Unique coating solutions for steel substrates used in photovoltaic solar cells

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Abstract - The work aims at developing a functional coating to keep the surface of photovoltaic solar panels and the respective structure always clean. Maintenance of photovoltaic (PV) solar panels is an expensive and hardworking operation. The PV solar panels without maintenance accumulate dust and the efficiency decreases. The economic assessment applied to the case study of a large-scale PV solar plant, demonstrated that there are cost savings and energy profit gained when is applied coating maintenance instead of manual maintenance. This MSc thesis proposes a protective coating, easy to fabricate, easy to applicate and inexpensive.

The sol-gel route was used to produce this coating. The coating was composed of ethanol(EtOH): trimethylethoxysilane(TMES): ammonium hydroxide (NH_4OH 2M) with a molar ratio of 5.78:1:3.78, respectively. This coating was applied by spray and dip-coating onto glass slides, steel and on a commercial thin-film PV solar panel surface. A compatible coating with both steel and glass was obtained and the contact angle measurements revealed superhydrophobicity (>155º). Moreover, it was found that the droplets rolled-off the surface without any inclination of the substrates – self-cleaning property. A characterization of the coating was made by comparing TMES sol-gel coating and a TMES sol-gel coating modified with silica nanoparticles (SNPs). Scanning Electron Microscopy (SEM) showed a homogeneous coating and optical microscopy(OM) a transparent coating. The percentage of transmission (%T) showed that the TMES sol-gel coating was anti-reflective (%T=100%) and that the TMES sol-gel coating modified with SNPs was 91%. Furthermore, the efficiency of organic solar cells (OPVs) was evaluated. The application of the TMES sol-gel coating diminished efficiency 0.244% and the TMES sol-gel coating modified with SNPs decreased 0.354%.

Keywords: Sol-gel, organosilanes, superhydrophobic, self-cleaning, solar cells, functional coatings.

1. Introduction

Maintenance of PV solar panels is a major concern due to the increase of operational expenditures (OPEX). Most of the large-scale PV solar installations are located in places with difficult access to water (*e.g.* deserts) where they receive the highest direct normal irradiance (DNI). To maintain the surface of the PV solar panels dust-free it is necessary a regular maintenance, which sometimes is not performed due to several reasons. The accumulation of particles decreases about 40% the solar power conversion for each 4 gram of dust deposited per square meter [1, 2]. For this reason, lower amounts of electricity are produced and the initial investments are not fully recovered during the panels lifetime. To avoid this problem, and to boost the market of renewable energies, a cheaper and practical maintenance procedure has to be developed. There is an urgent need for solutions to improve the efficiency of PV solar panels exposed to dust and pollution atmospheres. In the last years, a cost-effective solution to the PV solar panels maintenance was claimed by applying superhydrophobic coatings with self-cleaning properties in solar cells. Coatings tailored for this specific application are still scarce and most of the cases they have been just tested in glass slides. Thus, this MSc thesis aims at developing a unique coating, compatible both with steel and glass substrates, which is superhydrophobic and has self-cleaning properties. The possibility of using only one type of coating to the solar cells surface and its support structures is an important tool to reduce the operation and maintenance (O&M) costs.

This superhydrophobic coating must have water contact angles above 150º and self-cleaning properties which is when the water contact angle hysteresis and the sliding angle is lower than 10º. A superhydrophobic coating with self-cleaning properties maintains the surface clean because the water droplets slide and rolled-off the surface easily [3, 4, 5, 6].

The coating was produced through sol-gel route. This method allows to control the surface morphology and chemical composition of the coating. Consequently, an optimum combination of surface roughness and superhydrophobic functionality was obtained. Several alkoxides were used as precursors, namely tetraethoxysilane(TEOS), trimethylethoxysilane(TMES) [6], hexamethyldisilane(HMDS) [7] or trimethoxy(octyl)silane (TMOOS) which has never been used before for this finality. The multiple coatings produced were characterized through contact angle measurements, SEM and OM. Moreover, optical transmittance measurements were made to evaluate the transparency of the surface which is an important property to measure the absorption of light when a coating is applied to the surface. Then, an efficiency evaluation was made with a solar simulator to compare the efficiency between a coated and a bare organic solar cell surface.

2. Experimental section

2.1 Substrates pre-treatment

A pre-treatment is required to obtain a uniform coating. Glass slides and carbon steel substrates were cleaned in an ultrasonic bath with ethanol for 15 minutes. Steel was polished with paper grit of silicon carbide (SiC) with different granulometries of 180, 400 and 800 (Struers, LaboPol-25). An amorphous silicon(a-Si) thin film PV solar panel and organic solar cells were also used as substrates, but without any pre-treatment.

