Solar Energy Materials & Solar Cells 262 (2023) 112560

Contents lists available at ScienceDirect

Solar Energy Materials and Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Field tests of a self-sintering, anti-soiling, self-cleaning, nanoporous metal oxide, transparent thin film coating for solar photovoltaic modules

Kenneth A. Walz [a,*], Timothy D. Hoege [a], Joel W. Duensing [a], Walter A. Zeltner [b], Marc A. Anderson [b]

[a] Madison Area Technical College, 1701 Wright Street, Madison, WI, 53704, USA
[b] Microporous Oxides Science and Technology, 393 Lake Kegonsa Road, Oregon, WI, 53575, USA

ARTICLE INFO

Keywords:
Solar
Soiling
Self-cleaning
Coating
Nanoporous
Sol-gel

ABSTRACT

Nanoporous metal oxide ceramic coatings, deposited using sol-gel techniques, have the potential to impart self-sintering and self-cleaning coatings to silicon oxide glass. When used on solar photovoltaic modules, these coatings can impart anti-static properties, improve wetting behavior, and degrade soiling deposits through photocatalytic activity. This paper reports on a field trial of a mixed silicon and titanium oxide thin film coating conducted in the upper midwestern U.S. Coated modules demonstrated increased electrical generation relative to uncoated controls. The results are encouraging for the commercialization of this coating technology, and provide a strong motivation for further research and development efforts.

1. Introduction

As the world moves towards a zero-carbon emission goal, solar power needs to be a significant contributor to electricity generation. As such, it is imperative to produce photovoltaic (PV) modules that maintain their efficiency over their expected 25–30 year lifetime. Soiling is a primary cause for the decrease in power of solar modules over time [1]. This loss in efficiency is caused by contamination from many sources including mineral dust, bird droppings, mold, moss, pollen, automotive pollution, and agricultural products. These contaminants produce significant power losses that result from scattering, absorption, and reflection of the incident solar radiation. For example, it has been reported that a nearly €4–7 billion loss in revenue is expected in 2023 due to the soiling of PV systems in high soiling regions of India and China [2].

As a result, there has been considerable research interest in developing methods to keep the surfaces of solar modules clean [1–5]. These methods can be broadly classified as either mechanical or passive techniques. Mechanical methods include robotic cleaners, electric pulsating fields, and manual cleaning. However, these methods are costly, often require large quantities of water and detergents for cleaning, and mechanical failures of robotic cleaners require maintenance. Many researchers consider mechanical cleaning methods to be a less than satisfactory long-term option [2,3].

Passive techniques involve coating PV modules with self-cleaning films that can be either superhydrophobic or superhydrophilic. Both types of films utilize good wetting behavior that helps to wash away surface contaminants. In addition, many superhydrophilic films incorporate a titania-based photocatalyst that can photochemically break down contaminants. In all cases, these coatings should satisfy three criteria: 1) they should repel dust and other contaminants; 2) they should be antireflective to some degree; and 3) they should be robust enough to last for the lifetime of the solar module. Ideally, an antireflective coating should have a refractive index between 1.2 and 1.3 [3,6]. Regardless of the type of coating, all active systems try to meet this optical criterion while being cost effective, robust, easy to fabricate and apply.

There are different approaches taken to prepare superhydrophobic self-cleaning coatings whose contact angles with water are greater than 160^o, which allows water to bead up and run off, carrying the contaminating particles along [7]. One method relies solely on polymeric coatings such as fluorinated polymers. A variant of these approaches is to prepare films that mimic biological hydrophobic systems such as the lotus leaf effect [8,9]. Some superhydrophobic films, while being mostly organic, incorporate oxide nanoparticles [10,11]. There are also inorganic superhydrophobic self-cleaning films prepared using functionalized silica [12] or titania [13] nanoparticles. It should be cautioned that films containing organics, either wholly or in part, are subject to UV

* Corresponding author.
E-mail address: kwalz@madisoncollege.edu (K.A. Walz).

https://doi.org/10.1016/j.solmat.2023.112560
Received 27 June 2023; Received in revised form 13 September 2023; Accepted 17 September 2023
Available online 22 September 2023

degradation over time on exposure to solar radiation since some 5% of this radiation is in the UV spectrum.

Superhydrophilic self-cleaning coatings have contact angles less than 5°, which allows water drops to spread on the surface and flow off while also removing soiling particles. These coatings are typically fabricated from inorganic oxides such as SiO_2, TiO_2, and ZnO [14,15], often using sol-gel processing methods [3,16,17]. Of particular interest are coatings that contain both silica and titania because this mixture can be superhydrophilic, photocatalytic, and, also antireflective - all properties of great interest for fabricating self-cleaning coatings on solar modules.

The photocatalytic oxidation property of mixed silica and titania films is due to the presence of the titania component. When UV radiation with wavelengths around 380 nm or less strikes titania particles, these photons have enough energy to form an electron-hole pair. Although most photogenerated electrons and holes simply recombine to produce heat, some will separate and reach the surface of the titania particles where they can react with absorbed contaminants. In air, electrons will most often react with molecular oxygen to form reactive radical species while holes will oxidize other surface contaminants, thus helping to clean the surface. A detailed study of this process, its underlying mechanisms, and some applications is available in Schneider et al. [18]. Photocatalytic activity varies with the ratio of silica to titania in these films [19–21].

Schneider et al. [18] also includes a discussion of the possible mechanisms that have been proposed for the superhydrophilic property associated with silica-titania coatings. Of particular interest is that it is often observed that these coatings lose their superhydrophilicity when kept in the dark for extended periods but then become superhydrophilic when again exposed to light [19,20,22].

Antireflective surfaces are of great interest because they increase the transmittance of radiation through the cover glass that can then activate solar cells. As mentioned above, antireflective surfaces should have an index of refraction of 1.2–1.3, ideally about 1.23 [3]. Although the refractive index for both silica and titania crystals is higher than required for an antireflective surface, Yoldas [23] discovered that porous films of oxides have a refractive index that can be significantly lower than that of the individual crystalline oxides and that such porous films can provide antireflective coatings. Several studies have focused on the preparation of such antireflective oxide coatings, including TiO_2–SiO_2 films [24–28]. Sputter deposition has been used to create anti-reflective thin films, while offering the ability to control the composition of these films using small amounts of additional dopant materials [29]. By comparison, sol-gel synthesis and aerosol deposition of thin film anti-reflective coatings has also been demonstrated, providing advantages of being less energy intensive and simpler to implement on a high throughput manufacturing line for a mass production [30].

