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Photocatalytic, self-cleaning, antireflective coating for photovoltaic panels: Characterization and monitoring in real conditions

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ABSTRACT

A major problem in the operation of photovoltaic (PV) panels is the need for frequent maintenance and cleaning. In the present work, the effect of a self-cleaning, photocatalytic, antireflective glass coating on the efficiency of PV panels is investigated. The optical and photocatalytic properties of the coating were determined via UV–vis spectroscopy and degradation of organic pollutant Methylene Blue, respectively. Increased light transmittance in the visible light region and enhanced self-cleaning of the coated in comparison to the uncoated glass was demonstrated. The adhesion and the stability of the coating were tested in conditions of thermal fluctuations, UV weathering and sandblasting.

The outdoor performance of coated and uncoated PV panels and arrays were monitored for several months at different climate conditions (Greece and China) in order the extra energy produced due to coating to be measured. An average 5–6% gain was found for both cases for the entire period of time. It was established that specific conditions such as intensity and angle of the incident light, occurrence of rain and sand storms influence significantly the power difference (ΔPm) between coated and uncoated PV panels. The increase of ΔPm under diffused light (cloudy day) and irradiation with high incident angle (morning, evening) reached ~20% and 30% respectively, that were related to the anti-reflecting property of the glass coating. The coated surface showed better dust removal ability due to its superhydrophilicity ($\theta = 6°$). The superior efficiency of coated panels as well as the low-cost spraying procedure without any post-deposition treatment render the nanocomposite SurfaShield G coating very important especially for northern regions with limited sunlight periods.

1. Introduction

For the last decades, a lot of research has been focused on increasing the efficiency of solar cells, so as to take advantage of the naturally available sunlight for producing electricity. The research has primarily been focused on the increase of the semiconductor's efficiency, while assessing and reducing the impact of outdoor conditions on the panel efficiency is currently gaining more attention (Gaglia et al., 2017; Jelle et al., 2016). A real practical problem after installation such as the efficiency loss due to dust or stains depositing on the panel's surface is not much investigated (Mani and Pillai, 2010; Costa et al., 2016). The reported information on PV output energy reduction due to dust accumulation varies in the very wide range of 4.4–80% (El-Shobokshy and Hussein, 1993a, 1993b; Mastekbayeva and Kumar, 2000; Kalogirou et al., 2013; Zorrilla-Casanova et al., 2011). It has been documented that dust setting/accumulation is strongly dependent on the orientation, the slope, and the characteristics of panel like surface roughness, type of coating, etc. Energy losses caused by soiling and irradiance incidence angle were reported to be much higher in fixed horizontal panels (8–22%) than the losses in the 45° tilted panels (1–8%) (Garcia et al., 2011). Also, external parameters like temperature, humidity, wind speed, regional characteristics such as plants, traffic and air pollution play an important role in dust deposition. In addition, the chemical, biological and electrostatic properties of the dust as well as the size, weight and shape of the particles influence their accumulation on the panel surface (Mani and Pillai, 2010; Zaihidee et al., 2016). Several techniques have been employed to counteract the effect of dust accumulation such as well-established, low-cost dry-cleaning using manual

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and robotic systems (Shehri et al., 2016). New research stage technologies like water repellent microshell structures (Park et al., 2011), electrostatic curtains (Mazumder et al., 2013) etc. have been reported as well. Self-cleaning antireflective (Sakhuja et al., 2014), superhydrophilic (Son et al., 2012) and superhydrophobic (Mehmood et al., 2016) glass surfaces have been proposed to reduce dust accumulation and achieve enhanced outdoor performance of the PV units.

In general, thin films have been intensively investigated for application on photovoltaics (Faustini et al., 2010; Heft et al., 2007; Min et al., 2008). A moth-eye anti-reflective structure has been fabricated (Lee et al., 2013) by a complex method (hot-embossing and UV nanoimprint lithography) followed by a hydrophobic self-assembled monolayer. Compared to the solar panels covered with plain glass, the total increase in accumulated electrical energy of coated solar cells were 3.9% and 3.4%, after monitoring for 4 days. It has been stated (Sakhuja et al., 2014) that nanostructured glass substrates with self-cleaning and antireflective properties subjected to an outdoor exposure for 12 weeks at different angles of inclination showed improvement in performance of solar modules by only an insignificant drop of 0.3% in efficiency relative to a 2% drop in a planar glass solar module over a long-term exposure period. Comparative study (Son et al., 2012) on coated panels in terms of properties and solar cell performance during an outdoor test for 12 weeks revealed that solar cells with bare and fluorinated superhydrophobic glass exhibited a 7.79% and 2.62% efficiency drop, respectively, while solar cell with nanopatterned, superhydrophilic glass without surface treatment exhibited efficiency drop of only 1.39%. Single and multiwall carbon nanotubes have also been employed to enhance the antireflective and self-cleaning properties of the coatings in order the efficiency of solar sell to be improved (Hanaei et al., 2016).

In a different approach, the increase of the PV efficiency has been pursued by employing photocatalytic coatings to utilize the incident solar irradiation and provoke self-cleaning of the panel surface. When activated by UV radiation, titania (TiO_2) treated surfaces react with humidity and oxygen from the environment (Fujishima et al., 1999) granting photo-induced superhydrophilicity, self-sterilizing and antimicrobial (Carneiro et al., 2007; Fu et al., 2005; Sakkas et al., 2004) ability. Composite TiO_2/SiO_2 thin films have been applied on PV module by spraying to increase the produced electrical power through self-cleaning. Although the light absorption was not reduced, the self-cleaning behavior was rather low, which was related to the low thickness of the coating and the local atmospheric conditions (Yu et al., 2007). In addition, the TiO_2-containing coatings are considered promising as they can contribute to the purification of the air near the PV plants by photocatalytic oxidation of gaseous pollutants like Volatile Organic Compounds and nitric oxides NOx (Dalton et al., 2002; Karapati et al., 2014; Soklic et al., 2015; Todorova et al., 2015).

The effect of anti-reflective and anti-soiling coating on polycrystalline PV modules exposed outdoors for one year at Spain have been evaluated when using an anti-soiling coating product by Asahi Kasei Corporation (Piliougine et al., 2013). During the one-year exposure period, the coated PV modules demonstrated an average daily soiling loss of 2.5%, while uncoated modules a daily average of 3.3%.