2.2. Fabrication of superhydrophobic coatings

The coatings were synthetized through sol-gel route and used ethanol as solvent, one silane, or a combination of TEOS and other silane, as precursors and ammonium hydroxide(NH_4OH) 2M as catalyst. All silanes were purchased on Sigma-Aldrich. The molar ratio of H_2O:Silane+TEOS:EtOH was kept constant at 3.78:1:5.78 in order to obtain the silica films. Superhydrophobic coatings were achieved by varying the molar ratios between precursors (Silane/TEOS) and the pH of the solution. Additionally, 1 % of silica nanoparticles from Wacker (HDK®H2000) were added to the solution. When the molar ratio of TMOOS/TEOS was 0.5 and the pH=8 was obtained a coating with high hydrophobicity. When the pH=6.5 and using only HMDS or only TMES as precursors, superhydrophobicity was obtained. Superhydrophobicity was also attained with molar ratios of TMES/TEOS of 1, 1.1 and 2. In the absence of silica nanoparticles, the molar ratio HMDS/TEOS of 0.5 revealed behaviour close to superhydrophobic. In all the cases, the reaction mixture was stirred at room temperature for 1 hour. Then, each coating was applied on the pre-treated substrates by spray coating and dip-coating with a speed of 16 cm/min. In addition, the sol-gel coating was modified with 1 wt. % of SNPs and applied onto other substrates by the same route. After coating, samples were cured at 50ºC for 20h to remove residual solvent. In the following day, the substrates were removed from the oven and the characterization was started.

2.3. Characterization

The contact angle (CA) measurements were determined through Sessile drop method with a Goniometer. The sample was placed inside a thermostatted ambient chamber model 100-07-00 (Ramé-Hart, NJ, USA). The images of drops were obtained through a video camera (jAi CV-A50, Spain) mounted on a microscope Wild M3Z (Leica Microsystems, Germany) and they were studied by running the ADSA (Axisymmetric Drop Shape Analysis, Applied Surface Thermodynamics Research Associates, Toronto, Canada) software. The average static contact angles were obtained after measuring for 1 min each drop of pure water placed by a micrometric syringe in three different locations of the substrate surface. The sliding angle of the water droplets was observed directly with the substrate placed inside the chamber from the goniometer and with a slightly tilted surface or without inclination.

The microstructure of the coatings was observed by using Optical Microscopy (Leica DM 2700) and Scanning Electron Microscopy (FEG-SEM, JEOL JSM-7001F). Optical transmission measurements were performed using a UV-Vis spectrophotometer (PerkinElmer, Lambda 35) in the wavelength range between 300-700 nm. The organic solar cells efficiency evaluation was carried out by measuring the current in function of the applied voltage between -1 and 1.5 V. Those values were evaluated and converted into power and then the open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), fill factor (FF) and afterwards the efficiency (η) was obtained. The equipment used was a power voltage and current meter (*Keithley* 2400), a solar simulator AM 1.5 G from Newport brand and model *Oriel*, SOL 3A^{TM} as source of illumination, with a Xenon lamp power of 100 mW/cm^2 and a monochromator which enabled to measure the current in function of the wavelength – λ=300 nm.

3. Results and discussion

3.1. Contact angle measurements

<u>3.1.1. Coating with TMOOS+TEOS as precursors</u>

Several silanes were used as precursors:

- APTES (99%)- (3-aminopropyl)triethoxysilane;
- GPTMS(98%)- (3-Glycidyloxypropyl)trimethoxysilane;
- APTMS (97%)- (3-aminopropyl)trimethoxysilane;
- TMODS (90%)- trimethoxy(octadecyl)silane;
- TMOOS (96%)- trimethoxy(octyl)silane;
- TMES (98%) - trimethylethoxysilane;
- HMDS (99%)- hexamethyldisilane;
- TEOS (98%)– tetraethoxysilane;

However, the best results were achieved with TMOOS, HMDS and TMES. TMOOS has never been used before for this finality, but it has high potential because it is composed by a long n-alkyl chain length ($CH_3(CH_2)_6CH_2$-) which promotes strong hydrophobic interactions. When TMES was used as precursor this work adopted the approaches proposed by Sanjay *et al.* [6] and when HMDS was used, the Xiaoguang Li *et al.* [7] paper was used as reference.

Table 1 Contact angles from the uncoated substrates.

Uncoated substrates	Contact angles (º)
Glass slides	44.79
Carbon steel	57.26
Glass substrate from PV solar panel	72.63

The wettability with TMOOS precursor was studied in both glass and steel substrates. Different molar ratios were used between TMOOS/TEOS: 0:1, 1:2.6, 1:2, 1:1, 2:1 and 1:0 which corresponds to a %TMOOS of 0, 27.78, 33.33, 50, 66.67 and 100. In Figure 1 a) and Figure 1 b) is possible to observe higher hydrophobicity when the %TMOOS is 33.33 for both glass and steel substrates. Higher contact angles were achieved when the sol-gel coating was modified with silica nanoparticles. The highest contact angle for glass substrate was 137º and for steel was 129º, which means that were hydrophobic. Despite this result, the work performed opens the path for achieving a superhydrophobic coating with a new precursor.