Prof. Marc Anderson, formerly affiliated with the University of Wisconsin – Madison, has been investigating the preparation and applications of aqueous suspensions of nanoparticle oxides since the 1980's. A particular focus has been on the photocatalytic activity of TiO_2, ZrO_2–TiO_2, and SiO_2–TiO_2 films [21,31,32]. One outcome of these studies was the observation that thin films of titania would self-sinter when irradiated by sunlight [33]. This self-sintering effect also extends to mixed SiO_2–TiO_2 films.

Microporous Oxides Science and Technology, L.L.C. (MOST) was formed in 1997 to commercialize some of these nanoparticle oxide suspensions. The focus of this study is to measure the effectiveness of these films as self-sintering, self-cleaning, anti-soiling coatings for solar photovoltaic modules in active field settings.

2. Experimental methods

2.1. Coating material

The coating materials used in this experiment were deposited from a nanoparticulate suspension containing a mixture of titania, TiO_2, and silica, SiO_2, metal oxides. The detailed preparation of these materials is a proprietary process, but the general methods are known to science and can be shared here. The metal oxides were prepared using sol-gel chemistry techniques. The process involves mixing a metal alkoxide (e.g. titanium isopropoxide as shown in Fig. 1) with water and a catalyst (typically a strong acid or a strong base). The metal alkoxide reactant first undergoes hydrolysis reactions that cleave the alkoxide groups, replacing them with hydroxyls, and resulting in the formation of an alcohol byproduct. Subsequent condensation between two metal hydroxyl centers then results in the formation of metal-oxygen-metal bonding (e.g., Ti–O–Ti). As this process repeats, an amorphous metal oxide solid is formed. The resulting solid particles typically range in size from 2 to 100 nm, and form a colloidal suspension dispersed in the mixture of water and the alcohol byproduct. Gravimetric precipitation is avoided due to the small size of the nanoparticles, and further aggregation of the particles is prevented by electrostatic repulsion due to the particles' surface charge. The size of solid particles can be controlled by adjusting the rate of the synthesis reaction, which is achieved by controlling variables such as temperature, catalyst selection and concentration, and the composition of the solvent (primarily aqueous, but co-solvents and surfactants may also be added depending on the specific application). The sol-gel process is illustrated in Fig. 1.

In the case of the MOST materials, specific precursor reagents and catalysts were selected, and the sol-gel process was manipulated, to result in nanoparticulate suspensions of titania, TiO_2, and silica, SiO_2. A photo of the two suspensions (see Fig. 2) illustrates that the particles are so tiny that they are not visible to the naked eye, and their mass is small enough that they do not settle out of the suspension, nevertheless the colloidal materials are capable of scattering light such as that applied by a green laser. Dynamic Light Scattering was employed to determine the size distribution of the solid nanoparticles using a ZetaSizer 3000 instrument (Malvern, Inc.), according to methods previously described for incorporation of these materials in electrical devices [34,35]. Size distributions for the suspensions are shown in Fig. 2, with the peaks of the plots indicating the modal particle size. The mean particles sizes were 1.2 nm for the silica, and 4.6 nm for the titania material. Distribution widths at half maximum were 0.3 nm and 2.6 nm respectively, indicating that the nanoparticles were all small, similar in size, and little if any aggregation of the primary particles occurred (see Fig. 2).

Metal oxide thin films containing nanoparticulate photoactive materials such as titania are capable of sintering upon excitation from ultraviolet radiation [18]. This sunlight induced UV sintering process serves to chemically bond the nanoparticles to one another, and to the solar PV module's glazing surface, rendering a durable thin film that is resistant to wear and dissolution. This is an advantage to these sol-gel produced thin films - they do not need to be heated to adhere them to the underlying glass cover of the PV module, but rather the films consolidate, cure, bond, and harden upon exposure to sunlight in the field.

2.2. Application of the coating material in a controlled environment

Previous studies demonstrated that spray depositing the sol-gel coating materials on solar modules in the field was complicated by several challenges that limit the feasibility of this method for commercial application [36]. These challenges include wind velocity, humidity, sprayer control, safety considerations, etc. After observing the shortcomings of the in-situ field application, it became apparent that commercialization of the technology would likely require the coatings to be applied in a more controlled environment. Faculty in the Madison College renewable energy and automotive technology programs collaborated to develop methods for coating the solar modules using the spray booths in the college's collision repair facility. The facility offered a temperature and humidity controlled, dust free environment for spraying and drying the modules. The modules themselves could be laid

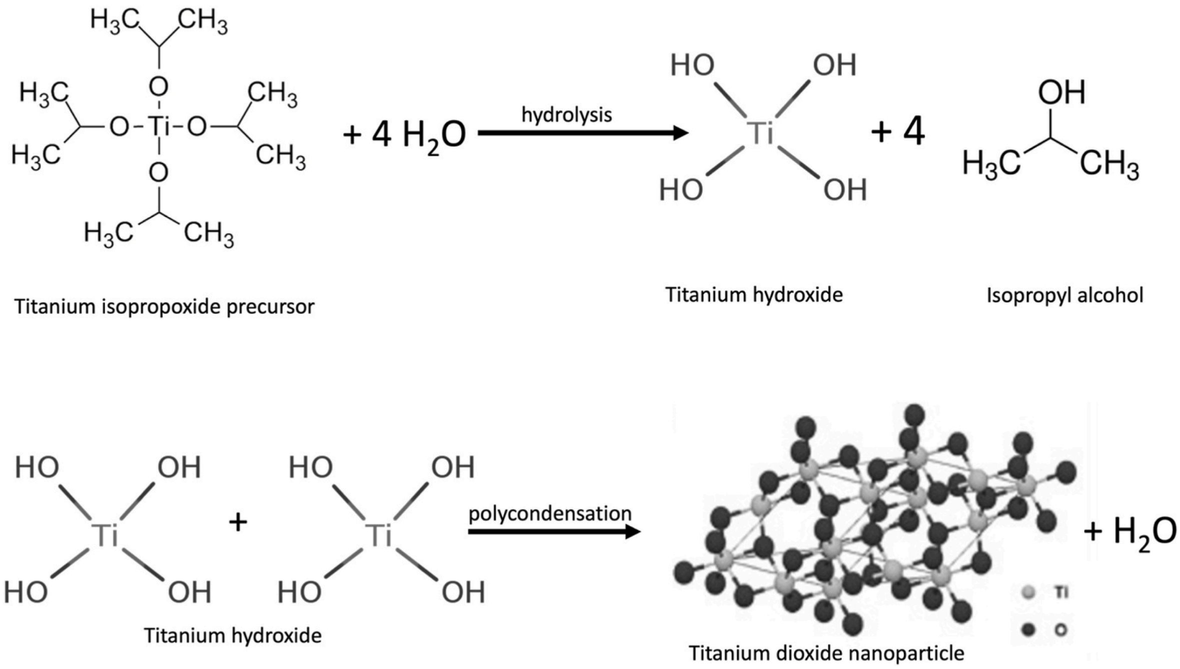

Fig. 1. Synthesis of TiO_2 nanoparticle coating materials via sol-gel chemical processing.