Although thin films properties have been intensively studied the publications on their effect on the PV panel's performance due to their photocatalytic self-cleaning and antireflective behavior are limited. In this work, the effect of a self-cleaning, antireflective coating on PV panels is presented. The formulation used for coating of the glass surface is produced by NanoPhos S.A. The product is known under the brand name SurfaShield G (SSG) with the SurfaShield® to be a registered trademark of the company (NanoPhos, 2017). The SSG is a water-based suspension which after application on glass creates an inorganic, nanostructured coating chemically bonded to the substrate. SurfaShield G contains metal oxides mixture mainly of nano-crystalline anatase/rutile titania (TiO_2) anchored with silica (SiO_2) nano-bridges. It is applied on glass surfaces using a simple air-sprayer and the coating does not need any thermal treatment in order to obtain good adhesion on glass. Notably, the coating can be easily reapplied when required. The novelty of this work is in the formulation of suspension for direct coating of glass surfaces on functioning and brand new PV panels that increase their efficiency in real conditions due to obtained high transparency, self-cleaning and antistatic properties along with air purification from organic and inorganic pollutants. To the best of our knowledge, coating formulation and application approach analogous to the SurfaShield G have not been reported in the literature.

This contribution aims in presenting the optical, self-cleaning properties and stability of the coating determined in laboratory conditions. Also, coated and uncoated PV units functioning in real conditions were monitored within 7 months in Attica (Greece) and 5 months in Neimeng province (China). The recorded variation of energy output difference is discussed in relation with the PV surface properties and the atmospheric conditions.

2. Experimental details

2.1. Coating deposition

The liquid SSG product was deposited on the glass substrates by sprayer Z-020-Tornador BLACK with consumption rate 60 m^2/L. The coated surfaces were left for curing at ambient conditions for at least 24 h before assessment.

Glass samples with dimensions 300 mm × 300 mm by Ying Li Solar were half treated in order the coated and uncoated areas to be simultaneously investigated.

2.2. Characterization and in-door testing of the coating

The morphology of the coating and the uncoated glass surface were examined using scanning electron microscope (SEM) Hitachi S4700 operating at 20 kV. The light transmittance of the coated and uncoated glass samples was measured within the wavelength range 300–2200 nm using a Perkin Elmer Lambda 19 Spectrophotometer.

The thickness of the coating was measured via White Light Reflectance Spectroscopy employing FR-Basic VIS/NIR (Theta Metrisis) instrument. The refractive index of the coating was measured by a spectroscopic ellipsometer J.A. Woollam Co. Inc., M-2000FI using the Cauchy dispersion model.

The samples with coated and uncoated areas were subjected to multiple thermal fluctuations, UV weathering and sandblasting adhesion tests to determine their stability upon temperature variation and exposure to UV and sand attack. Thus, thermal cycle test has been conducted in accordance with IEC 61215 10.11. The applied range of temperature fluctuations was from −40 °C ± 2 °C to +85 °C ± 2 °C and the number of changes (cycles) was 200 times. UV weathering was performed in accordance with IEC 61215 10.10. The samples were exposed to irradiation with intensity 60 kWh/m^2 in the wavelength range between 280 nm and 385 nm and at least 5 kWh/m^2 in the range between 280 nm and 320 nm. The temperature was maintained within 60 °C ± 5 °C. The sand blasting tests were conducted in a sand test chamber according to IEC 60668-2-68. The quantity/speed of the dust and the position of the glass samples in the chamber were adjusted to simulate specific weathering conditions. Four combination of key parameters such as particles' diameter, wind speed and duration, defined as conditions C1-C4 (Table 1) were selected for testing.

The hydrophilicity of the surfaces was estimated through the contact angle between a water drop and the glass surfaces. The measurements were performed using an optical tensiometer (Attension KSV Instruments). The photocatalytic activity of the coating was estimated by the degradation of model pollutant Methylene Blue (MB). 5 mg of MB powder were dissolved in 500 mL of water and 200 μL of the obtained solution were deposited on both coated and uncoated area of a half-coated glass specimen. The specimen was irradiated for 30 min in a

Table 1
Sand test conditions.

Conditions	Dust type	Particles' diameter (μm)	Wind speed (m/s)	Test duration (h)
C1	Talk	100	2	4
C2	Talk	100	5	8
C3	Quartz	200	5	8
C4	Quartz	200	10	24

solar simulator (ALLREAL Solo APOLLO) equipped with a calibrated Xenon lamp. Spectrum AM1.5 and irradiance 1000 W/m^2 were applied to simulate the exposure under real-life conditions.

2.3. Power generation performance at outdoor exposure

The outdoor power generation performance was evaluated using two different experimental set-ups. In the one set-up, the evaluation of PV panels (without inverters) was targeted. Two brand new panels were directly connected to two identical resistances able to fully consume the current produced from the PV. The tilt of the investigated panels was fixed at 32°. All the operational parameters were exactly the same except from the covering layer. The experimental analyses were conducted at the Science and Technology Park of Lavrio in Greece (φ = 37°42′). In the second set-up, the evaluation of PV system was targeted. Two arrays, one coated with SSG and one uncoated, consisted of more than 2000 panels each were used. The operational parameters were the same and the measurements were performed following standards requirements. The experimental analyses were conducted at Baoergai PV plant in China (φ = 40°45′) where the tilt of the panels was 34°. The two experimental set-ups are described in details below.