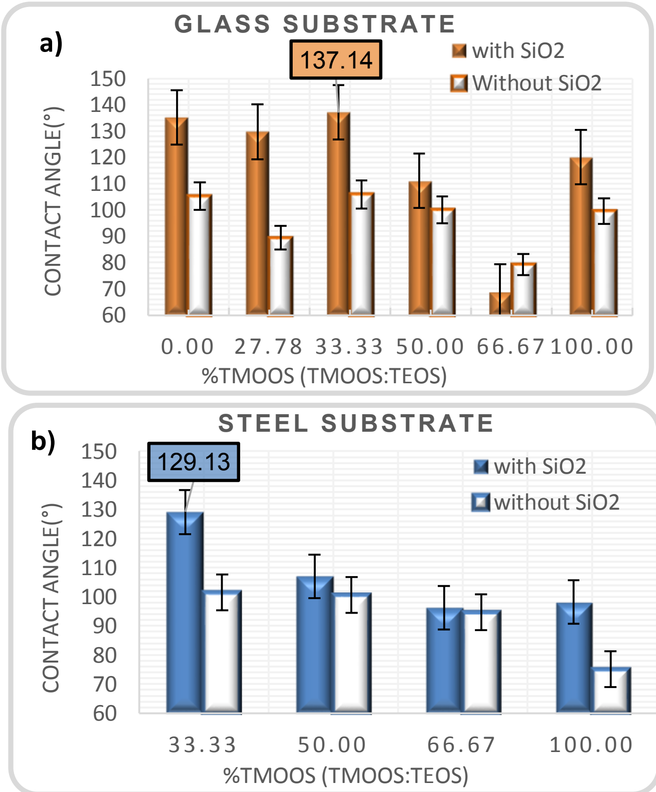


Figure 1 Variation of the contact angles in both glass(a)) and steel(b)) substrates with different percentages (%) of TMOOS (TMOOS: TEOS molar ratios).

<u>3.1.2. Coating with HMDS+TEOS as precursors</u>

The following coating was inspired in the paper from Xiaoguang Li *et al.* [7]. This coating was prepared by varying the molar ratios between two precursors, which were: HMDS and TEOS. The contact angles obtained on glass substrate are presented in Figure 2. In case of HMDS sol-gel coating, the highest contact angle achieved was 142º when HMDS: TEOS molar ratio was 1:2. Then, the HMDS sol-gel coating modified with 1 wt.% of silica nanoparticles was superhydrophobic when was only used HMDS precursor and the contact angle was 153º.

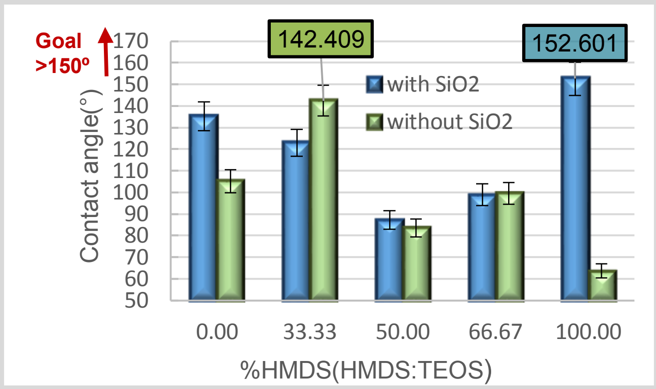


Figure 2 Contact angle measurements with different HMDS: TEOS molar ratios and with HMDS sol-gel coating and HMDS sol-gel coating modified with 1 wt. % of silica nanoparticles.

3.1.3. Coating with TMES+TEOS as precursors

A coating was prepared with TMES precursor besides TEOS. This coating was inspired on Sanjay *et al.* paper [6]. However, it is important to remind that all the coatings of this work used information published in papers, but most of the experimental conditions were modified and optimised, such as the formulation of the reaction mixture and the pH. The contact angles were compared, when the pH was equal to 6.5 and 10, when different TMES: TEOS molar ratios were used and when the TMES sol-gel coating was unmodified or modified with silica nanoparticles. The pH influence on this coating was studied and a higher number of superhydrophobic coatings were obtained at pH=6.5 – Figure 3.

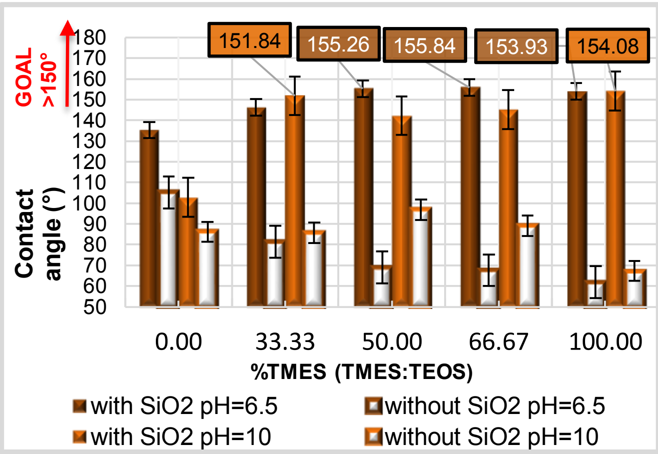
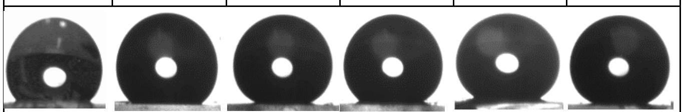


Figure 3 pH influence on the contact angles. Variation of %TMES and application on glass substrates.

At pH=10 the superhydrophobicity was achieved using TMES: TEOS molar ratios of 1:2 and 1:0. The coating formed at pH=6.5 revealed superhydrophobicity when using TMES: TEOS molar ratios of 1:1, 2:1 and 1:0, as shown in Figure 3. These results were obtained when the TMES sol-gel coating was modified with 1 wt. % of silica nanoparticles. The superhydrophobicity was maintained both at pH equal to 6.5 and 10 when only TMES is used as precursor. In these conditions the contact angles were 154º in both pH's. The contact angle measurements obtained for the TMES sol-gel coating modified and pH equal to 6.5 are presented on Table 2.

Table 2 Contact angle measurements through Sessile Drop Method of TMES sol-gel coating modified with silica nanoparticles when the pH=6.5.