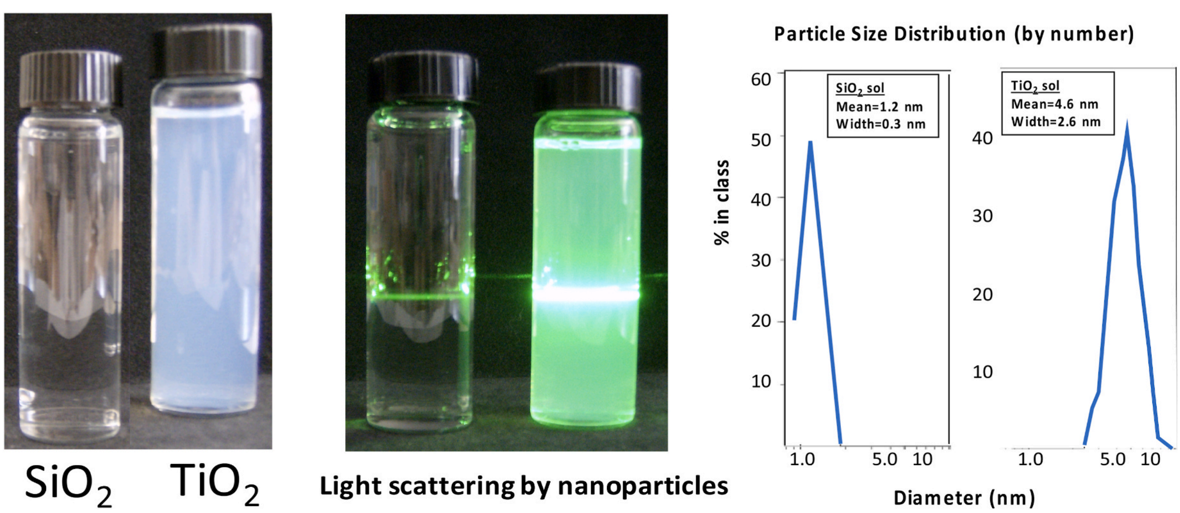

Fig. 2. SiO_2 and TiO_2 sols, scattering of green laser light, and particle size distributions of the metal oxide nanoparticles.

flat on a horizontal surface to minimize streaking. Professional spray equipment could be used with regulated air pressure, selection of various spray gun styles and nozzles, and the ability to accurately measure the quantity of material consumed in the spray process. Working on level ground eliminated the need for cumbersome fall protection harnesses. In addition, by working with students and faculty from the collision repair program, we could leverage the experience of individuals who were skilled technicians, experienced with surface preparation (a crucial step for spray coating), and who were able to apply the coatings with a consistent and reproducible technique.

The solar modules were placed in an automotive collision repair spray booth for the coating procedure, organized lengthwise in two rows of three modules each (see Fig. 3). Sikkens anti-static 385014 cleaning fluid was then used to saturate the module and allowed to soak for several minutes. A Scotchbrite 07445 light duty cleansing pad was used to scrub any remaining residue from the module with additional Sikkens fluid sprayed as needed. The modules were then double wiped to remove

Fig. 3. Spray deposition of coatings in a controlled environment.

any excess cleaning fluid and allowed to dry. This was followed with two treatments of Spray Away SW-050 glass cleaner to remove any residual solvents, leaving a clean surface which was allowed to air dry. After cleaning and drying, the modules were blown with compressed air and wiped with BASF B120 tack cloth to remove any airborne dust that might have deposited on the module. The modules were then spray coated immediately following the blow and tack procedure.

To prepare the liquid suspension used to coat the solar modules, the two precursor sols were mixed in appropriate volumes, along with additional proprietary wetting agents to arrive at the desired formulation for the given application. Two different spray guns and nozzles were used for this test. The first being a Sata 5500 HVLP (high volume low pressure) gun with a JetX 1.3 mm nozzle. The second being a Sata 5500 RP (reduced pressure) gun with a Jet X 1.2 mm nozzle. The spray guns were operated by two different technicians, who traded guns midway through the process for comparison purposes. Both guns were found to perform similarly with nearly identical deposition rates of the liquid coating material. The technicians deposited the material while holding the spray gun at a distance from the module surface of about 30 cm. Five passes were made with the sprayer, with the technician moving at a steady pace along the length of the modules. About 6 s were required for each pass, corresponding to a spray gun velocity of approximately 1 m/s. After spraying, the modules were allowed to air dry in the spray booths, which were maintained at 15% relative humidity. Several small glass microscope slides (Fisher Catalog No 12-544-7) measuring 25 mm × 25 mm x1mm were also coated to use for laboratory characterization of the spray coated thin film materials.

The volume of sol consumed was roughly 33 mL per module for a single coat. After allowing for about 10% loss due to overspray, this resulted in the deposition of roughly 15 mL/m^2 of module surface area. Assuming random close packing of the metal oxide nanoparticles, and after drying and consolidation of the material, this resulted in a thin film coating with a thickness of roughly 350 nm. After drying for 30 min, the modules were inspected visually. There was only a trace of evidence of the transparent thin film coating that was apparent to the naked eye. The film integrity was tested by dragging a fingertip across the surface, which did not result in any sort of streaking or removal of material. The modules were then boxed and packaged in a pallet for delivery to the desired field installation site.

3. Results and discussion

3.1. Laboratory characterization of the thin film coatings

A Thermofisher Genesys-30 UV–Visible Spectrophotometer was used to evaluate the optical properties of the thin film coatings deposited on the glass microscope slides. The percentage of light transmitted was measured while scanning from 350 to 900 nm, with measurements taken every 1 nm. The resulting transmission spectra for uncoated and coated glass are shown in Fig. 4. The coating process resulted in barely detectable changes in the transmission for wavelengths in the range of visible light (400–700 nm). As expected, the coated slide demonstrated lower transmission in the ultraviolet region of 350–400 nm, which is consistent with the known behavior of TiO_2 as an absorber of ultraviolet radiation. The coated slides also demonstrated slightly elevated transmission in the infrared region of 700–900 nm, with the coated slide transmitting between 0.4 and 0.7% more than the coated slide. This is likely due to the coated slide absorbing UV, and then releasing this energy back to the surroundings as additional infrared heat radiation (see Fig. 4).

