Analysis of the Local Factors that Influence the Cementation of Soil and Effects on PV Generation at the Plataforma Solar Del Desierto De Atacama, Chile

Douglas Olivares[1], Mauricio Trigo-González[1] , Aitor Marzo[1], Pablo Ferrada[1], Jaime Llanos[2], Francisco Araya[1],Gabriel López[3], Jesús Polo[4], Joaquín Alonso-Montesinos[5] and Christian Gueymard[6]

[1] Centro de Desarrollo Energético Antofagasta, Universidad de Antofagasta, Antofagasta (Chile)

[2] Universidad Católica del Norte, Antofagasta (Chile)

[3] Ingeniería eléctrica y térmica de diseños y proyectos, Universidad de Huelva. Huelva (España)

[4] Photovoltaic Solar Energy Unit (CIEMAT), Madrid (España)

[5] CIESOL, Joint Centre of the University of Almeria-CIEMAT, Almería (España)

[6] Solar Consulting Services, Colebrook (United States of America)

Abstract

The Atacama Desert is one of the world's top places for the development of photovoltaic (PV) projects due to the abundant sunlight available for conversion into electricity. The desert environment, however, adversely affects the optimal performance of PV systems. These effects can be caused by high temperatures, ultraviolet radiation, or concentration of dust in the atmosphere. This study evaluates the soiling effects on the energy production of PV systems at the Atacama Desert Solar Platform (PSDA), and attempts to determine their possible relationships with local atmospheric variables. In particular, the research focuses on the cementation processes that typically occur on glass panels during a typical day, as influenced by solar radiation, humidity, ambient temperature and wind speed, and on quantifying their effects on the optical properties of PV panels as well as their energy production. X-ray diffraction (XRD) revealed the presence of hygroscopic particles (gypsum) that interact with humidity, promoting the adhesion of insoluble substances onto the glass cover of PV modules. This effect is intensified due to the prolonged exposure times to local environmental conditions, reaching an average deposition density of 0.7 mg cm^{-2} during four weeks of exposure. In terms of glass transmittance effects, typical optical losses of 38% relative to the clean condition were also measured, while the PV current density dropped at a rate of 21 mA cm^{-2}/mg cm^{-2}.

Keywords: Soiling, Dust, Transmittance loss, Photovoltaics, Atacama Desert

1. Introduction

The Atacama Desert has one of the highest solar irradiation levels on the planet. Values above 8 kWh/m^2 per day or 2920 kWh/m^2 per year have been recorded in some areas (Escobar et al., 2014). This excellent solar resource has allowed the proliferation of solar projects and the increase of public policies (Marzo et al., 2017; Zurita et al., 2018). This growth has also brought with it challenges related to the local geography, because the northern zone of Chile experiences an extreme aridity, high salinity, shortages of rain, the influence of the Pacific ocean, the presence of a strong mining industry, and local specific humidity phenomena called "Camanchaca" (Olivares et al., 2017). One of the direct consequences of Atacama's desert environment is the effect of soiling on photovoltaic (PV) systems. The soiling is defined as layers of dirt that are deposited on the glass surface of PV modules, thus increasing their optical losses (Sarver et al., 2013).

The dust accumulation processes depend mainly on three factors: meteorological conditions, type of dust, and PV installation characteristics (Sarver et al., 2013). The meteorological variables to consider are: temperature, solar radiation, humidity, wind speed, and wind direction. Regarding dust, its chemical composition has an important role, and involves contaminants that can be inorganic (salt, silicates, etc.) or organic (e.g., bird dropping) (Sayyah et al., 2014). In addition, other characteristics, such as solubility, pH, chemical composition, or particle size, interact in the accumulation processes (Javed et al., 2017). Finally, the PV installation factors include effects from the surroundings (mining, industrial, coastal, desert, etc.) and the installation's geometry (tilt and azimuth) (Mussard and Amara,

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2018). All the variables mentioned above interact to dynamically create and alter various possible mechanisms of deposition, which are divided into five stages:

(i) Deposition: It is the process through which the airborne particles are transported from the environment to the glass surface of a PV module. More specifically, some atmospheric variables, such as wind speed, wind direction, or humidity, interact with physical parameters such as particle size, electrical charges of the particles, or module geometry. This constitutes the first stage of deposition (Taylor et al., 2014; Figgis et al., 2017a).

(ii) Initial adhesion: At this stage the particles adhere to the surface of the PV module. The particles are already stable on the glass surface in spite of disturbances created by, e.g., wind interactions with the module's tilt angle or orientation. A few atmospheric variables (particularly humidity and temperature) affect various dust properties, such as particle size, chemical composition, or electrical charges of the particles (Tomas, 2004; Kazmerski et al., 2017).

(iii) Particle-particle interaction: This is the interaction that takes place between particles deposited on the surface of a PV module. This interaction is strongly influenced by Van der Waals forces, capillarity, physicochemical properties, and related electric charges. These parameters also interact directly with atmospheric variables such as humidity or temperature. This mechanism is increased in the cementing process discussed below (Figgis and Brophy, 2015; Figgis et al., 2017a; Kazmerski et al., 2016).

