. *Clean. Eng. Technol.* **2022**, *8*, 100497. [CrossRef]

32. El-Sybaee, I.; El-keway, A.; Elmeadawy, M.; Abdel-Maksoud, M. Study the effect of dust deposition on solar photovoltaic and solar radiation. *Misr J. Agric. Eng.* **2018**, *35*, 1397–1408. [CrossRef]
33. Pan, A.; Lu, H.; Zhang, L. Experimental investigation of dust deposition reduction on Solar Cell covering glass by different self-cleaning coatings. *Energy* **2019**, *181*, 645–653. [CrossRef]
34. Kazem, H.A.; Chaichan, M.T.; Al-Waeli, A.H.A.; Sopian, K. Effect of dust and cleaning methods on mono and polycrystalline solar photovoltaic performance: An indoor experimental study. *Sol. Energy* **2022**, *236*, 626–643. [CrossRef]
35. De Jesus, M.A.M.L.; Timò, G.; Agustín-Sáenz, C.; Braceras, I.; Cornelli, M.; Ferreira, A.d. Anti-soiling coatings for solar cell cover glass: Climate and surface properties influence. *Sol. Energy Mater. Sol. Cells* **2018**, *185*, 517–523. [CrossRef]
36. Solar Sharc. Available online: https://solarsharc.com/about/ (accessed on 12 May 2022).
37. Sutha, S.; Suresh, S.; Raj, B.; Ravi, K.R. Transparent alumina based superhydrophobic self–cleaning coatings for solar cell cover glass applications. *Sol. Energy Mater. Sol. Cells* **2017**, *165*, 128–137. [CrossRef]
38. Mozumder, M.S.; Mourad, A.I.; Pervez, H.; Surkatti, R. Recent developments in multifunctional coatings for solar panel applications. *Sol. Energy Mater. Sol. Cells* **2019**, *189*, 75–102. [CrossRef]
39. Agyekum, E.B.; Praveen Kumar, S.; Alwan, N.T.; Velkin, V.I.; Shcheklein, S.E.; Yaqoob, S.J. Experimental Investigation of the Effect of a Combination of Active and Passive Cooling Mechanism on the Thermal Characteristics and Efficiency of Solar PV Module. *Inventions* **2021**, *6*, 63. [CrossRef]
40. Agyekum, E.B.; PraveenKumar, S.; Alwan, N.T.; Velkin, V.I.; Adebayo, T.S. Experimental Study on Performance Enhancement of a Photovoltaic Module Using a Combination of Phase Change Material and Aluminum Fins—Exergy, Energy and Economic (3E) Analysis. *Inventions* **2021**, *6*, 69. [CrossRef]
41. Sarkin, A.S.; Ekren, N.; Saglam, S. A review of anti-reflection and self-cleaning coatings on Photovoltaic Panels. *Sol. Energy J.* **2020**, *199*, 63–73. [CrossRef]
42. Elshazly, E.; El-Rehim, A.A.; El-Mahallawi, I. Comparison of dust and high-temperature effects on mono and poly photovoltaic panels. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1172*, 012019. [CrossRef]
43. Elshazly, E.; El-Rehim, A.A.A.; Kader, A.A.; El-Mahallawi, I. Effect of Dust and High Temperature on Photovoltaics Performance in the New Capital Area. *WSEAS Trans. Environ. Dev.* **2021**, *17*, 360–370. [CrossRef]
44. Heller, A. Chemistry and Applications of Photocatalytic Oxidation of Thin Organic Films. *Acc. Chem. Res.* **1995**, *28*, 503–508. [CrossRef]
45. Sydam, V.; Duan, X. Different nanoparticles in paraffin wax as enhanced phase change materials. *J. Therm. Anal. Calorim.* **2019**, *135*, 360–370.
46. Chien, D.M.; Viet, N.N.; Kieu, V.N.T.; Phong, P.N.T. Characteristics modification of TiO2 thin films by doping with silica and alumina for self-cleaning application. *J. Exp. Nanosci.* **2019**, *4*, 221–232. [CrossRef]
47. Syafiq, A.; Pandey, A.K.; Balakrishnan, V.; Abd Rahim, N. Study on self-cleaning performance and hydrophobicity of TiO_2/silane coating. *Pigment. Resin Technol.* **2018**. *ahead-of-print*. [CrossRef]
48. Ragesh, P.; Ganesh, V.A.; Naira, S.V.; Nair, A.S. A review on 'self-cleaning and multifunctional materials'. *Mater. Chem. A* **2014**, *2*, 14773. [CrossRef]