Surface wetting can be quantified through the measurement of the contact angle, which is the angle at which the interface of the solid surface, water, and air meet. Low contact angles demonstrate the tendency of water to spread and adhere on a hydrophilic surface, whereas high contact angles show a more hydrophobic surface's tendency to repel water. The microscope slides were also used to measure the contact angle with water as a means of assessing the hydrophilic nature of the coatings and the wettability of both coated and uncoated surfaces.

A 1 mL syringe with a 25 gauge needle having an inner diameter of 0.26 mm was used to deliver small droplets of microfiltered deionized water for contact angle goniometry. The drop volume was measured using a Sartorius analytical balance with 0.0001 g accuracy. Average drop size was 6.0 μL ± 0.04 μL. The contact angle was measured for uncoated glass and for glass with the freshly deposited self-cleaning thin film. The slides were then exposed to sunlight outdoors, receiving 6 h of sunshine, with an average irradiance of about 700 W/m^2 at an ambient temperature of about 25 °C, and the contact angle measurements were repeated. The contact angle of the freshly coated glass was about 30% lower than the value measured for the uncoated glass. This is similar to previous results documented by Anderson et al. [37]. It was also observed that exposure to sunlight dramatically reduced the contact angle to the point that it was too small to measure accurately. This is also consistent with the previously described UV induced sintering mechanism for consolidation and curing of these nanoporous coatings that contain titanium dioxide, TiO_2.

3.2. Real-world performance of self-cleaning solar modules

The solar test field site at Madison College's Commercial Avenue campus includes sixteen Philadelphia Solar 370 Watt bifacial modules. Half of the modules received the self-cleaning coating, and the other half served as uncoated controls. The modules are mounted on a flat commercial roof surface with a white TPO membrane roof. Two different styles of racking were compared, the first being an Equilibrium Eco Foot south facing fixed rack with 10-degree tilt, and the second being a Point Load Power PV Booster, vertical axis tracking rack with 30-degree tilt (see Fig. 5). Each module is connected to a SolarEdge P505 DC optimizer that provides module level power electronics and monitoring of the individual module. The optimizers are connected to a SolarEdge SE 14.4 kWac inverter, which transmits data to the cloud where it can be monitored and archived for long term data preservation. The solar modules were installed and commissioned in November of 2021. The panels have been allowed to weather in place, and no cleaning of the

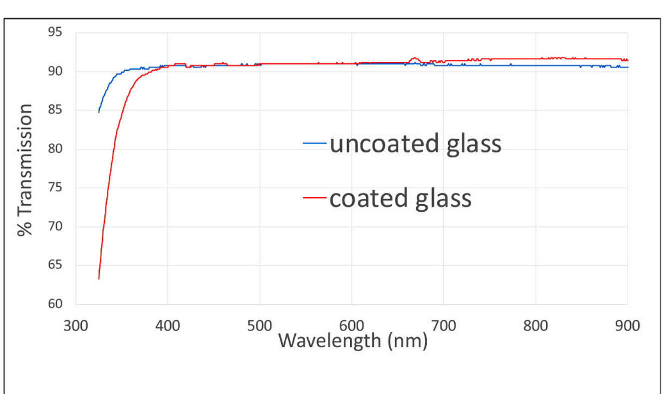

Fig. 4. UV–visible transmission spectra for uncoated and coated glass.

Fig. 5. Solar modules at the Commercial Avenue test site.

panels has occurred since that time other than that provided naturally by rain and snow fall.

Visual inspection of the modules demonstrated marked differences in appearance in the weeks following installation. This site in question lies next to a grassy area that has several mature trees, and is often visited by birds. Within a few days of the installation, some of the solar modules had become soiled by bird droppings. The soiled modules were observed daily over the period of a week, and differences were noted in the weathering of the droppings (see Fig. 6).

Soiling residues on the uncoated modules were thick and concentrated in spots of about 5–10 cmˆ2. Even after a day of light rain, these residues did not dissolve or migrate much on the module surface. By comparison, soiling residues on the coated modules were clearly thinner, and had spread out over a much larger surface area. The coating's photocatalytic activity appeared to be breaking down the organic molecules in the bird droppings, and then smaller compounds were washed down the module surface, seemingly spreading through the thin film matrix. This is consistent with the mechanism for photocatalytic degradation of large organic molecules previously documented by the authors for titanium dioxide thin film coatings prepared using similar experimental methods as those employed in this study [38–40].

Coated and uncoated solar modules also demonstrated significantly different wetting behavior in the field that was easily visible to the naked eye. As shown in Fig. 7, rain deposited on the uncoated panels tended to bead up, forming raised droplets on the surface. By comparison rain on the coated panels tended to sheet, wetting a much larger portion of the panels surface. Contact angles may also be observed as a means of assessing wetting behavior in the field, although field conditions are not as carefully controlled. The composition of rainwater contains many solutes, that are not present in laboratory microfiltered deionized water. The size of rain drops is also highly variable, and the temperature of the water and the solar module surface can vary throughout the rain event. Nevertheless, contact angle observation in the field can still be quite informative.

As shown in Fig. 8, the contact angle for uncoated panels ranged from 30 to 60° with an average of about 45°. By comparison, the contact angle for the coated panels ranged from 17 to 30° with an average of about 25°. Furthermore, far fewer droplets of any size were seen on the coated panels, since many of the drops had flattened out, completely wetting the surface.

Solar Electric Production from the Commercial Avenue Field Site was gathered and is reported for the period of Nov 11, 2021 through June 13, 2023 (see Table 1). The coated modules mounted in the fixed tilt south facing racks and those on the vertical axis tracking racks both outperformed the corresponding uncoated modules that served as controls for these surface treatment groups. The coatings imparted a mean lifetime energy gain measured over the duration of this report that was slightly higher for the for the 10-degree tilt, fixed mount modules (3.52%) than for the 30-degree tilt tracker units (3.05%). This is consistent with the fact that soiling is more problematic for modules that are at low tilt angles (less cleansing from rain). This result is easiest to explain by considering a perfectly flat horizontal module. In this case, a light rain would not be expected to produce any cleansing effect at all, since the module would get wet, but then the water would simply evaporate and leave behind all the soiling residues without removing them from the module surface.