Contact angles(º)					
TMES:TEOS molar ratios					
0:1	1:2	1:1	1.1:1	2:1	1:0
					
135º	146º	155º	154º	156º	154º

For further studies, was selected a coating only with TMES precursor and pH equal to 6.5. The reason for selecting this coating is because in addition to superhydrophobicity, with a contact angle of 154º, it seems to have self-cleaning properties. The droplets were applied by a micrometric syringe with different dimensions into the substrate inside the camera from the Goniometer and the droplets rolled-off easily without or with an inclination of the substrate close to zero – Figure 4.

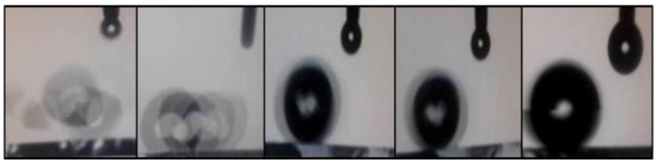


Figure 3 Self-cleaning observation (sliding angle<10º) through multiple shots taken by a digital camera while measuring the static contact angles in the goniometer with the different substrates.

3.1.4. Compatibility between different substrates

First, it is important to highlight that the coating chosen for further studies was obtained according to the conditions presented in Table 3.

Table 3 Conditions from the final coating chosen.

Molar ratios	H_2O:TMES: EtOH	3.78:1:5.78
pH	6.5	
Stirring	1h at RT	
Applications	Spray	
	Dip-coating	
Substrates	Glass	
	Steel	
	PV solar panel	
Curing	20h at 50ºC	

The TMES sol-gel coating modified with silica nanoparticles revealed superhydrophobicity (CA>150º) with self-cleaning properties. This coating was the only one that evidenced self-cleaning properties.

The TMES sol-gel coatings, without and with silica nanoparticles modification were compared. The coatings were studied when applied on glass and on steel using different application techniques. Figure 5 a) shows the results for the spray coating and in Figure 5 b) for a dip-coating.

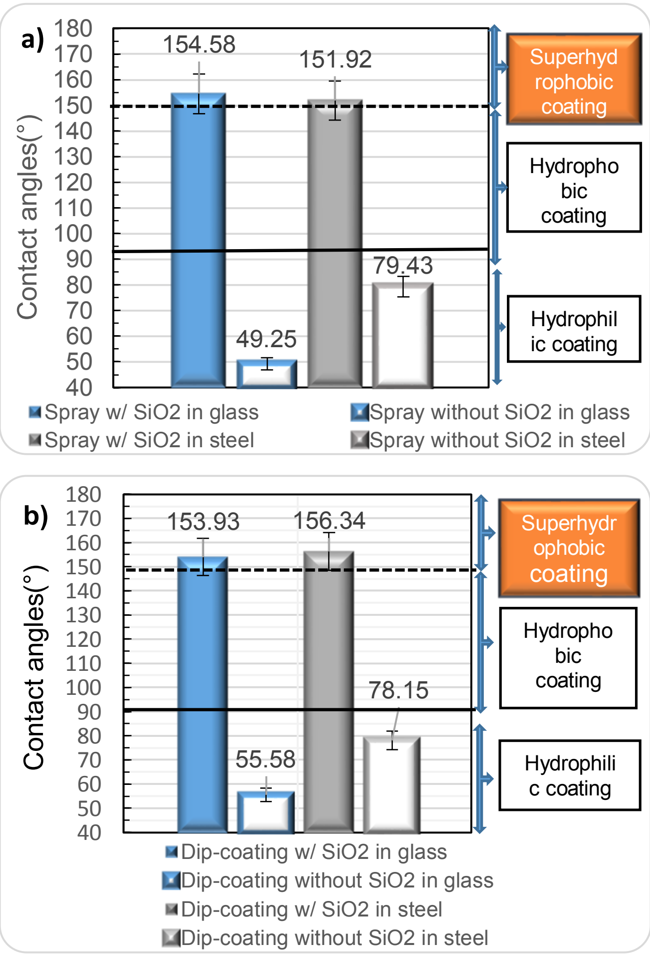


Figure 5 - Contact angles from the TMES sol-gel coating with and without SiO_2 by spray (a)) and dip-coating (b)) application to both glass and steel substrates.

TMES coatings modified with 1 % of silica nanoparticles revealed superhydrophobic behaviour in both steel and glass substrates and when applied by spray and dip-coating techniques. For spray and dip-coating on glass substrates the contact angles were 155 and 154º and for steel substrates were 152º and 156º, respectively. The coatings were hydrophilic when silica nanoparticles were not added – Figure 5.

The coating was also applied onto a commercial PV solar panel. This solar panel was composed of amorphous solar cells, which have Indium Tin Oxide (ITO) onto the surface. As shown on Table 1, the glass substrate of the solar cell surface revealed a contact angle of 72.63º. Both TMES sol-gel coating and TMES sol-gel coating modified with silica nanoparticles were applied by spray or dip-coating – Figure 6. TMES sol-gel coating modified with silica nanoparticles revealed superhydrophobicity, with contact angles above 156º regardless the application route – Figure 6. When it was sprayed, as thicker or thinner layer, the contact angles were 157º and by dip-coating the contact angle was 158º. When the TMES sol-gel coating was not modified, the applied coatings were all hydrophobic. The contact angles had an average of 93º in case of dip-coating and a sprayed thin layer and with a sprayed thick layer were obtained 120º. Therefore, TMES sol-gel coating modified with silica nanoparticles presents superhydrophobicity with self-cleaning properties regardless the substrate and coating application route – Figure 6. The best contact angles achieved in each substrate are presented on Table 4.