The Science and Technology Park of Lavrio is an industrial area (former silver and lead ore processing plant) located next to the sea shore. Due to the predominant windy weather and the existing soil hills nearby, heavy dusty conditions are naturally created. For the experiments, two identical, monocrystalline silicon panels were provided by Sunrise Solartech (SRM-80P). Each panel consists of 36 cells with dimensions 125 mm × 125 mm, maximum power Pm = 80 W, maximum voltage Vm = 17.8 V, maximum current Im = 4.49 A, open circuit voltage Voc = 21.6 V and short circuit current Isc = 4.91 A. The experimental set up of the panel is depicted in Fig. 1a. The PV panel inverts from 4–20 mA to 0–32000 mA and converts from 0–24 V to 0–10 V DC acting as inverter and converter, respectively. An incandescent lamp was placed to provide a load. It should be mentioned that the created special load curve may mask the effect of higher operating temperature and thus reduced performance improvement for the treated module to be observed. The resulting data were collected using the CPU ADVANTIS and were recorded in a computer via the Power Logic ION Enterprise program. The data were recorded every minute on a daily basis and were available on the protected website of the University of Athens. The measured parameter was the output energy as a function of time. The meteorological conditions were documented by a Davis Vantage Pro2 meteorological station located next to the PV installation. The brand new panels were left to function for ~2 months and calibration data were collected to evaluate the difference in the efficiency of the panels. The difference ΔPd (%) curve is presented in Fig. 1b. The mean value was used for the normalization of the data presented in this work.

After the calibration period, both panels were carefully cleaned and one of the panels was sprayed with SSG to create a coating, while the other panel was left untreated. Both panels were exposed to the same ambient environment making sure that not only the solar irradiation but also the wind conditions are exactly the same.

The Baoergai grid-connected PV plant in China was built in 2012 with 30 MWp PV panels (HT60-156P-240) installed. It is located in west China where dry weather prevails and the area is frequently plagued by sandstorms, especially in winter and spring. Two stable 5 kWp PV arrays that had almost the same power generation in 2014 were chosen as experimental group (coated with the SSG) and control group (uncoated). The arrays were exposed to the same ambient environment with similar solar irradiation and wind conditions. Each array (more than 2000 panels) and had a capacity of 500 kW. Each panel comprised of 60 cells with dimensions 156 mm × 156 mm, maximum power Pm = 240 W, maximum voltage Vm = 30.5 V, maximum current Im = 7.87 A, open circuit voltage Voc = 37.5 V and short circuit current Isc = 8.49 A.

The experimental set up of the arrays with uncoated and coated glass surfaces is depicted in Fig. 2. The power generated from the arrays is transferred to the 110 kV grid through combiner boxes and PV inverters by Samlipower (Solar Ocean 500TL). Each array was connected to an inverter and the inverters were manufactured in the same batch to ensure the consistency. The data were collected by data-collector that was connected with PV inverters by PC and remote monitoring system and recorded daily every 15 min. The measured parameter was the output energy as a function of time.

The power difference values between the two panels/arrays per day (ΔPd) were calculated using the Eq. (1):

$$\Delta Pd\,(\%) = \frac{Pd_2 - Pd_1}{Pd_1}\cdot 100 \tag{1}$$

where Pd_1 is andPd_2 is the power produced by the uncoated panel 1/array 1, and the coated panel 2/array 2 per day.

The power difference values between the two panels/arrays per minute (ΔPm) were calculated using the Eq. (2):

$$\Delta Pm\,(\%) = \frac{Pm_2 - Pm_1}{Pm_1}\cdot 100 \tag{2}$$

where Pm_1 is and Pm_2 is the power produced by the uncoated panel 1/array 1 and the coated panel 2/array 2 per minute.

It should be mentioned that the type of the cover glass of the PV panels in Greece and China according to the manufacturers was low iron tempered glass. In each case the reference and the treated panels were from the same manufacturer and the results from the two experimental set-ups are evaluated in a complementary way.

3. Results and discussions

3.1. Coating properties

The average thickness of the coating measured by White Light Reflectance Spectroscopy at different spots was approximately 150 nm. The surface morphology of the uncoated and the coated glass is depicted in Fig. 3a and b, respectively. The SEM image of the uncoated sample revealed a typical smooth glass surface. For the coated surface, regularly arrayed nanoparticles can be observed. The coating appeared homogeneous without cracks and defects. The Energy Dispersive X-ray Spectroscopy (EDS) analysis revealed similar composition for the two surfaces toward the major elements: oxygen (~52 at.%), sodium (~12.5 at.%) and silicon (~27.5 at.%). On the coated surface, Ti element in quantity 0.21 at.% was found.

The transmission spectra of coated and uncoated glass are comparatively presented in Fig. 4. It can be observed that the light transmittance of the coated glass is significantly enhanced in comparison to the uncoated glass granting antireflective properties of the coated surface. The effect is especially prominent in the visible light range, which is important for better utilization of the incident solar irradiation by the PV units.

The measured water drop contact angle θ on the uncoated and the coated glass surfaces is evident in Fig. 5a and b, correspondingly. The θ value was reduced from 39° on the uncoated glass to 6° on the coated surface demonstrating superhydrophilic property of the latter. This