To evaluate the performance of the solar installation, the specific solar yield, expressed as kWh of solar energy produced per kilowatt of installed module capacity was calculated over a twelve-month period. As shown in Table 2, the coated modules mounted on south facing racks at 10-degree fixed tilt had a mean annual yield of 1097 kWh/kW, outperforming the uncoated controls which had a yield of 1058 kWh/kW. Solar yields are highly location dependent, but these values are consistent with Madison College's experience at the flagship Truax campus which hosts the largest rooftop solar PV array in Wisconsin using the same EcoFoot racking system installed on the same TPO membrane roof material. The Truax campus is located only two miles from the commercial avenue campus, so it provides a good local reference point from a climate and weather perspective. In 2022, the Truax campus had a solar yield of 975 kWh/kW. This value is only slightly lower than the yields observed in the Commercial Avenue field trial, which likely represents the fact that the Commercial Avenue panels are newer, whereas the Truax system was constructed and installed in 2018–2019. The solar yields for the coated and uncoated modules mounted on the PV booster vertical axis tracking racks were 1406 and 1361 kW/kWh respectively. These values are consistent with the predictions from Point Load Power (the manufacturer of the PV booster tracking units) which advertises a possible 30% improvement in solar yield as a result of the tracking apparatus.

One-tailed T-tests were performed to determine the statistical significance of the observed differences in performance between coated and uncoated solar modules. The differences in performance between the coated panels and their uncoated controls were significant at the 90% confidence level for the 30-degree tilt vertical axis tracker units, and at the 95% confidence level for the 10-degree tilt fixed south facing modules (See Table 3). This is rather impressive considering that the sample sizes per treatment used in this study were small (only four modules each). Furthermore, there is inherent variance between modules that is a result of the manufacturing process and limitations on the quality control and reproducibility of silicon photovoltaic fabrication techniques. So, the positive demonstration of the effectiveness of the self-cleaning coatings and the resulting increase in energy production is

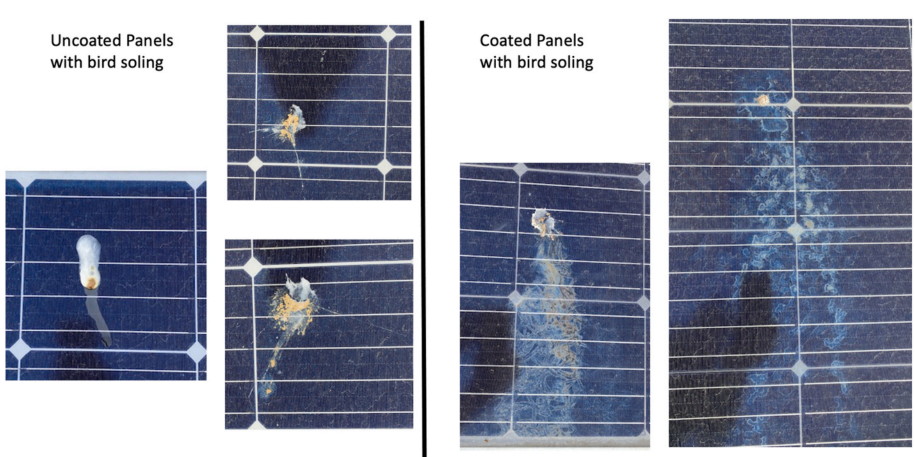

Fig. 6. Images of soiled PV modules from the self-cleaning field tests.

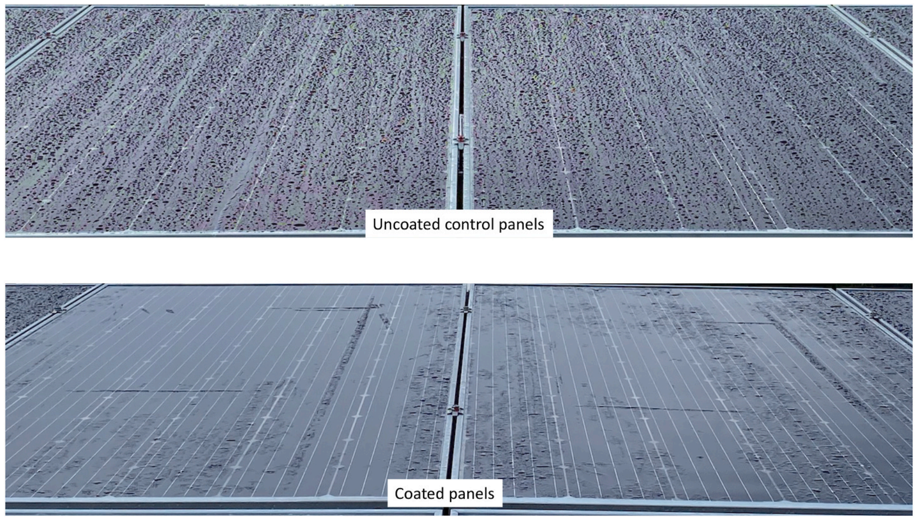

Fig. 7. Appearance of rain drops on the uncoated control panels (top) and on panels that were treated with the MOST self-cleaning coatings (bottom). The photos were taken within a few moments of one another on a spring day with a light misting rain.

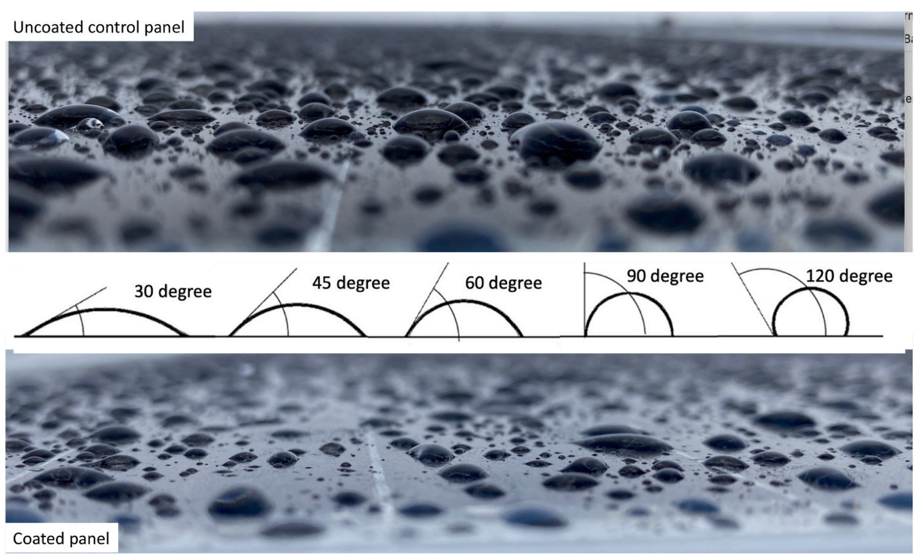

Fig. 8. Contact angles formed by rain drops on an uncoated control panel (top) and a panel treated with the MOST self-cleaning coating (bottom).