(iv) Cementation: This is the stage during which the soluble and hygroscopic particles are able to attract water and convert the mix into a chemical solution. Consequently, at the time of recrystallization, this substance becomes a kind of cement that glues together the soluble and insoluble particles to the glass cover. In this process, atmospheric variables such as humidity and temperature are important because they interact with the chemical composition and the size and electrical charges of all particles (Cuddihy, 1980, 1988).

(v) Re-entrainment: At that final stage, some (or nearly all) particles are removed from the PV panel through the natural cleaning action of a fluid (such as rain drops) that is created or affected by humidity, dew, wind speed, and wind direction. The physicochemical properties of the deposited material, which directly influence this mechanism, are the size, shape, chemical composition, electrical charges at the module surface, electrical charges of the particles, as well as installation factors such as geometry (relative to the dominant wind direction) or type of structure (modules with or without frame) (Figgis and Brophy, 2015; Figgis et al., 2017b).

The first four processes are illustrated in Fig. 1. The particles are transposed and deposited (1), some particles may have enough energy to bounce off (2) and others not (3). The particles that remain deposited on the PV module's cover then undergo solubilization and recrystallization processes that occur during the day. This means that the greater the exposure time, the greater the dirt layer that will be generated (3). Finally, if the soiling particles are exposed to the natural cleaning fluid being developed with enough energy, they can be removed from the surface (4).

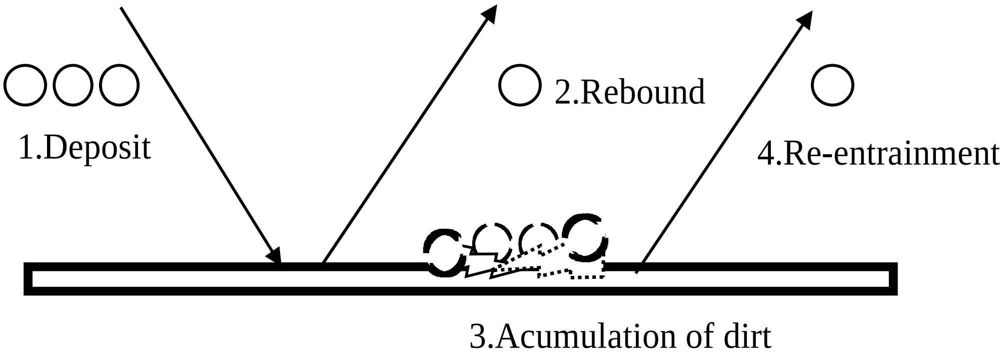


Fig. 1: Stages of the soiling process for PV modules. (1) Initial deposition and movement of airborne particles; (2) Bouncing of particles that do not have the ability to adhere to a surface; (3) Accumulation process of the particles that adhere to the surface of a module by action of the soluble material and electric charges; and (4) Re-entrainment, whereby adhering dirt is removed from the surface (image based on Figgis et al., 2017) .

Different authors have quantified the negative effects of soiling on PV power generation. Some extreme cases, with daily output power losses of ≈1.5%, have been reported in Abu Dhabi (UAE), Kuwait City (Kuwait), and Dhaka (Bangladesh) (Al Hanai et al., 2011; Sayyah et al., 2014; Rahman et al., 2012). In the case of Chile, a study of the high potential of PV energy in the Atacama Desert (Ferrada et al., 2015) indicated that there are no long-term scientific data to help understand the local behavior of soiling. This lack of precise data is a source of uncertainty, which translates into a larger risk for investors. The authors of the aforementioned study concluded that optical losses due to dirt are expected to vary depending on the location and weather conditions, with negative impacts that may be widely variable.

The present study focuses on the cementation process by analyzing the local atmospheric variables and physicochemical properties of soiling. The goal is to obtain a deeper understanding on how these factors interact. For this purpose, the chemical composition of the soiling particles has been determined, while the wind characteristics, the relative humidity, and the density of deposited particles were also monitored. As a result, the impact of the cementation process is evaluated in terms of optical response and generated output current.