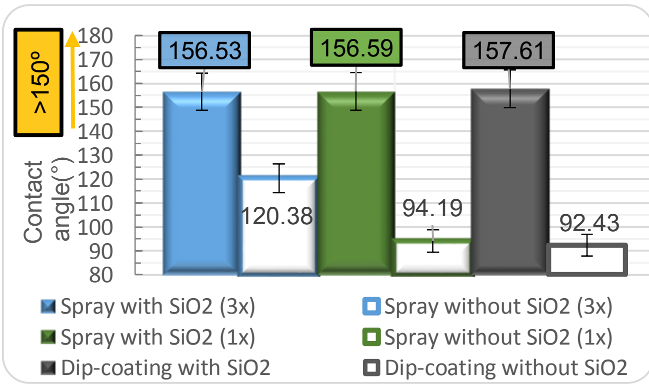
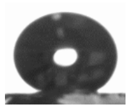
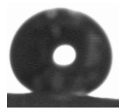
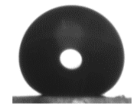


Figure 6 Contact angles with TMES sol-gel coating without and with addition of silica nanoparticles obtained in the solar panel surface through spray coating (3x and 1x sprayed) and dip-coating techniques.

Table 4 Best contact angles achieved with TMES sol-gel coating modified with silica nanoparticles in glass, steel and a PV solar panel substrate.

Contact angles(º)		
Substrate		
Glass	Steel	Solar panel
		
155º	156º	158º

3.2. Scanning Electron microscopy characterization

<u>3.2.1 Glass slides substrates</u>

Figure 7 compares the morphology of the TMES sol-gel coating and the TMES sol-gel coating modified with silica nanoparticles on glass substrates.

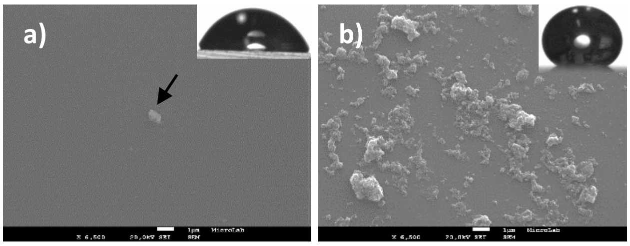


Figure 7 SEM micrographs with HV=20kV from a) TMES sol-gel coating and b) TMES sol-gel coating modified with silica nanoparticles on glass substrates. Scale 1 µm and mag=6500x.

SEM micrograph - Figure 7 a) revealed a smooth coating which is beneficial for solar panels application. The irregularities may be silica related due to the precursor TMES and the sol-gel process reactions - hydrolysis, polymerisation and condensation.

The glass coated with TMES sol-gel coating modified with SNPs - Figure 7 b) - revealed the presence of some particles in the coating. The agglomerations are due to the cross-linking between the tetramethylethoxysilane (TMES) chain to the silica nanoparticles. As shown by the SEM micrographs presented on Figure 7, 8 and 9, a uniform distribution of the coating along the surface it is obtained when dip-coating technique is used.

<u>3.2.2 Steel substrates</u>

The Figure 8 a) shows a smooth surface and through OM was seen a transparent coating. Figure 8 b) revealed a good surface coverage with silica particles.

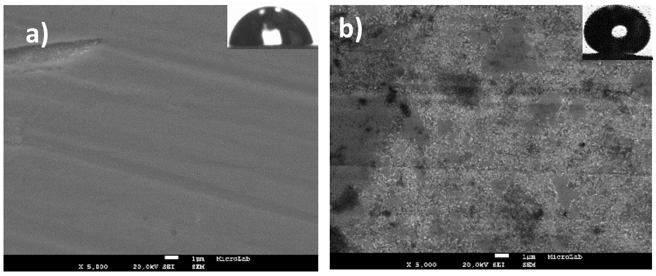


Figure 8 SEM micrographs with HV=20kV from a) TMES sol-gel coating and b) TMES sol-gel coating modified with silica nanoparticles on steel substrates. Scale 1µm and mag=5000x.

<u>3.2.3 PV solar panel surface</u>

The SEM micrographs of the TMES sol-gel coating presented on Figure 9 a), b) and c) present irregularities along the surface with a size around 6.5 µm. Another important aspect is that neither cracks nor fractures were observed. In respect to TMES sol-gel coating modified with SiO_2 nanoparticles it is possible to observe a different surface morphology – Figure 9 d), e) and f). The SEM micrographs showed round shape silica particles with d<10 nm and also some agglomeration of the particles. These agglomerations of silica nanoparticles (SNPs) forms clusters which promotes superhydrophobicity [8]. The coating is homogeneous, thick and can be observed a few cracks.

