Characterization of Changes in the Soiling Properties and Deposition Rates Because of Groundworks Near a PV Plant in the Atacama Desert.

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Abstract

Solar Plants expansions, site upgrades, and other types of groundworks can affect solar plants by making the soil less compact and more prone to increase of airborne dust in windy events. This causes the soiling rate of photovoltaic panels to rise significantly compared to normal operating conditions. The aim of the paper is to generate information that will help operators and companies make the right decisions in PV plant maintenance plans and in the execution of works to reduce the impact of earthworks on plant performance and maintenance costs. This paper presents the results of a study on the impact of earthworks on soiling properties of PV plants. The methodology is based on the comparison of the soiling rate and its physicochemical and morphological properties before, during and after the groundworks. In addition, the duration of these changes over time after the completion of the earthworks in the area was analysed. The results show that before the works, quartz was the predominant material, which was displaced by gypsum during the works, then at the end of the study, after one year, the site returns to its original composition before the disturbance. Another effect observed is the change in the size of the deposited material, which before the works was dominated by fine material smaller than 10 µm, while during the works most of the particles were between 20 and 30 µm and later returned to their size of 10 µm. Measurements of the deposited dust show that it takes three months (after completion of the works) to return to pre-works contamination levels.

Keywords: Soiling, Dust, Transmittance loss, Photovoltaic, Solar Energy, Operation & Maintenance, Atacama Desert

1. Introduction

Renewable energies (RE), especially solar energy, have a recognized national and international potential for clean energy generation. Internationally, these energy sources have become a real option for the diversification of the energy matrix, dominated for decades by fossil sources based on coal, gas, oil and nuclear energy (Rhodes, 2010). Global warming, citizen empowerment and the modification of public policies have allowed the incorporation of these technologies, through hourly tenders, generating a great industrial and technological development worldwide. The participation in the market of commercial powers such as China has driven a reduction in the prices of materials, equipment and inputs that have favored photovoltaic (PV) technologies, which have shown a higher growth in the last decade, according to the International Energy Agency.

The technological development of PV has grown rapidly to become a profitable and environmentally friendly source of energy and economic activity. In 2020, PV broke the record in installed capacity, reaching a total cumulative capacity of 760,400 MW. In that year alone, the world installed 139,000 MW of new solar PV capacity, with China, the United States, Japan, Germany and India being the main countries contributing to this growth ("Fotovoltaica - La solar fotovoltaica bate récord del mundo - Energías Renovables, el periodismo de las energías limpias.," n.d.). This great development has not only been experienced by these countries, but also by those that are linked to the Photovoltaic Energy Systems Program of the International Energy Agency (IEA PVPS), which consists of 27 nations and concentrates 85% of the global photovoltaic capacity. Countries such as Chile, Australia, Japan, China and the European Union stand out (IEA, 2015).

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Chile leads the incorporation of solar PV energy in Latin America, with a solar market that has grown rapidly in recent years, being the high radiation, temperature, and hours of clear skies of the Atacama Desert a natural laboratory for the development of solar energy worldwide. With a surface area of 105,000 km^2, values of more than 8 kWh/m^2 of global radiation (GHI) per day have been recorded (Marzo et al., 2018). Its cloudiness index is 3%, so it has clear sky conditions during most of the year (Escobar et al., 2014). This is mainly due to the influence of the Cordillera de la Costa and the Cordillera de los Andes in their role as a climatic screen in the Atacama Desert (Marzo et al., 2021), preventing oceanic or Amazonian influence in the interior of the desert, which gives this desert a very stable climatology over time. Because of this, the Atacama Desert has a natural potential for solar technologies that has allowed, e.g., the insertion of monofacial and today particularly bifacial photovoltaic technologies. Currently, 1.08 GWp are installed in the Antofagasta region, 0.35 GWp are being tested and 1.4 GWp are under construction, which will reach 2.83 GWp by 2022 (Comisión Nacional de Energía et al., 2022). However, these territorial and radiation advantages are attenuated by local conditions that impose effects such as high UV radiation, temperature and soiling, which affect the performance of PV plants (Cordero et al., 2018; Marzo et al., 2018).

The irruption of PV technology in high radiation desert areas has brought with it a series of challenges related to the operation and maintenance of PV plants, with soiling being one of the major effects to be considered. Soiling is defined as the process by which organic dirt (pollen, bird droppings, silver debris) and inorganic dirt (minerals, salts and sand) accumulate on the surface of the PV module (Conceição et al., 2018a, 2018b; Muñoz-García et al., 2021; Olivares et al., 2020).The presence of deposited material drastically reduces the amount of light reaching the solar cell, generating optical and electrical losses, affecting economically a PV project and making it necessary to look for ways to mitigate its effect (Lorenz et al., 2014; Olivares et al., 2017; Reza et al., 2016) .According to a study presented by Ilse et al. (Ilse et al., 2019) in an optimal cleaning scenario, soiling reduces the current global solar energy production by at least 3%-4%, leading to losses of at least 3-5 billion euros per year, which may increase by 4-7 billion euros by 2023. This is a conservative estimate, as it does not consider the optimized costs for residential installations, which represent 29% of the installation.