2. Material and methods

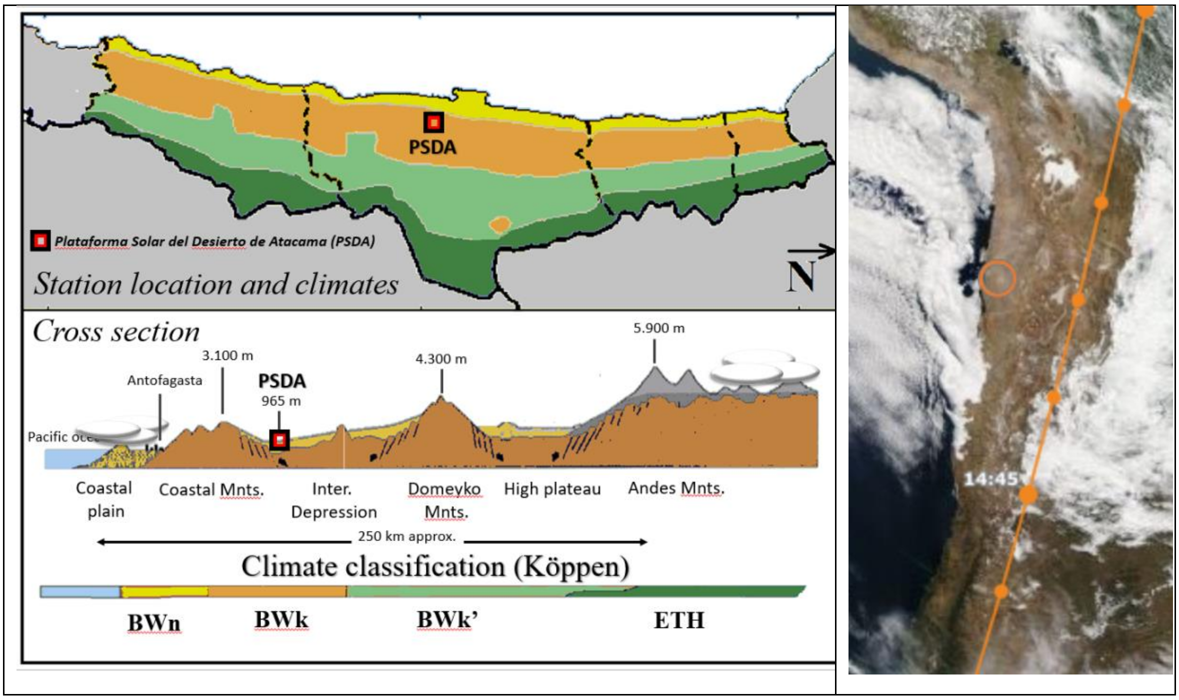


Fig. 2: Top left: localization of Plataforma Solar del Desierto de Atacama (PSDA). Bottom left: cross section of the Antofagasta Region and climate classification according to Köppen (Image based on Marzo et al., 2018). Right: picture taken by the MODIS-Terra instrument from space, April 30th 2019 (http://aeronet.gsfc.nasa.gov). The orange circle highlights the PSDA location and the orange line marks the satellite transit on that day.

Plataforma Solar del Desierto de Atacama (PSDA) belongs to the Universidad de Antofagasta, Chile. It is located at an elevation of 1000 m in the inner part of the Atacama Desert (24.09°S, 69.93°W). It is characterized by a BWK climate, according to the Köppen climate classification (Kotter et al., 2007), which corresponds to an arid zone (Fig. 2). At PSDA, many atmospheric variables are routinely monitored and analyzed, while experimental installations are set up to measure soiling-related quantities, including chemical composition of particles, rate of dust surface density deposition, and transmittance losses of standard glass.

An important experimental activity involves the physical-chemical characterization of the soiling particles. Dust samples from the material deposited on the surface of PV modules are analyzed in the laboratory. For this purpose, the samples are collected using a hard filament brush to collect any form of sedimented and deposited dust. The samples are stored in plastic bags and taken to the laboratory. These samples are then processed in a rotating micro riffler of Quantachrome, in order to improve the statistical representativeness of the samples. This device uses mechanical (vibratory) energy that provides a constant flow of material from its support. The material passes through a divider head that rotates at a constant speed, minimizing segregation. The amplitude of the vibratory motion and the velocity of the circular motion can be controlled separately. These specifications are essential to correctly subdivide the different flow variables and obtain representative samples. Once the samples are collected and processed, they are submitted to two types of analysis for their physical-chemical characterization.

First, samples are analyzed in a Powder X-ray diffraction (PXRD), using a Bruker AXS D8 advanced diffractometer in the range 2–60°, with CuKα radiation ($\lambda = 1.5045$ Å) at 40 kV and 30 mA. These measurements are made at room temperature. The qualitative analysis is performed using the PDF-4 powder diffraction file in relational database format (Kabekkodu et al., 2002). For the quantification of samples deposited on the surface of PV modules, the TOPAS program is used, applied to the diffractograms obtained by X-ray diffraction. TOPAS is specialized software used here to analyze crystalline profiles and structures by means of the Rietveld method, providing analytical results.

Another type of analysis is conducted using scanning electron microscopy (SEM) and energy dispersive X-ray spectrometry (EDX) microanalysis. These tests are performed to analyze the morphology of the smallest particles and determine the chemical composition of soiling as a whole. A Jeol JSM-6360 LV scanning electron microscope is used together with an energy dispersive spectrometer (Oxford Inca C200).