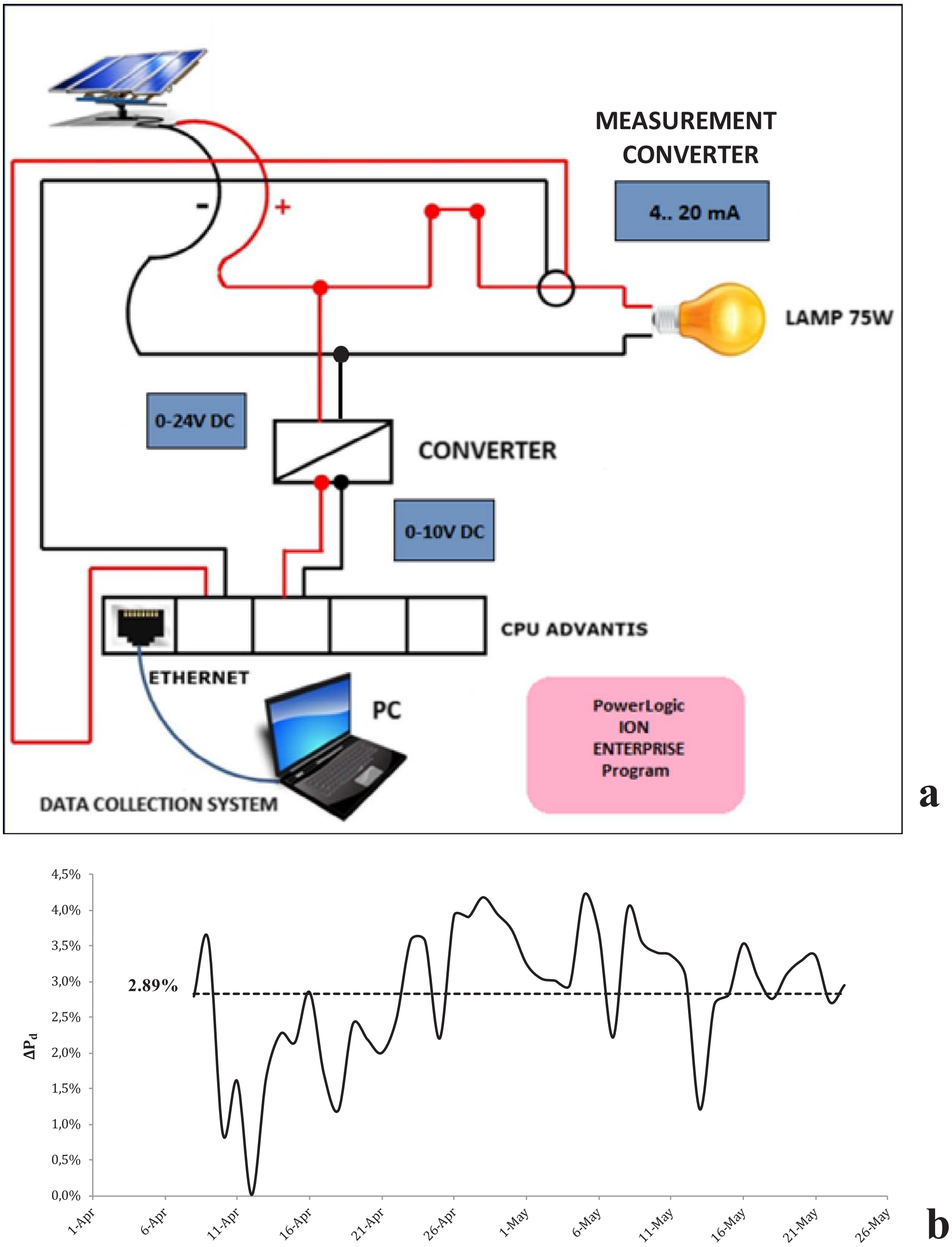

Fig. 1. Experimental set-up of the panel in Greece (a) and calibration results (b).

property allows the chemisorbed H_2O layer on the TiO_2 to attract water molecules through van der Waals forces and hydrogen bonds obstructing thus the contact between the glass surface and the adsorbed contaminants. The impurities deposited on the coated surface can be easily removed by the spreading action of water and consequently, the coated TiO_2 glass surface exhibits a self-cleaning effect (Ganesh et al., 2012).

The photocatalytic degradation of Methylene Blue on the glass surfaces under UV illumination is shown in Fig. 6. It is important to note that the concentration and the amount of MB deposited on the uncoated (a) and the coated glass (c) is the same. The lighter color on the coated surface (a) is caused by the wider spreading of the liquid due to the superhydrophilic property of the coating. After 30 min irradiation, the color intensity on the coated surface was significantly decreased in comparison to the uncoated one (d). The outcome is attributed to the photocatalytic activity of the nano-sized TiO_2 component of the coating. According to the well-established photocatalytic mechanism (Fujishima et al., 1999) the photo-generated electrons and holes reach the surface of the TiO_2 nanoparticles and participate in the formation of highly reactive radicals which attack and decompose the organic compound to inorganic CO_2 and H_2O. The photocatalytic activity tests indicate that the SurfaShield G coated PV panels are expected to exhibit self-cleaning activity towards other organic contaminants reaching the glass surface and consequently increased efficiency in solar light utilization.

3.2. In-door thermal cycling, UV weathering and blasting adhesion testing

The ability of the coating to withstand thermal shock, fatigue and other stresses caused by repeated changes of temperature was investigated by subjecting the coated glass sample to temperature fluctuations from $-40\,°C \pm 2\,°C$ to $+85\,°C \pm 2\,°C$. It was established that the multiple dramatic changes of temperature would not severely affect the structure and thus the properties of the coating. Specifically, after the 200 cycles of temperature treatment, the measured average light transmittance of the coated glass sample exhibited only a slight drop

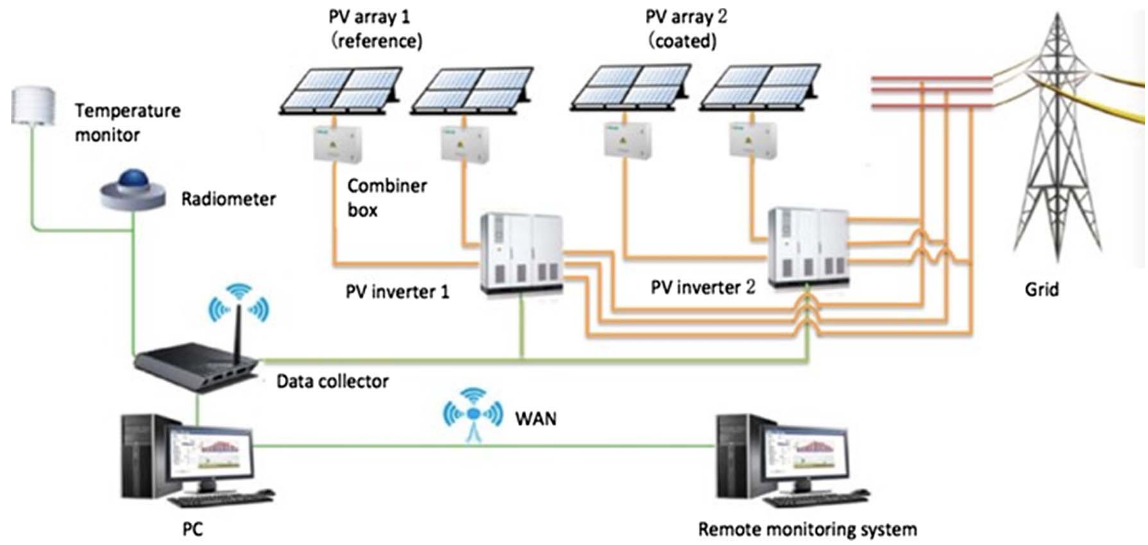

Fig. 2. Experimental set-up of the panels in China.

from 94.94% to 93.35% in the region 400 nm–1100 nm. Notably, the light transmittance after the thermal treatment was still higher than the respective value of the uncoated glass (92.58%).The exposure of the coated glass on 60 kW/m^2 dose UV irradiation decreased the average light transmittance from 95.07% to 92.20%. After the two types of testing, i.e. thermal treatment and UV irradiation, the morphology of the coating was not affected. The nanostructure and the arrangement of the nanoparticles were preserved as evidenced by the SEM images presented in Fig. 7.