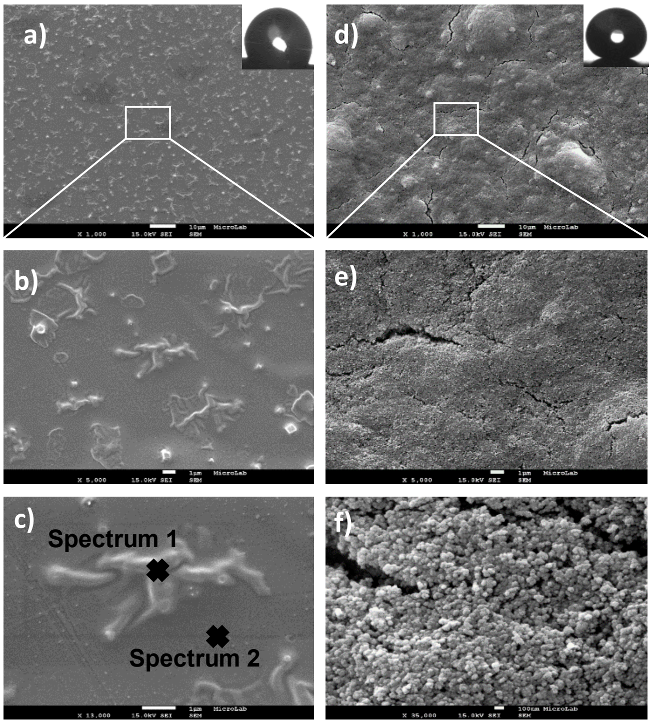


Figure 9 Solar panel with a), b), c) TMES sol-gel coating and d), e), f) TMES sol-gel coating modified with hydrophobic SiO_2 nanoparticles. SEM micrographs with HV=15 kV: a) scale=10µm and mag=1000x; b) scale=1 µm and mag=5000 µm; c) scale=1 µm and mag=13,000 µm.; d) scale=10µm and mag=1000x; e) scale=1µm and mag=5000 µm; f) scale=100 nm and mag=35,000x.

The irregularity on Figure 9 c) gave the chemical composition depicted in Spectrum 1 and the surroundings in Spectrum 2 – Figure 10 - which was investigated through an Energy Dispersive Spectrometer (EDS). The spectrum from Figure 10 shows that the chemical composition from the irregularity is the same as the surroundings.

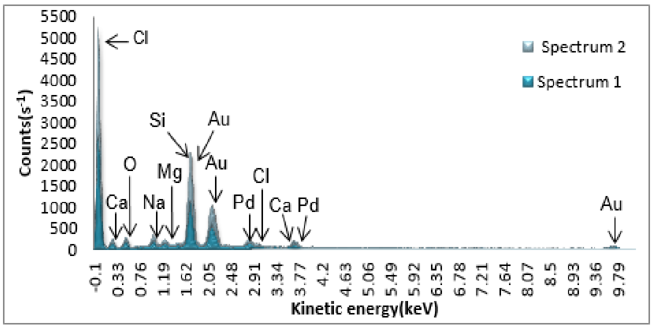


Figure 10 Energy Dispersive Spectrum (EDS) from the PV solar panel with TMES sol-gel coating.

3.3. Transmittance measurements

These measurements were made to assess the transparency of the coating. The highest the percentage of transmission (%T), the highest the transparency. This study was made with glass substrates. It was compared the transparency between TMES sol-gel coating and TMES sol-gel coating modified with silica nanoparticles (SNPs). The wavelengths ranged between 300 and 700 nm. The absorption measurements were converted to %T through equation (1) [9]:

$$A = 2 - \log(\%T) \qquad (1)$$

TMES sol-gel coating was antireflective because the percentage of transmission was 100%. For the TMES sol-gel coating modified with SNPs it was in average 91% of transmission along the wavelength interval (Figure 11). It is also noticed a decrease in optical transmission at lower wavelength values.

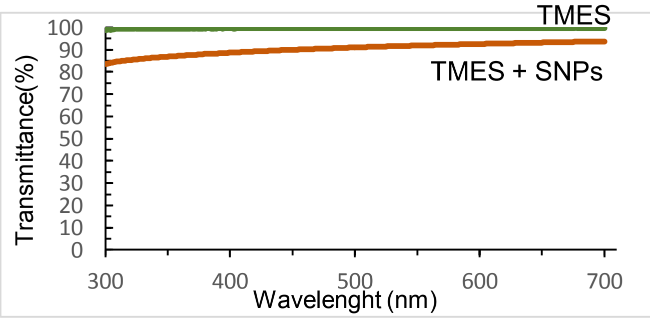


Figure 11 Optical transmission spectra for glass samples with TMES sol-gel coating and TMES sol-gel coating modified with silica nanoparticles (SNPs).

3.4. Solar cells efficiency evaluation

Efficiency is an important parameter to evaluate the influence of the coating on the solar cell performance. Two organic solar cells encapsulated with glass were used and each solar cell revealed different efficiencies due to the active layer characteristics. First, it was measured with light the uncoated surface current in function of the applied voltage from both organic cells. Then, the experiment was performed, but on a coated surface with TMES sol-gel coating in the organic cell 1 and TMES sol-gel coating modified with SiO_2 nanoparticles (SNPs) in the organic cell 2. The data was transformed in J-V curves (Current Density (mA/cm^2) – Voltage (V) curves) and the following performance parameters were evaluated to calculate the final efficiency: J_{sc} (short-circuit current density), V_{oc} (open-circuit voltage), P_{max} (maximum power point) where current density(J) and Voltage (V) achieve the maximum values, FF (fill factor) and η(efficiency). Table 5 shows the performance parameters results from both organic solar cells (OPVs) tested. The equations used were (2) and (3) [10]:

$$FF = \frac{P_{max}}{V_{OC} I_{SC}} \ (2) \qquad \eta = \frac{J_{SC} V_{OC} FF}{P_{in}} = \frac{(JV)_{max}}{P_{in}} = \frac{P_{max}}{P_{in}} \ (3)$$

Table 5 Organic cells (OPVs) performance parameters: J_{sc}, V_{oc}, P_{max}, FF and η with uncoated and coated surface.