To better understand the deposition and adhesion processes of the airborne material deposited on PV surfaces, various key atmospheric variables are obtained from the PSDA meteorological station. The Global Horizontal Irradiance (GHI) is measured with a CMP21 Kipp & Zonen pyranometer, while ambient temperature (T_{amb}) and relative humidity (RH) are recorded with a thermometer and hygrometer (Young models CS215-L11 and HMP60-L11, respectively). Wind speed (WS) and direction are measured by an anemometer (Young 05103-5). Measurements are taken at a frequency of 1 Hz and recorded as an average value per minute. The surface dust density deposition rate was measured by exposing samples over periods of one month and recording their mass changes each week. This process was repeated until reaching 7 months of measurements. The campaign consisted of placing the objects in triplicate with a size of (5×9 cm^2) on the surface of PV modules fixed at a tilt of 20°. The method used was gravimetric for mass gain.

Changes in optical properties (such as glass transmittance) caused by soiling of the glass cover of PV modules were monitored with reference silicon cells under natural light at normal incidence. Transmittance measurements were performed on standard PV glass samples exposed to outdoor conditions with different surface densities. The measured PV glass samples size was 4.7 x 6.5 cm, with a thickness of 3.2 mm.

3. Results and Discussions

3.1 Physicochemical characterization

The chemical characterization of the soiling particles was carried out by XRD of samples taken from an entire PV string, as shown in Fig. 3. It can be observed that, at PSDA, the natural dust accumulated on the surface of the PV modules is composed mainly of clays and silicates, which correspond to the geology of that location, as reported recently (Olivares et al., 2017; Ferrada et al., 2019). The minerals found correspond to (a) Anorthite ($CaAl_2Si_2O_8$), (b) Muscovite ($KAl_2(AlSi_3O_{10})(OH)_2$), (c) Orthoclase (**$KAlSi_3O_8$**), (d) Illite ($(K,H_3O)(Al, Mg, Fe)_2(Si, Al)_4O_{10}$), (e) Quartz ($SiO_2$), (f) Albite ($NaAlSi_3O$), and (g) Gypsum. In Fig. 3, the letters (a) to (g) refer to the mineral species used in the diffractograms, as just described.

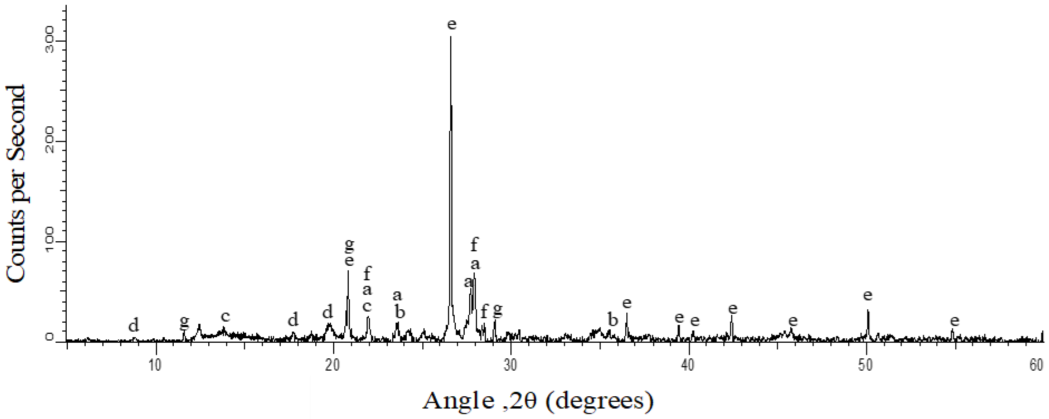


Fig. 2: XRD for soiling samples deposited on a string of PV modules installed at PSDA.

After this qualitative step, the presence of each species was evaluated with the TOPAS software program. This process was actually just a partial quantification, because the concentration of some materials was below the detection threshold of the equipment. As a result, low signals can lead to confusion due to overlapping. The analysis revealed the following material fractions (from highest to lowest, on average): Quartz (27%), Anorthite (20%), Albite (19%), Orthoclase (11%), Muscovite (11%), Illite (6%), and Gypsum (6%).

These results are consistent with the diffractograms in the sense that the most pronounced signals correspond to quartz, which is the main compound, closely followed by the signals of anorthite and albite. By means of the characterization explained above, the presence of a soluble salt (gypsum, $CaSO_4$) was found in low quantity in comparison with the other species. Despite its low quantity, gypsum appears responsible for the process of cementation, generating crusts of a mixture of insoluble and soluble materials on the glass surface. In order to obtain a deeper view of the deposited material, an SEM analysis was performed. Particles with predominantly prismatic shapes were found, thus seemingly confirming the presence of gypsum—considering that the latter has a crystalline monoclinic structure (Fig. 3b). This is observed with elemental mapping through EDX, where the existence of calcium and sulfur confirms the presence of gypsum (Fig. 3c). Figure 3a also reveals that most of the particles have a spherical or prismatic geometry, according to previous studies carried out at the same location (Ferrada et al., 2019). This result can be explained by the *Akinobu-Otsuka model* (Otsuka et al., 1988), which states that the first particles deposited on a clean surface are those with a random morphology and size less than 100 µm (Biryukov, 1996; Figgis et al., 2017a). Over time, the spaces available on the glass surface tend to decrease. At this point, the smaller particles (mostly spherical) begin to fill these available spaces, mainly because these particles contain a contact point, which facilitates their interaction with the glass, unlike particles with other geometries.