A comparison of the morphology of coated samples exposed to indoor sandblasting at different conditions is presented in Fig. 8.

From the SEM images it can be perceived that the sand with diameter 100 μm did not affect the coating when the wind speed is less than 5 m/s and the testing duration is less than 8 h (Conditions 1). On the contrary, the stability of the coating was significantly reduced when the sandblasting parameters became more severe. Specifically, the structure and the adhesion of the coating appeared disrupted after blasting with sand larger than 100 μm, wind speed higher than 5 m/s and time period more than 8 h (Conditions 4).

3.3. Outdoor power generation performance of PV panels

The power per minute difference (ΔPm) and the intensity of the incident solar irradiation (R) recorded during a sunny day right after coating in Attica Greece (Fig. 9a) revealed that ΔPm between the coated and uncoated panels during the day is constant at ~6%, while the ΔPm reaches an increase up to 30% during the morning and the evening hours. This outcome can be attributed to the antireflective properties of the coated glass surface that utilized the sunlight irradiation with high incident angle (Fig. 9b). Since one of the components of the SSG coatingTiO_2 is known to have high refractive index, the increase of the light transmittance can be explained by the relation between the

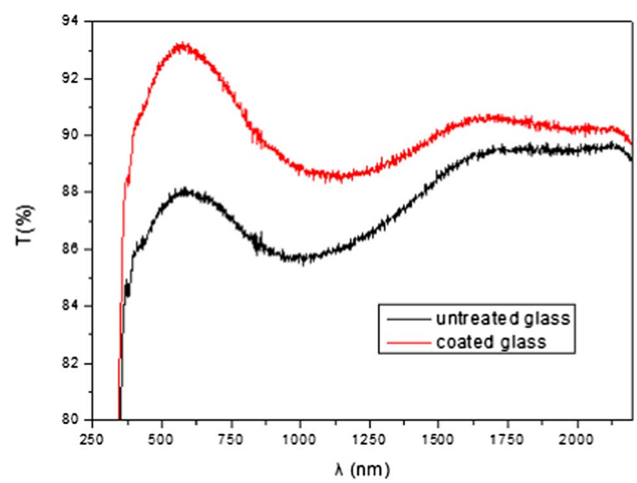

Fig. 4. Transmission spectra of coated and uncoated glass.

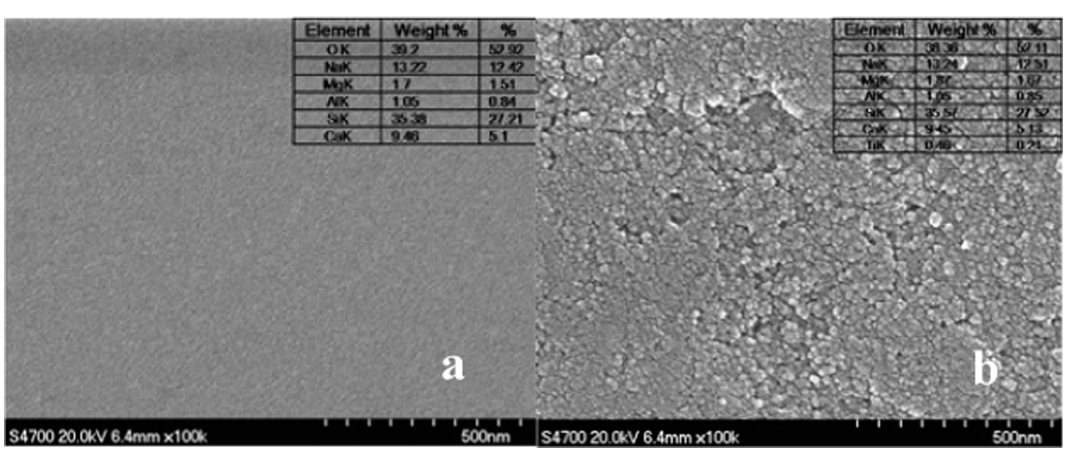

Fig. 3. SEM images and EDS results of uncoated (a) and coated (b) glass surface.

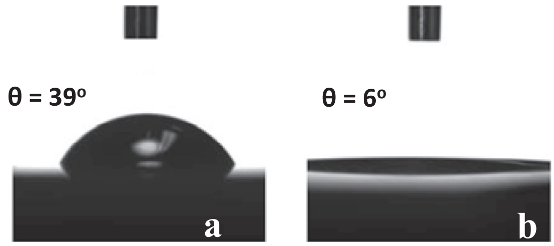

Fig. 5. Contact angle between water droplet and (a) uncoated glass and (b) coated glass.

refraction indexes of the two media, i.e. air and glass surface (3):

$$n_1\ sin\theta_1 = n_2\ sin\theta_2 \tag{3}$$

where n_1 and n_2 are the refraction indexes of the air and the glass respectively; θ_1 is the angle of incidence and θ_2 is the angle of refraction.

It is known that the refractive index of the air (n_1) is 1.00 and the refractive index of uncoated soda lime glass (n_2) is 1.51. The measured refractive index of the coating ($n_{2'}$) was 1.47 which is lower than that of the uncoated glass. Consequently, during the morning and evening, when the incident sunlight angle obtained high values, the smaller $\theta_2{}'$ caused by lower index of the coating could ensure higher light transmition leading to increased power output.

The antireflective behavior of the coating exhibited during a sunny day in the morning and evening when sunlight is limited, can be noted during a cloudy day as well (Fig. 9c). The explanation is based on the altering of the surface roughness. The uncoated PV panel glass exhibited sub-micron roughness i.e. between 200 and 300 nm, while the roughness of the coated surface was between 40 nm and 60 nm. After application, the nanoscaled particles fill up the gaps on the glass creating nano-roughness and pores which help the panel to trap more scattered and diffused light. Therefore, for the cloudy days with higher component of scattered and diffused light, the transmition of light through the glass is higher.