Table 1
Contact angle measurements characterizing the wettability of coated and uncoated glass.

	Uncoated Glass	Coated Glass	Coated Glass after 6 h of sunlight
Drop 1	33	24	Unable to Measure Accurately. Contact Angles <1°.
Drop 2	35	21	
Drop 3	36	20	
Drop 4	34	23	
Drop 5	33	24	
Mean	34.2	22.4	
Std Dev	1.30	1.82	

quite encouraging.

While a 3 to 3.5% energy gain may appear modest, improvements of this magnitude would be of significant financial importance to the industry. For this small test system, a 3% energy gain would only result in a benefit of about $10 per year. However, for a 2 MW commercial rooftop system such as that at Madison College's flagship Truax campus, a 3% gain would amount to over $6000 per year of electricity savings. And for a large utility scale solar farm, a 3% gain could easily amount to increased electricity revenues of over $1 M per year, along with significant labor savings due to the reduced need for cleaning solar modules in the field.

4. Conclusions and next steps

The initial observations indicate a difference in the benefit of the coatings for modules at a steep pitch (30°) compared to those at a low pitch (10°). This is important because the former steep angle is typical of what is used for the construction of ground mounted solar arrays, whereas the latter low pitch angle is typical of flat commercial roof mounted systems, where angles are reduced to minimize wind loads. To further explore the effectiveness of the coating, larger scale field trials using a much greater number of modules are needed at both steep and low pitch tilt angles. Madison College recently installed several hundred coated solar panels as part of a 135 kW photovoltaic array at one of its rural campuses in Watertown, WI, and we hope to report on the field results of that experiment in the year ahead.

Table 2
Comparison of coated solar module electrical output with uncoated controls.

Module Surface Treatment	Rack	Azimuth	Tilt Angle	Mean Lifetime Energy (kWh)	Standard Deviation	Percent Gain	2022 Mean Annual Yield (kWh/kW)
Uncoated	EcoFoot fixed tilt south	180°	10°	586.68	18.97	3.52%	1058
Coated	facing			607.33	8.78		1097
Uncoated	PV Booster vertical axis	60° to	30°	786.93	29.77	3.05%	1361
Coated	tracking	300°		810.01	3.37		1406

Table 3
Statistical Analysis of the coated solar modules compared with uncoated controls.

Tilt Angle	Surface Treatment	n	Degrees of freedom	Mean lifetime energy (kWh)	Sum of squares	t-value	p-value
10°	uncoated	4	3	586.68	1080.11	−0.198	0.0478
	coated	4	3	607.32	230.96		
30°	uncoated	4	3	786.93	2658.55	−1.6	0.0803
	coated	4	3	810.91	33.96		

This field study also found a much larger variance in the performance of the uncoated control panels, than for those with the self-cleaning coating. The reason for this difference is uncertain. However, it was anecdotally observed that some of the panels were heavily soiled by bird droppings during the field trial, and the soiling on a few of the uncoated panels persisted long after the panels with the self-cleaning coatings had cleared. It may be speculated that this could be the source of the greater variance in the uncoated control panels. Future experiments might attempt to document this effect using video recordings or time lapse photography to quantify how long various types of soiling persist after initial deposition.

Preliminary results from Madison College indicate that solar modules treated with the anti-soiling and self-cleaning coatings generated more energy than identical uncoated modules when tested in head-to-head field trials. However, because of the variability in climate, and the variability in the types of soiling materials and methods of deposition, it is difficult to predict if the energy gains obtained at Madison College would manifest in the same way in other parts of the world. Soiling in southern Wisconsin generally comes from three forms, urban aerosols, windblown agricultural soils, and biological material deposited by birds. Southern Wisconsin also has greater precipitation than other parts of the country both in the form of rain and snow. It would be very interesting to repeat these trials in other locations with different types of soiling mechanisms, (e.g. tree pollen, sand storms, sea spray, biofilms, etc.), and in places having more arid and/or more humid climates. A recent comparison of many different anti-soiling coatings found that various types of hydrophobic and hydrophilic coatings performed better or worse in different locations, depending on the type of climate, type of soiling, and quantity of rain received [41]. MOST and Madison College are currently working to set up additional field tests in other locations around the U.S. with the pilot trials being launched at schools in Northern Wisconsin and Colorado in the fall of 2023. We hope to have ten or more field sites operational by the end of 2024 in geographic locations across the U.S.

The panels used in this study were manufactured by Philadelphia Solar. To verify that the self-cleaning coating materials and the spray deposition techniques used in this study are broadly effective, Madison College recently undertook a follow up experiment to apply the coatings to several other solar module types. As of August 2023, we have successfully coated modules from several different manufacturers, including Adani, Axitec, Crossroads, REC, Silfab, Trina and Yingli. We hope to report on field tests using those coated modules in the next year or two.

It would be desirable to further characterize the self-cleaning thin film coatings, particularly to compare properties before and after weathering in the field. Based on the UV–visible transmission data, it appears that reflectance of light is not impacted by the MOST anti-soiling coating, however some panel manufacturers would prefer that this property be measured directly. Other useful data to obtain would be film thickness, hardness, porosity, flatness and uniformity. Since the MOST coatings are made of metal oxide ceramic materials, they are expected to be considerably tougher than other organic anti-soiling products. Accelerated weathering tests would also be of interest to ascertain the durability and to predict the longevity of the MOST coating. As a two-year community college, Madison College lacks both the instrumentation and technical expertise for this sort of work. MOST is currently exploring partnerships with research universities and national laboratories that might provide such data, and MOST is also pursuing additional funding so that the company might be able to procure these measurements from a contracted lab services provider in the future.