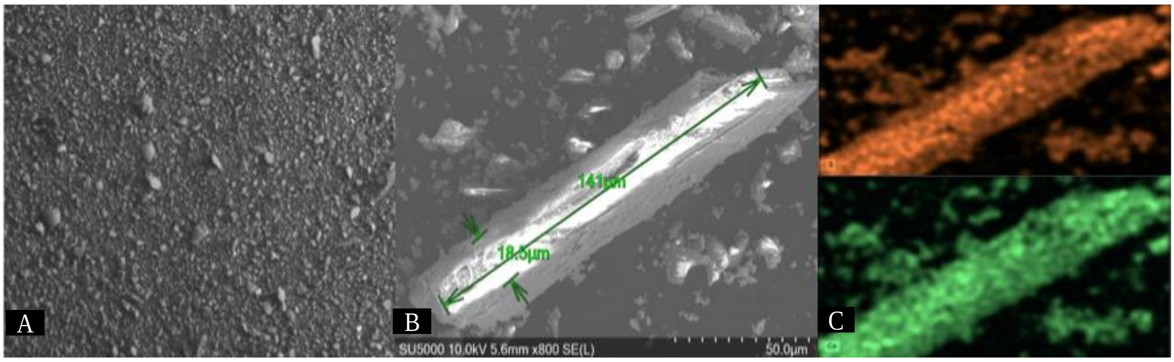


Fig. 3: Scanning electron microscopy of dust samples deposited on the surface of PV modules. (A) Particles with prismatic and spherical shape; (B) Prismatic particle; and (C) Elemental mapping of two prismatic particles: a sulfur particle (orange) and a calcium particle encapsulating the deposited material (green).

3.2 Atmospheric variables and their interaction in the sedimentation process

Regions with high concentrations of dust in the air and high humidity conditions can support the cementation processes by increasing the adhesion of the particles onto the glass surface (Ilse et al., 2016). In desert and semiarid zones, like Atacama, the diurnal variations of temperature and humidity are substantial. This phenomenon explains why surfaces are typically wet in the morning (because condensation during the night is intense), and why dry stains of dirty moisture appear because of the high temperatures experienced in the morning. This overall effect can be seen in Fig. 4, exemplifying modules of two different technologies installed on PSDA: thin film and polysilicon. Dry droplet stains contain soluble material that evaporates at some point, leaving a characteristic whitish color. The difference in appearance and soiling losses between the two types of PV module appears important and will be investigated in a subsequent contribution.

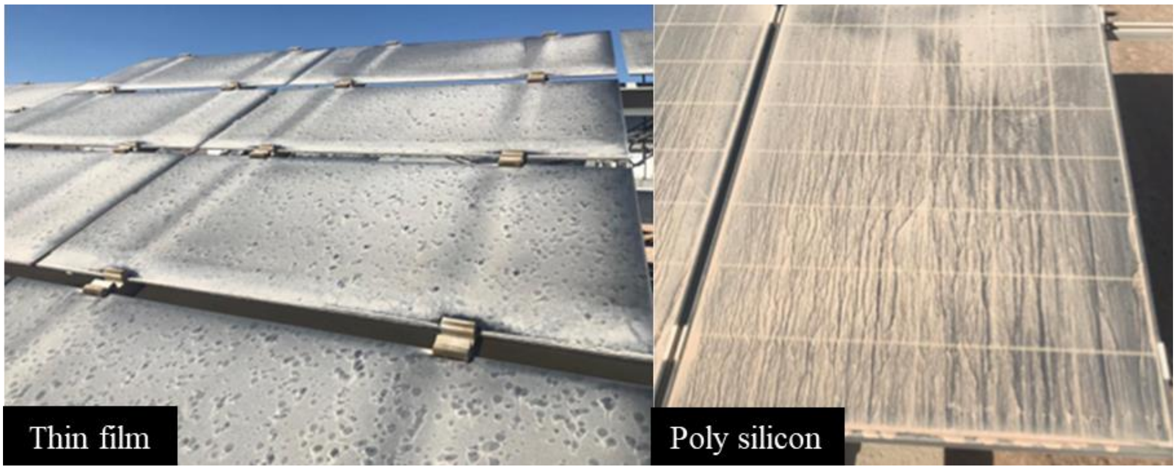
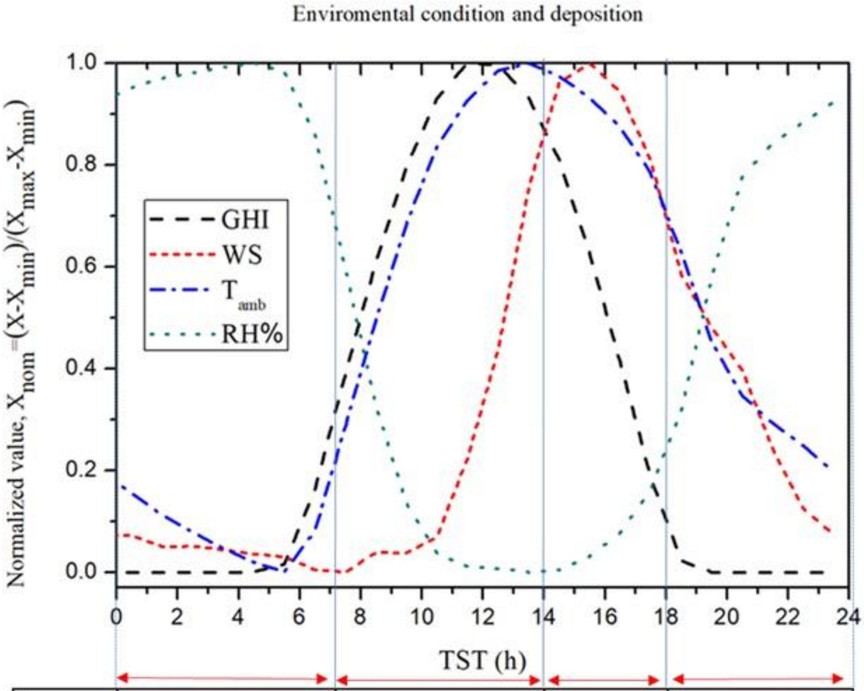