The effect of dust accumulation on the power generation of the PV panels can be assessed by comparing two sunny days with time difference ~70 days. The selected days were in June and August that is day 16th and day 83rd after coating application, respectively. The type of the ΔPm curves (Fig. 9d) is similar revealing large ΔPm values for the morning and evening hours and lower ΔPm values stable during the rest of the day. It is evident that the average 5% power difference recorded at 17/06 (day 16th) increased to 9% at 26/08 (day 83th). It must be underlined that there was no rain between the two dates which practically means that the larger difference in power generation between the coated and uncoated panels is caused by dust accumulation on the uncoated panel.

The power difference ΔPd between the two PV panels for each day of the monitored period (from June to December) is presented in Fig. 10. It can be observed that from the very first day of application (1stof June) there is an increase of 2.43%, which is undoubtedly due to the antireflective property of the coating as both of the panels were clean.

It is important to evaluate the change in power ΔPd with respect to the weather conditions. At the beginning of the monitored period (during the summer), the ΔPd values revealed a moderate power increase of ~5%. Dust accumulation was observed on the uncoated panel only demonstrating the antistatic properties of the coating since no rains occurred meanwhile. Higher power increase was recorded in the beginning of September when the first rains appeared. Rain converted dust into muddy stains on the uncoated panel while it was more efficient in washing off dust on the coated panel due to the hydrophilic nature of the coating (inset in Fig. 10a). During the next months, a satisfactory gain in energy production was recorded. In December, the gained power difference was attributed to the antireflective property of the coating as it was raining continuously and both of the panels were clean.

On the 4th of October which was a cloudy day with sunlight intervals, a spike with high power difference of 19.81% was recorded (Fig. 10b). A closer look at the instantaneous power difference values during this day revealed that the phenomenon can be related to the antireflective property of the coating. Specifically, when the light intensity was low (cloudy intervals), the coated panel produced more energy reaching a maximum of 50%. On the other hand, when the light intensity was high (sunlight intervals) the power difference reached

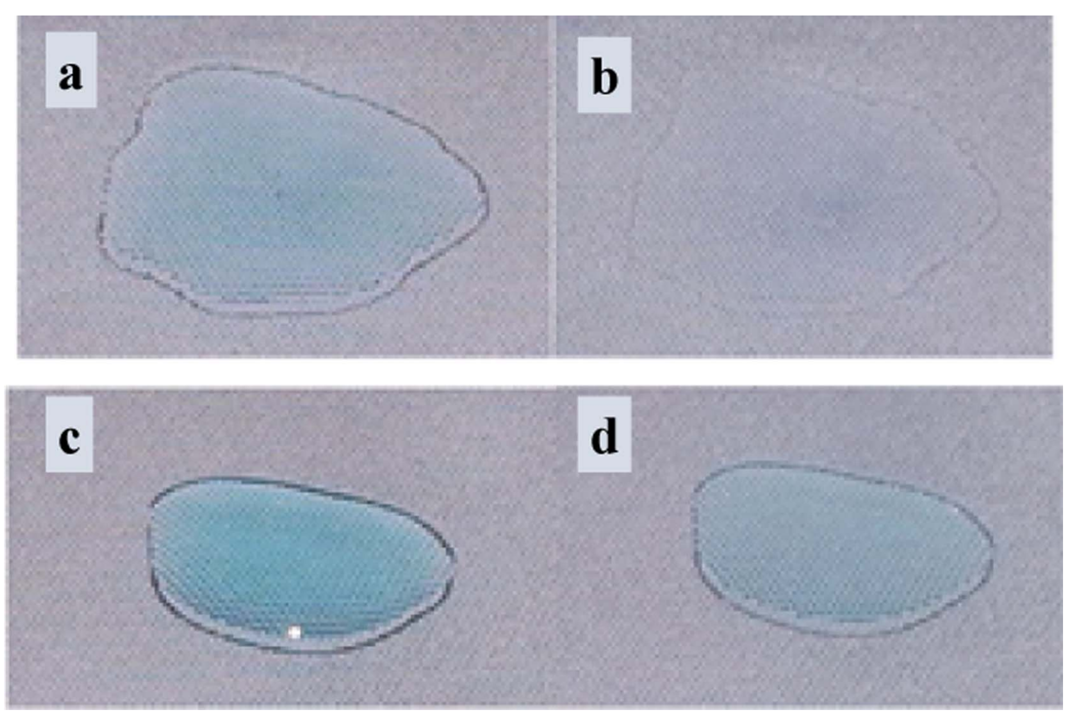

Fig. 6. Images of Methylene Blue on: coated glass before (a) and after (b) irradiation; uncoated glass before (c) and after (d) irradiation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

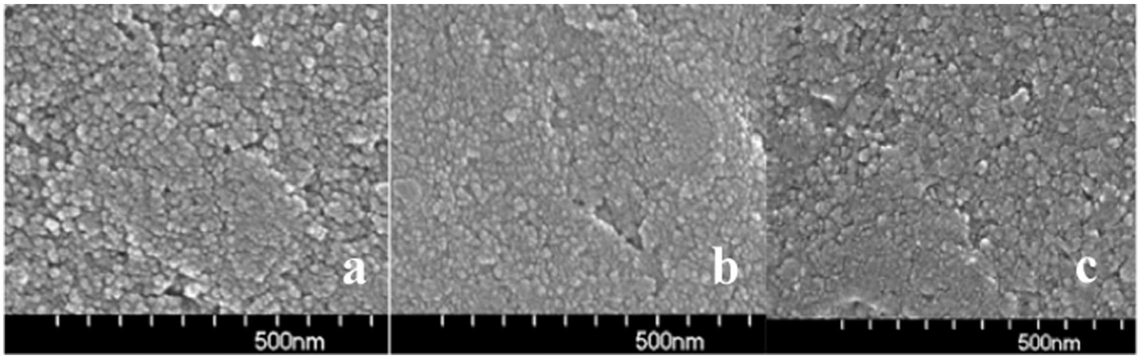

Fig. 7. SEM images of the coated glass before testing (a) and after the thermal cycling (b) and UV irradiation (c) tests.

minimum evidencing that the coating transmits better the diffuse radiation.