The cost of the thin film coating materials used in this study was approximately $80 USD per liter, based on small volume synthesis in batches ranging from 2 to 4 L. This works out to a cost of about $2.60 per panel for the solar modules used in this study. That translates to an incremental cost of about $0.0070/Watt, or in increase of roughly 1.4% in the cost of the panel production (assuming prevailing wholesale module prices of $0.50 per Watt), which compares favorably with the 3–3.5% increase in electrical energy generated by the coated panels. Furthermore, actual costs associated with large volume manufacturing on a commercial scale would be significantly less, since the reagents could be purchased in bulk quantities, delivery of the sol and co-solvent additives could be done using inline syringe pumps and a mixing manifold to eliminate residual volume left in containers, and overspray would be minimized through implementation of an electromechanically controlled ultrasonic spray head system integrated into the assembly line. Thus, it appears clear that the MOST coatings tested in this study have strong potential to be a commercially viable product for solar manufacturing.

CRediT authorship contribution statement

Kenneth A. Walz: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Timothy D. Hoege:** Writing – review & editing, Methodology. **Joel W. Duensing:** Writing – review & editing, Methodology. **Walter A. Zeltner:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Marc A. Anderson:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This material is based upon work supported by the National Science Foundation under grants #1600934, 2000714, and 2201631. Jeffrey Brownson, Hao Jiang, Seth Keel, Tim Lee, Jennifer Sanfillipo, Ashley Scholes, Jessica Silva, Chee Thao, and Walker Willis all contributed to early research efforts that led to this work. Cris Folk, Scott Liddicoat, and Joel Shoemaker helped with the design and installation of the solar PV system. Institutional support for this work was provided by Kevin Mirus, Todd Stebbins, Randy Way, and Lucas White.