Fig. 3: Stains produced by dew, drizzle and high humidity, and their interaction with high temperatures in the morning, for two different PV technologies installed at PSDA: thin film and polysilicon.

Cementing processes are strictly linked to the region where PV plants are installed, since the pollutants and environmental conditions vary locally. These conditions may result in more or less intense soiling rates. In highly humid locations, such as Singapore for instance, the accumulation of dust and the soiling effect of dirt are not a problem (Hee et al., 2012), because precipitations are frequent and intense. Wherever rain is only occasional and/or of low intensity, however, it does not have the expected beneficial cleaning effect and conversely accelerates the cementing processes.

Using data from the PSDA meteorological station, all measurements were analyzed to generate a “typical soiling day”, summarizing the combined behavior of the main environmental variables. The diurnal variation of all key variables is taken into account, and their values are normalized. This “typical day” concept is facilitated by the low latitude of PSDA, which makes daylength relatively constant during the year. The time is reported in true solar time to obtain the maximum irradiance at solar noon. For such a day, the behavior of the key atmospheric variables is shown in Fig. 4. The wind begins to blow near solar noon (maximum value of GHI), increasing in the afternoon, and decreasing near sunset. Relative humidity increases at night up to a maximum at sunrise and decreases to minimum values during periods of insolation. In contrast, temperature increases with solar radiation and reaches its minimum just after sunrise. This behavior is repeated every day of the year in the Atacama Desert, except for a few days when adverse meteorological phenomena occur (e.g., rain or thunderstorms, which are scarce).

Based on this analysis, it is possible to identify those periods when deposition and cementation occur. Three such moments have been characterized during the typical day. The first one corresponds to the actual deposition of dust: particles are raised and transported to be deposited on the surface of the PV modules, as explained elsewhere (Sayyah et al., 2014). This phenomenon occurs between 14:00 and 18:00 solar time. The second event corresponds to the inertial deposition and solubilization of soluble compounds, when the hygroscopic components are able to interact with the humidity or water contained in the air. This process occurs at night when the relative humidity is high, as also explained by Figgis et al. (2017). The third stage consists of the recrystallization process, during which the soluble particles start to crystallize, generating a kind of cement between the insoluble material and the surface of the PV module. This phenomenon happens during the late morning when both temperature and solar radiation levels are high. The soluble compound identified in section 3.1 is gypsum. Even though its relative concentration is low in comparison with the other salts, it is sufficient to generate crusts that stick onto glass surfaces. The soiling cycle just described repeats every day, affecting the deposition and sedimentation ratios.



Stage	0< t < 6-7 h	6-7 < t < 15-16 h	14 < t<18h	18 < t< 24h
1	Sedimentation, inertial deposition	Dawatering and compaction	Dust is Raised	Sedimentation
2	Solubilitazation of minerals	Recrystallization, Moisture drying		

Fig. 4. Evolution of atmospheric variables during a typical day and factors that affect the sedimentation of soiling.