The monitored period of time covered parts of summer, autumn and winter seasons in Greece and the recorded phenomena are expected to be observed during the rest of the year. An average of 5% power gain due to the coating was calculated for the entire period of time.

The performance of the PV arrays in Qinghai province (China) was monitored for the time period from November to March. The experimental data on the power output difference between uncoated and coated PV panels is presented in Fig. 11a. The average power difference per day (ΔPd) exhibited increasing trend for the entire period. The highest increase of the ΔPd was recorded in January that was attributed to the sandstorm occurred in the PV plant location on January 21st. The ΔPd value reached 12.43% and kept growing to 13.17% for 6 days due to the dust accumulated on the uncoated array. Although the rain on January 29th ended the continuous increase, the muddy stains observed on the untreated panels after the rain (Fig. 11b) made the power difference go up again. The consequent drop of the ΔPd to approximately 2% was associated with cleansing performed at January 31st. It should be mentioned that regular cleansing procedure (every two months) is practiced for simulating the real maintaining conditions in most of the PV plants in western China. Overall, the data collected revealed an average 6% power increase during the entire exposure period.

4. Conclusions

Nanostructured titania-containing SSG formulation was deposited on the glass surface of photovoltaic panels via one-step, cost-effective spraying procedure. Homogeneous coatings with thickness 150 nm consisted of regularly arranged nanoparticles were obtained at ambient conditions without any post-treatment. The coatings demonstrated excellent stability in thermal and UV weathering as well as in not drastic sandblasting conditions. The light transmittance and hydrophilicity of

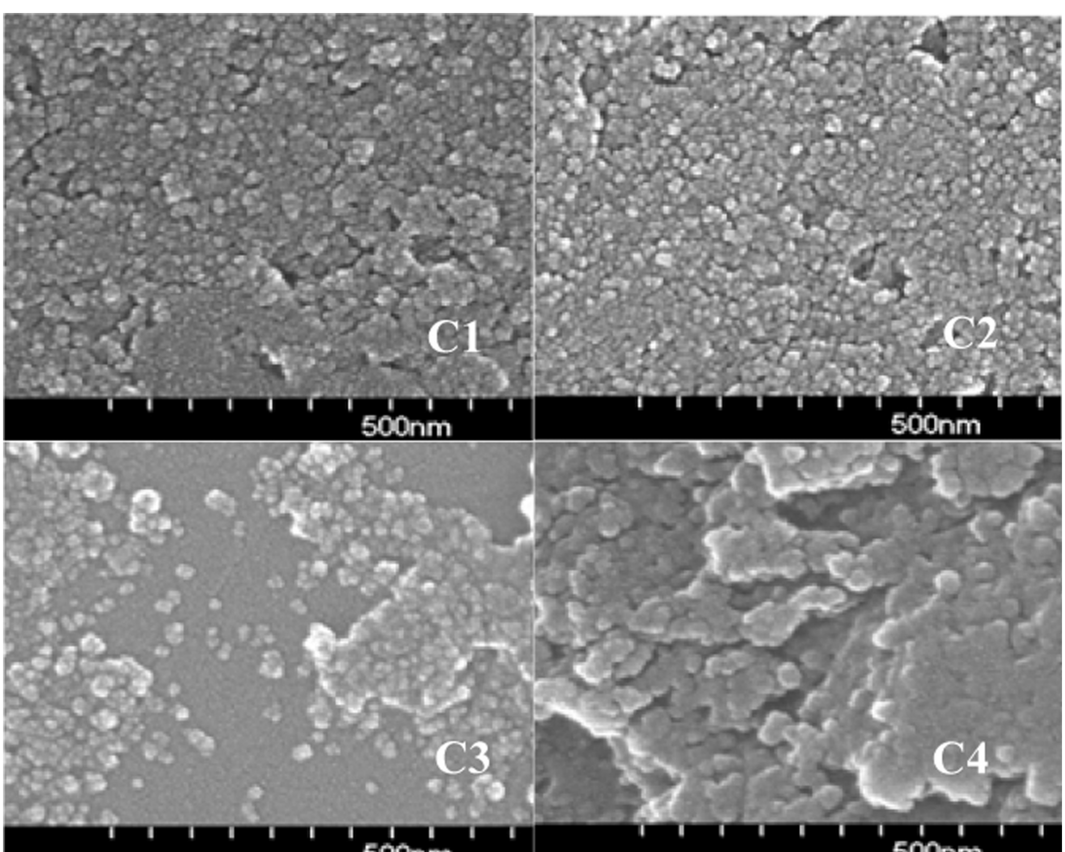

Fig. 8. SEM images of the coated glass after sandblasting tests at Conditions 1–4 (C1-C4).