	Organic cell 1		Organic cell 2	
	Uncoated surface	TMES sol-gel coating	Uncoated surface	TMES sol-gel coating modified with SNPs
J_{sc}(mA/ cm^2)	-2.627	-2.419	-7.229	-6.914
V_{oc}(V)	0.944	0.975	0.947	0.968
P_{max}(mW)	1.485	1.241	3.743	3.389
FF (%)	59.51	54.00	54.49	51.59
η(%)	1.485	1.241	3.743	3.389
$\eta_{uncoated}$-η_{coated}(%)	0.244		0.354	

In order to compare the uncoated and the coated surface efficiency, it was necessary to plot the J-V curves of each solar cell – Table 6. The efficiency of the OPVs decreased 0.244% with TMES sol-gel coating and decreased 0.354% with TMES sol-gel coating modified with silica nanoparticles. Efficiency decreased more for the coated surface with TMES sol-gel coating modified with SNPs.

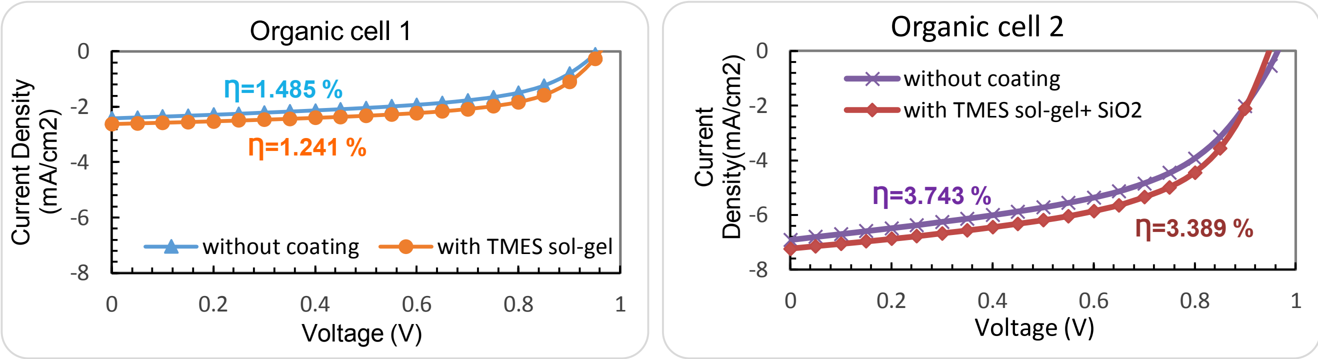


Figure 40 J-V curves from: Organic cell 1 - comparison between uncoated surface and surface with TMES sol-gel coating; Organic cell 2 - comparison between uncoated surface and surface with TMES sol-gel coating modified with silica nanoparticles.

4. Economy viability of using coating maintenance in PV solar panels and Martifer Case study

Presently, due to the quick science evolution, is becoming more difficult to find innovative ideas to improve technologies. In this MSc thesis, the proposed product is a novel coating which is intended to replace other types of maintenance and to be an economical alternative. Although, the economic viability of the coating needs to be study to have a clear picture of the benefits of using coatings maintenance for PV solar panels instead of manual maintenance. The coating selected for this study was the TMES sol-gel coating modified with silica nanoparticles which revealed superhydrophobicity with self-cleaning properties. Therefore, the Martifer Solar case study was selected and the costs of using the coating maintenance in large-scale were evaluated.

4.1. Overview of the coating maintenance investment

In order to apply coatings maintenance, the cost is dependent on the area of each solar panel (€/m^2) due to the amounts of solution required.

The coating can be applied in two cases: to already installed PV solar panels or to implement during production of PV solar panels. In the Martifer Solar case study the PV solar plant was already installed. The maintenance is made by an operator of the plant or from an outside supplier which must apply a spray the coating over each photovoltaic solar panel.

The labour expenses will be higher if the coating is applied by someone outside the installations instead of a plant operator. Also the access is costly due to the transportation costs. As a result, microgeneration installations have a higher cost of maintenance per square meter compared to PV solar plants.

4.2. Implies a reduction in maintenance cost

A PV solar plant is planned for an average lifetime of 30 years. Manual maintenance requires more cleaning frequency and the time during cleaning – downtime - is higher compared to the use of coating maintenance. When selective coatings are used, the cleaning frequency is with an interval of 10 years (1 initial application more 2 reapplications in 30 years) and a reapplication downtime of 15 days. However, the degradation of a coating can vary, depending on the environment. If the coating degrades slowly is recommended a single reapplication at halfway through the plant lifetime. In case of intermediate and early degradation of the coating, the optimal re-application is estimated with an interval of 2.5 years [11].

4.3. Martifer Solar Case study

The Algarve Projects from Martifer Solar includes Avalades PV plant and Ferreiras PV plant – Table 7. This case study has the purpose to show the high maintenance costs savings and the higher energy produced when protective coatings are used instead of manual maintenance.

Table 6 Specifications from the PV plants used in the Martifer Solar case study [12, 13].