Figure 5 shows the density of deposited dust over time, during a 7-month exposure period. The glass samples were exposed to outdoor conditions in different one-month measurement campaigns. During each campaign, soiling samples were collected each week to evaluate changes in their weight, until the period of exposure was completed (at the end of March 2019). Figure 5 shows that the density of cemented soil increases with the exposure time. For normal months (months #1, #2 and #3), it is found that the dirt density does not exceed 0.05 mg cm^{-2}, with a temporal pattern suggesting an asymptotic behavior, at least in some cases. However, Fig. 5 also shows that, during months #4 and #5, the amount of cemented material in the samples abruptly increased to values reaching 0.65 mg cm^{-2}, i.e., 13 times larger or more. This anomaly was apparently caused by intensive groundwork performed from mid-December 2018 to January 2019, in relation with the construction of a new PV plant in the area. This generated considerable amounts of suspended dust. During months #6 and #7, the amount of cemented powder decreased progressively. This closely follows the building activity, which ended in the middle of the 5th month. Soiling levels clearly decreased and stabilized.

Wind transport is another important factor, which has a significant local component. Wind-induced soiling can be explained by two variables: wind erosion and transport, both of which being also dependent on terrain factors. Each region is dynamically and differently affected by superficial soil particles and by wind: dust starts to rise when wind starts to blow or is highly variable. The entrainment of ground particles starts when the friction velocity (u^*) of the wind exceeds the friction threshold velocity (u^*_t) (Torres Hugues and Cruz Nardo, 2014). The latter is defined as the minimum velocity to mobilize a particle of given size, shape, and density (Flores et al., 2006). During the first three months of the experiment (weeks 0–11 in Fig. 5), the soiling process maintained a consistent behavior (equilibrium). When the groundwork started in mid-December 2018 (week 13), however, a strong disturbance occurred that altered the stability of the soil particles. This changed the drag parameters. Finally, at the end of the groundwork (week 18, month #5), a stabilizing trend started, showing a slow and progressive trend back toward normal undisturbed conditions.

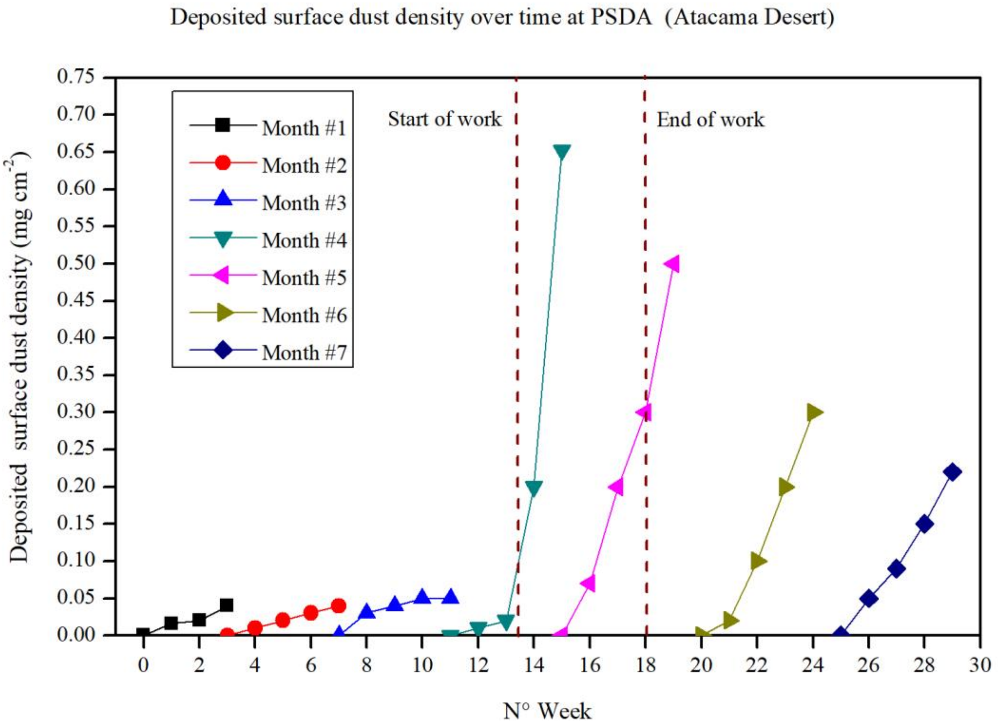


Fig. 5. Soiling ratio cemented during 7 months of exposure. An increase in deposited dust is observed as exposure time increases. Vertical dotted lines delimit the time period of the groundwork for the installation of a nearby PV plant.

3.3 Effects of soiling

The measured transmittance of PV glass samples exposed to outdoor conditions at PSDA is shown in Fig. 6. The surface dust density of the exposed glass panes reached 0.66 mg cm^{-2}. This value corresponds to a measured transmittance of 0.65, comparatively to a normal transmittance of 0.92 under clean conditions. This has been the maximum loss of transmittance for the period of exposure of the samples, corresponding to a relative loss of approximately 29%. As shown in Fig. 6 (left), the glass transmittance linearly decreased with increasing soiling dust density. Alternatively using a linear fit to describe the progressive transmittance loss (Fig. 6), the minimum glass transmittance at the end of the experiment would now be 0.57, corresponding to a relative transmittance loss of 38%.