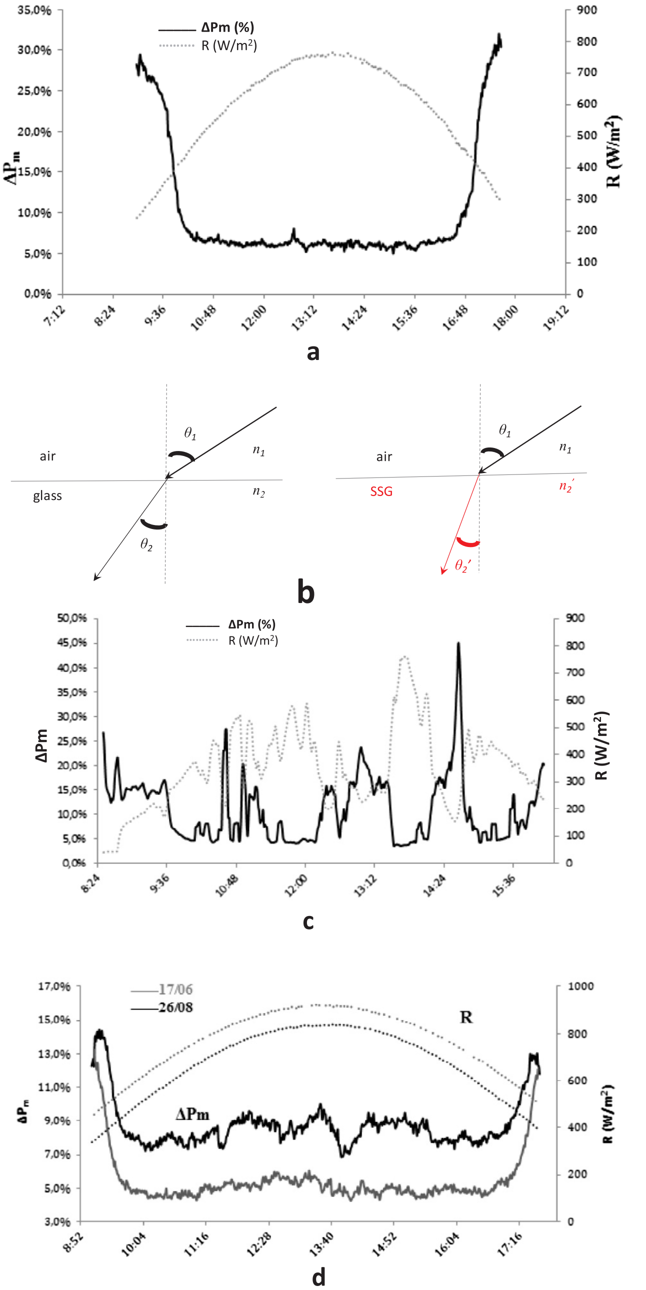

Fig. 9. Outdoor performance of PV panels: (a) power per minute difference measured during the first day after coating the panel; (b) schematic presentation of light transmition through non-coated and coated glass; (c) power per minute difference measured in a cloudy day; (d) power per minute difference measured 16 days and 86 days after coating the panel.

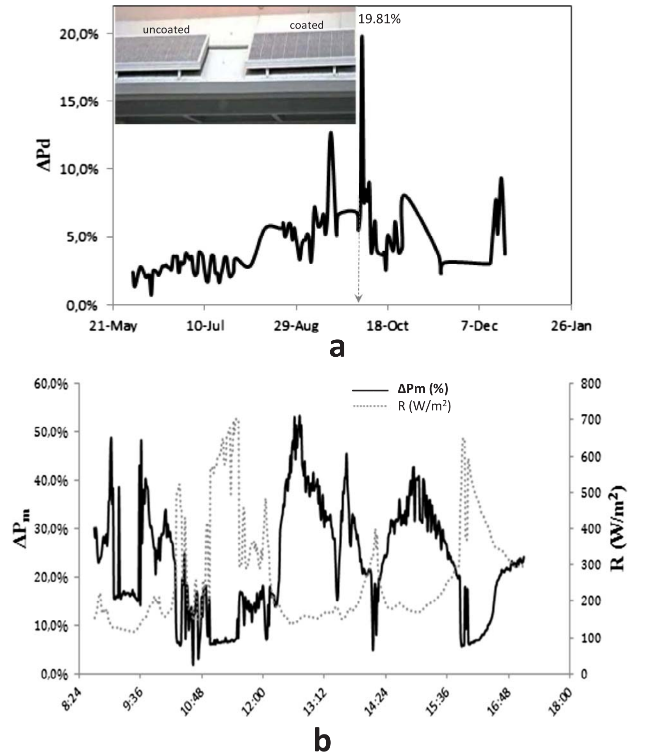

Fig. 10. Outdoor performance of PV panels in Greece: (a) power difference per day for the examined period of time; (inset) picture of the uncoated and coated PV panels after rain; (b) power difference during the day where the maximum value was measured.

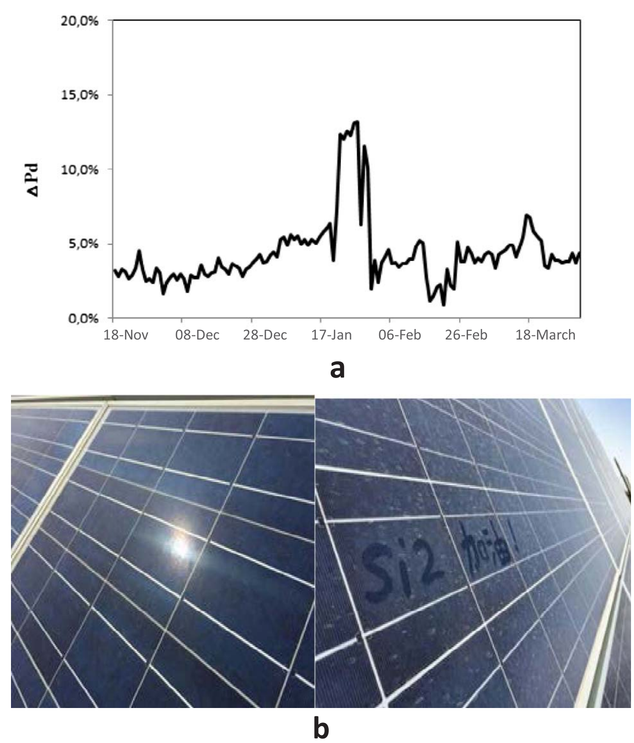

Fig. 11. Outdoor performance of PV panels in China: (a) power difference per day for the examined period of time; (b) picture of the uncoated and coated PV panels after rain (finger scrubbing marks clearly show the dust accumulated).

the coated glass were significantly enhanced in comparison to the uncoated glass endowing better antireflective and self-cleaning toward dust properties. In addition, the coatings exhibited self-cleaning behavior toward organic compounds (MB) owing to the photo-catalytically active component.

Under outdoor real conditions, the coated PV panels demonstrated an average gain of 5–6% for the monitored period of time. The gain (*ΔPm*) was significantly increased in conditions of diffuse light (up to 19%) and irradiation with high incident angle (up to 30%) that was attributed to the antireflective properties of the coating and the reduced dust accumulation on the glass surface as well. The fact that the SSG coated panels exhibited high weathering resistance and excellent performance during mornings, evenings and cloudy days could be especially important for regions with severe climate and limited sunlight periods.

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