Case Study Algarve PV plants(Martifer Solar)	Avalades	Ferreiras
Capacity(MW)	15.6	6.8
System size(MW)	22.4	
Investment(Annual Report 2012)(M€) [13]	14,8	5,6
Investment Cost(Avalades+Ferreira)(M€)	20,4	
Lifetime(years)	25	
Energy Produced(GWh/year)	37.4	
Total area(m^2)	570,000	
Area from 1 module(m^2)	2	
Module Quantity(HSL 72S Poly module from Hanwa Solar)	94,400	
Area from the total modules(m^2)	188,800	

4.3.1. Coating characteristics

In this work, several attempts were made in the lab to prepare the desired coating. The components of the optimised coating were: TMES, EtOH, a pre-prepared solution of NH_4OH 2M and 1 % of silica nanoparticles. In order to introduce the coating into all the modules (188,800 m^2) are needed 37,156 L from the solution presented in Table 8. The total cost of that amount is 190,2 k€. Labour costs are included in this coating price because for industrial applications the purity grade of the reagents is lower and the price of the coating will decrease substantially.

Table 7 Coating constitution (small-scale).

Laboratorial Scale dimensions (for 0.06 m^2 application)		
Reagents	Volume(mL)	Price(€)
EtOH	6.85	0.43
TMES	3.22	6.08
NH_4OH 2M	1.37	0.39
Silica hydrophobic nanoparticles (g)	0.0975	0.02
Total	11.5	6.92

4.3.2. Saving Costs in O&M

In order to compute the cost savings, five scenarios were presented and estimated for the PV solar plant lifetime of 25 years. The 1st scenario is the case that often happens when the regular manual maintenance is not accomplished - each three years. The 2nd scenario is the manual maintenance recommended in Portugal, which is yearly. For the 3rd, 4th and 5th scenario the coating maintenance was applied. The 3rd is applied a durable coating which is applied three times through lifetime, the 4th scenario is when is applied only one half through lifetime and the 5th is when is applied each 4 years [1, 11, 13, 14, 15]. The obtained cost saves are presented on Table 9:

Table 8 Money saved by comparing each scenario.

Comparisons	Saves(M€)
Between 1st scenario and 3rd scenario	2,69
Between 1st scenario and 4th scenario	2,88
Between 1st scenario and 5th scenario	1,93
Between 2nd scenario and 3rd scenario	9,22
Between 2nd scenario and 4th scenario	9,41
Between 2nd scenario and 5th scenario	8,46

4.3.3. Increments in Energy Production

Maintenance frequency influences energy production of the PV solar panels. The five scenarios from O&M were used to study the Energy Production profit (€/m^2). The considerations made to compute were: the decrease in energy production each year with and without coating is 2% and 10%, respectively [16, 17] and secondly the profit obtained from each kWh produced (Table 10) taking into account the Portuguese Decree Law – DL35 from February 28th of 2013 – is 0.036 €/kWh [18].

Table 9 Energy production profit during the lifetime from the PV solar plant [16, 17, 18].

Energy Production Profit (M€/ 25 years)		
Manual Maintenance	1st scenario	27.59
	2nd scenario	30.29
Coating Maintenance	3rd scenario	30.57
	4th scenario	30.40
	5th scenario	32.02

Afterwards, was investigated the increase in energy production profit when is used coating maintenance instead of manual maintenance – Table 11. According to the results, the coating maintenance achieves always higher energy production and turns out to be a more cost-effective solution.

Table 10 Energy profit gained with coating maintenance instead of manual maintenance.

Energy Profit gained with coating maintenance(M€/25 years)	
Between 3rd and 1st scenario	2.98
Between 4th and 1st scenario	2.81
Between 5th and 1st scenario	4.43
Between 3rd and 1st scenario	0.27
Between 4th and 1st scenario	0.11
Between 5th and 1st scenario	1.73

5. Conclusions

This MSc thesis has achieved the goal of obtaining a unique functional coating possible to be applied on photovoltaic solar cells. Compatible coatings with glass and steel substrates were obtained through sol-gel route with TMOOS, TMES, HMDS and a combination of these silanes with TEOS. Superhydrophobicity was achieved with coatings which have TMES or HMDS precursors. Moreover, was obtained only one coating which is superhydrophobic with self-cleaning properties and has TMES precursor and addition of silica nanoparticles. This coating is compatible with glass and steel substrates with contact angles above 152º and in the PV solar panel presents contact angles above 157º regardless the coating application route. Spray coating was the chosen application for already installed PV solar panels and spray or dip-coating application to PV solar panels during the fabrication process. The optical transmission measurements revealed that TMES sol-gel coating is anti-reflective and when the coating is modified with SNPs the transparency diminishes slightly to 91%. Regarding the efficiency assessment, coated organic solar cells with addition of SNPs presents a higher decrease in efficiency. However, the results obtained are acceptable due to the advantages of the coating, such as: high optical transmission, easy to produce, simple to apply and inexpensive. The economic viability study and the Martifer Solar case study points out the advantages of using coating maintenance compared to manual maintenance. The money is saved and the energy production profit increases when is used coating maintenance. Therefore, it is beneficial to apply this coating as maintenance strategy in large-scale PV solar plants.

In the future, it is recommended to verify the long-term storability of this coating, the resistance to degradation with time, compute with a tensiometer the dynamic contact angles and proceed with the coating with TMOOS precursor which is new for this purpose.

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