The soiling effects can be quantified in terms of PV power using a spectral electrical model (Ferrada et al., 2017). The model evaluates the photo-generated current density (J_{ph}) in terms of solar spectral irradiance (F), external quantum efficiency of a specific PV technology (EQE), and experimental optical transmittance of the cover (τ), and can be described by the following equation:

$$J_{ph}(T) = \frac{q}{hc} T \int_{\lambda_1}^{\lambda_2} F_{AM1.5}(\lambda)\, EQE(\lambda) \lambda d\lambda. \qquad \text{(eq.1)}$$

For the present study, the global solar spectral irradiance at air mass 1.5 is obtained from the ASTM G173 standard—although it might not be perfectly representative of the Atacama conditions (Marzo et al., 2018). Additionally, the quantum efficiency of a standard monocrystalline silicon solar cell is used (see Ferrada et al., 2017 for details). The decrease of photo-generated current with surface dust density is shown in Fig. 7. Because the glass transmittance is determined experimentally by using silicon photocells, its value is representative of the spectral range and spectral response of each PV technology considered. This range extends approximately from 300 to 1200 nm for polysilicon, for instance. Considering that glass transmittance is almost spectrally invariant, τ is obtained over the whole wavelength range as a broadband value. J_{ph} is obtained through Eq. 1. It is found that the current density drops at a rate of 21 mA cm^{-2}/mg cm^{-2}, thus showing a behavior similar to that of the transmittance, as clearly appears when comparing Figs. 6 and 7.

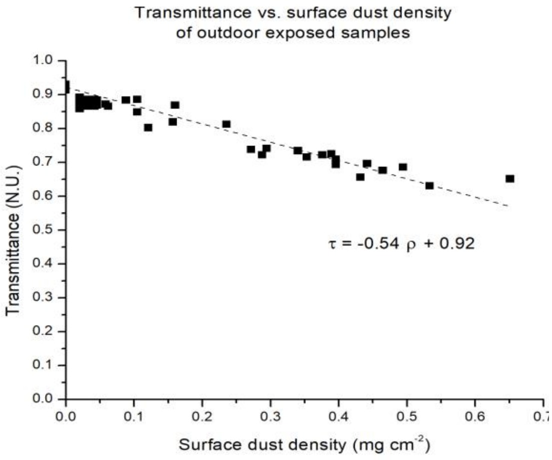


Fig. 6. Measured transmittance of outdoor exposed PV glass covers versus surface dust density.

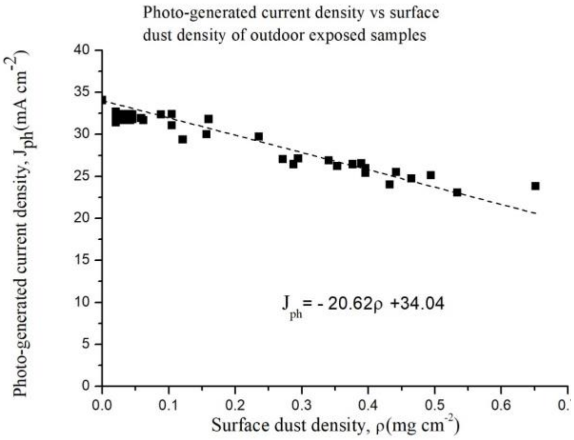


Fig. 7. Estimated photo-generated current density of outdoor exposed glass covers versus surface dust density of samples.

4. Conclusions

During a 7-month experimental study conducted at the Plataforma Solar del Desierto de Atacama (PSDA) in Chile, a detailed analysis of the atmospheric variables and chemical composition of the material deposited in glass samples resulted in the evaluation of the characteristics of dirt during a typical day. The concept of typical day simplifies the study of dirt deposition and cementation on photovoltaic surfaces. The outdoor experiment and laboratory measurements revealed at what exact times (always in the evening) dust is transported from the environment and adheres to the surface of the PV modules. During the night, the physical-chemical interactions between moisture, dew and deposited particles convert the gypsum particles into a soluble state. Other reactions occur in the morning: the progressive increase in temperature causes the soluble material to recrystallize, thus triggering a cementation cycle that repeats itself over time. In addition, it was observed that some nearby intensive groundwork that lasted 6 weeks triggered a considerable increase in the amount of cemented dust, negatively affecting PV performance. After the end of that perturbing period, the level of soiling was found to decrease progressively, while taking an estimated 17 weeks to stabilize back to its original background level. The effects of dirt on optical transmittance losses were measured according to the amount of dirt present on the PV glass. It was found that, for a surface dust density of 0.65 mg cm-^{2}, the transmittance of dirty glass was 57%, which is equivalent to a current density of 21 mA cm-^{2}. These values mean that the relative losses of transmittance and current density were 38.2% and 39.4%, respectively, with respect to clean surfaces. These results will contribute to the development of efficient cleaning and dirt-mitigation processes in the future. It was also found that the appearance and accumulation rate of soiling was somewhat dependent on the type of PV technology (thin film vs. polysilicon). Further research will be needed to better explain and predict such effects.

5. Acknowledgements

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