References

[1] S.C.S. Costa, A.S.A. Diniz, L.L. Kazmerski, Dust and Soiling Issues and Impacts Relating to Solar Energy Systems: Literature Review Update for 2012–2015, Renewable and Sustainable Energy Reviews, 2016.
[2] D. Adak, R. Bhattacharyya, H.C. Barshilia, A State-Of-The-Art Review on the Multifunctional Self-Cleaning Nanostructured Coatings for PV Panels, CSP Mirrors and Related Solar Devices, vol. 159, Renewable & Sustainable Energy Reviews, 2022.
[3] A. Syafiq, V. Balakrishnan, M.S. Ali, S.J. Dhoble, N. Abd Rahim, A. Omar, A. Abu Bakar, Application of transparent self-cleaning coating for photovoltaic panel: a review, Curr. Opin. Chem. Eng. 36 (2022).
[4] M.A. Bahattab, I.A. Alhomoudi, M.I. Alhussaini, M. Mirza, J. Hegmann, W. Glaubitt, P. Lobmann, Anti-soiling surfaces for PV applications prepared by sol-gel processing: comparison of laboratory testing and outdoor exposure, Sol. Energy Mater. Sol. Cell. 157 (2016) 422–428.
[5] T. Sarver, A. Al-Qaraghuli, L.L. Kazmerski, A comprehensive review of the impact of dust on the use of solar energy: history, investigations, results, literature, and mitigation approaches, Renew. Sustain. Energy Rev. 22 (2013) 698–733.
[6] U. Mehmood, F.A. Al-Sulaiman, B.S. Yilbas, B. Salhi, S.H.A. Ahmed, M.K. Hossain, Superhydrophobic surfaces with antireflection properties for solar applications: a critical review, Sol. Energy Mater. Sol. Cell. 157 (2016) 604–623.
[7] M. Load, B. Ghule, Fabrication techniques of superhydrophobic coatings: a comprehensive review, Phys. Status Solidi A (2022) 219.
[8] W.S.Y. Wong, Z.H. Stachurski, D.R. Nisbet, A. Tricoli, Ultra-durable and transparent self-cleaning surfaces by large-scale self-assembly of hierarchical interpenetrated polymer networks, ACS Appl. Mater. Interfaces 8 (2016) 13615–13623.
[9] C.R. Crick, I.P. Parkin, A single step route to superhydrophobic surfaces through aerosol assisted deposition of rough polymer surfaces: duplicating the lotus effect, J. Mater. Chem. 19 (2009) 1074–1076.
[10] S. Barthwal, S. Barthwal, B. Singh, N.B. Singh, Multifunctional and fluorine-free superhydrophobic composite coating based on PDMS modified MWCNTs/ZnO with self-cleaning, oil-water separation, and flame retardant properties, Colloids Surf. A Physicochem. Eng. Asp. (2020) 597.
[11] Y.R. Lan, Y.C. Wang, H. Zhang, P. Shan, X.M. Shi, M.Y. Long, A facile approach to achieve multifunctional polyethylene terephthalate fabrics with durable superhydrophobicity, photocatalysis and self-quenched flame retardance, New J. Chem. 44 (2020) 14198–14210.
[12] D.A. Schaeffer, G. Polizos, D.B. Smith, D.F. Lee, S.R. Hunter, P.G. Datskos, Optically transparent and environmentally durable superhydrophobic coating based on functionalized SiO2 nanoparticles, Nanotechnology (2015) 26.
[13] Y. Lu, S. Sathasivam, J.L. Song, C.R. Crick, C.J. Carmalt, I.P. Parkin, Robust self-cleaning surfaces that function when exposed to either air or oil, Science 347 (2015) 1132–1135.
[14] D.F. Zambrano, R. Villarroel, R. Espinoza-Gonzalez, N. Carvajal, A. Rosenkranz, A. G. Montano-Figueroa, M.J. Arellano-Jimenez, M. Quevedo-Lopez, P. Valenzuela, W. Gacitua, Mechanical and microstructural properties of broadband anti-reflective TiO_2/SiO_2 coatings for photovoltaic applications fabricated by magnetron sputtering, Sol. Energy Mater. Sol. Cell. (2021) 220.
[15] S.H. Jeong, J.K. Kim, B.S. Kim, S.H. Shim, B.T. Lee, Characterization of SiO_2 and TiO_2 films prepared using rf magnetron sputtering and their application to anti-reflection coating, Vacuum 76 (2004) 507–515.
[16] G.S. Vicente, R. Bayon, A. Morales, Effect of additives on the durability and properties of antireflective films for solar glass covers, J. Solar Energy Eng.-Transact. Asme 130 (2008).
[17] C.K. Jung, I.S. Bae, Y.H. Song, J.H. Boo, Plasma surface modification of TiO_2 photocatalysts for improvement of catalytic efficiency, Surf. Coating. Technol. 200 (2005) 1320–1324.
[18] J. Schneider, M. Matsuoka, M. Takeuchi, J.L. Zhang, Y. Horiuchi, M. Anpo, D. W. Bahnemann, Understanding TiO_2 photocatalysis: mechanisms and materials, Chem. Rev. 114 (2014) 9919–9986.
[19] R. Fateh, R. Dillert, D. Bahnemann, Preparation and characterization of transparent hydrophilic photocatalytic TiO_2/SiO_2 thin films on polycarbonate, Langmuir 29 (2013) 3730–3739.
[20] K.H. Guan, Relationship between photocatalytic activity, hydrophilicity and self-cleaning effect of TiO_2/SiO_2 films, Surf. Coating. Technol. 191 (2005) 155–160.
[21] X.Z. Fu, L.A. Clark, Q. Yang, M.A. Anderson, Enhanced photocatalytic performance of titania-based binary metal oxides: TiO_2/SiO_2 and TiO_2/ZrO_2, Environ. Sci. Technol. 30 (1996) 647–653.
[22] M. Houmard, G. Berthome, J.C. Joud, M. Langlet, Enhanced cleanability of super-hydrophilic TiO_2-SiO_2 composite surfaces prepared via a sol-gel route, Surf. Sci. 605 (2011) 456–462.
[23] B.E. Yoldas, Transparent porous alumina, Am. Ceram. Soc. Bull. 54 (1975) 286–288.
[24] Z.Q. Guo, Z. Zhu, Y. Liu, C.J. Wu, H. Tu, J.H. Wang, X.P. Su, Closed-surface multifunctional antireflective coating made from SiO_2 with TiO_2 nanocomposites, Materials 14 (2021).
[25] M. de Jesus, G. Timo, C. Agustin-Saenze, I. Braceras, M. Cornelli, A.D. Ferreira, Anti-soiling coatings for solar cell cover glass: climate and surface properties influence, Sol. Energy Mater. Sol. Cell. 185 (2018) 517–523.
[26] C.Y. Tao, X.S. Zou, K. Du, G.R. Zhou, H.W. Yan, X.D. Yuan, L. Zhang, Fabrication of robust, self-cleaning, broad-band TiO_2-SiO_2 double-layer antireflective coatings with closed-pore structure through a surface sol-gel process, J. Alloys Compd. 747 (2018) 43–49.
[27] O. Kesmez, H.E. Camurlu, E. Burunkaya, E. Arpac, Sol-gel preparation and characterization of anti-reflective and self-cleaning SiO_2-TiO_2 double-layer nanometric films, Sol. Energy Mater. Sol. Cell. 93 (2009) 1833–1839.
[28] D. Lee, M.F. Rubner, R.E. Cohen, All-nanoparticle thin-film coatings, Nano Lett. 6 (2006) 2305–2312.
[29] D.F. Zambrano-Mera, R. Espinoza-González, R. Villarroel, A. Rosenkranz, N. Carvajal, M.I. Pintor-Monroy, A.G. Montaño-Figueroa, M.J. Arellano-Jiménez, M. Quevedo-López, P. Valenzuela, W. Gacitúa, Optical and mechanical properties of Zr-oxide doped TiO_2/SiO_2 anti-reflective coatings for PV glass covers, Sol. Energy Mater. Sol. Cell. (2022) 243.
[30] E. Zäll, M. Järn, S. Karlsson, H. Tryggeson, M. Tuominen, M. Sundin, T. Wågberg, Aerosol-based deposition of broadband antireflective silica coating with closed mesoporous structure, Sol. Energy Mater. Sol. Cell. (2023) 250.
[31] A. Sirisuk, C.G. Hill, M.A. Anderson, Photocatalytic degradation of ethylene over thin films of titania supported on glass rings, Catal. Today 54 (1999) 159–164.
[32] X.Z. Fu, L.A. Clark, W.A. Zeltner, M.A. Anderson, Effects of reaction temperature and water vapor content on the heterogeneous photocatalytic oxidation of ethylene, J. Photochem. Photobiol. Chem. 97 (1996) 181–186.
[33] J.R.S. Brownson, M.I. Tejedor-Tejedor, M.A. Anderson, Photoreactive anatase consolidation characterized by FTIR Spectroscopy, Chem. Mater. 17 (2005) 6304–6310.
[34] J.S. Kim, C.S. Johnson, J.T. Vaughey, S.A. Hackney, K.A. Walz, W.A. Zeltner, M. A. Anderson, M.M. Thackeray, The electrochemical stability of spinel electrodes coated with ZrO_2, Al_2O_3, and SiO_2 from colloidal suspensions, J. Electrochem. Soc. 151 (2004) A1755–A1761.
[35] K.A. Walz, J.J. Szczech, L.C. Stoiber, A.N. Suyama, W.E. Suyama, W.A. Zeltner, M. E. Armacanqui, M.A. Anderson, Stabilization of iron (VI) ferrate cathode materials using nanoporous silica coatings, J. Electrochem. Soc. 153 (2006) A1102–A1107.
[36] K.A. Walz, J.B. Shoemaker, A.J. Scholes, H. Jiang, J.M. Silva, J. Sanfilippo, W. A. Zeltner, M.A. Anderson, Experimental Field Trial of Self-Cleaning Solar Photovoltaic Panels, ASEE Annual Conference & Exposition Proceedings, 2018.
[37] M.A. Anderson, J.R. Brownson, J. Sanfillipo, K. Leonard, Self Sintering Transparent Nanoporous Thin-Films for Use in Self-Cleaning, Anti-fogging, Anti-corrosion, Anti-erosion, Electronic and Optical Applications, US Patent Application US20100221513A1, Wisconsin Alumni Research Foundation, 2009.
[38] M.V. Boldrin-Zanoni, J.J. Sene, M.A. Anderson, Photoelectrocatalytic degradation of Remazol Brilliant Orange 3R on titanium dioxide thin-film electrodes, J. Photochem. Photobiol. Chem. 157 (2003) 55–63.
[39] P.A. Carneiro, M.E. Osugi, J.J. Sene, M.A. Anderson, M.V. Boldrin-Zanoni, Evaluation of color removal and degradation of a reactive textile azo dye on nanoporous TiO2 thin-films, Electrochim. Acta 49 (2004) 3807–3820.
[40] D.S. Winke, Evaluation of Photocatalytic Oxidation for Treating Exhaust Gas from Soil Vapor Extraction Operations, Master's Thesis, University of Wisconsin, 2010.
[41] M.Z. Khan, A. Ghaffar, M.A. Bahattab, M. Mirza, K. Lange, I.M.S. Abaalkheel, M.H. M. Alqahtani, A.A.A. Aldhuwaile, S.H. Alqahtani, H. Qasem, V. Naumann, C. Hagendorf, R. Gottschalg, K. Ilse, Outdoor performance of anti-soiling coatings in various climates of Saudi Arabia, Sol. Energy Mater. Sol. Cell. (2022) 235.