The exponential growth that has existed in Chile involves the construction and expansion of PV projects. This has generated problems due to the increase of dust resulting from the earthworks, affecting the performance of the modules installed on site and nearby plants. This paper presents the results of a study on the impact of groundworks on the soiling properties of a PV plant located in the Atacama Desert.

2. Materials and Methods

This study was conducted at the Plataforma Solar del Desierto de Atacama (PSDA). This site is an outdoor laboratory for studying and testing different types of solar technologies. The PSDA is operated by the Centro de Desarrollo Energético de Antofagasta (CDEA) belonging to the Universidad de Antofagasta (UA). From the point of view of local environmental characteristics, more specifically in terms of soil and solar resources, the PSDA is a representative site of the conditions found in the area of interest for the solar industry in the Atacama Desert. This is because it is located at 1000 m.a.s.l. in the interior of the Atacama Desert (24.09°S, 69.93°E) between the Cordillera de la Costa and the Cordillera de los Andes. . According to the Köppen climate classification, this site is characterized by a cold arid desert zone (BWk) climate (Peel et al., 2007).

To characterize the impact of nearby earthworks, standard PV glass on the surface of photovoltaic modules were exposed to outdoor conditions during September 2018 and August 2019. Ground movements were conducted between February and March 2019. However, soil mechanics testing and machinery movements were performed in late 2018. A physicochemical characterization, quantification of the mineral composition of the dirt and a morphological analysis (size and shape) were performed. These analyses were carried out during and after the soil movements, completing a whole year of experimentation.

The powder samples collected before, during and after the works were analyzed by X-ray diffraction (XRD), using a Bruker AXS D8 Advance diffractometer in the range of 2-60°, with CuKα radiation (λ = 0.15045 nm) at 40 kV and 30 mA. These measurements were performed at room temperature. The powder diffraction file (PDF-4) in database format (Kabekkodu et al., 2002) was used to determine the compounds detected by XRD. The TOPAS software was used for their quantification. This program uses the Rietveld method to indicate the amount of each species present in a sample.

To analyze dust particles' size and morphology, an optical microscope was used (Leica DM IRB) to obtain a digital image including a size bar. The images were taken at a 20x magnification and were analyzed with ImageJ software. By analyzing the image with the software, the following parameters for dust particles were obtained: area (A), perimeter (P), and aspect ratio (Ct). From the area and aspect ratio of the particle, its longest projection (l) was obtained with eq. (1) In addition, a detailed examination of the dust particles was made with scanning electron microscopy (SEM) Joel SEM JSM-6360LV and energy dispersive X-Ray spectroscopy (EDX) for its elemental analysis.

$$l = \sqrt{\frac{4AC_t}{\pi}} \qquad \text{(eq. 1)}$$

Morphology was studied through the shape factor (A_{shape}). This parameter is defined as the inverse of the particle circularity and is associated with particle complexity. This factor is calculated through eq. 2, where P and A are the perimeter and area of the particle, respectively. A shape factor close to 1 would correspond to a perfect circle. More than 300 particles from each sample were analyzed to ensure representativeness.

$$A_{shape} = \frac{P^2}{4\pi A} \qquad \text{(eq. 2)}$$

The deposition rate of surface dust density was measured by exposing the samples for periods of one month and recording their mass changes every week. This process was repeated until 12 months of measurements were reached. The campaign consisted of placing the objects in triplicate with a size of (5×9 cm^2) on the surface of the photovoltaic modules fixed at an inclination of 20° with north orientation. The method used was gravimetric for mass gain.

Changes in optical properties (such as glass transmittance) caused by soiling were monitored outdoors under natural light at normal incidence. This transmittance was calculated as the ratio of the measured solar irradiance using a Si photocell with dusted PV glass on top of it to the measured solar irradiance using a different Si photocell with no glass on top. In this way, the broadband transmittance of the dust-glass system was determined, being representative for the 300-1200 nm spectral range. These measurements were performed on standard PV glass samples having different surface densities for the study year, a size of 4.7 x 6.5 cm and a thickness of 3.2 mm.

3. Results and Discussion

3.1 Physicochemical characterization

Characterization by X-ray diffraction showed that the material deposited on the photovoltaic modules before the work was composed of: a) Albite ($NaSi_3O_8$), b) orthoclase (K ($AlSi_3O_8$)), c) muscovite ($KAl_2(AlSi_3O_{10})(OH)_2$), d) quartz ($SiO_2$) and e) gypsum ($CaSO_4 \cdot 2H_2O$) as its main components (for more details see (Ferrada et al., 2019). In the diffractograms corresponding to the analysis during and after the works, the same materials were found, as shown in Fig. 1. However, it can be observed that there are differences in the diffractograms of the analyses performed before and after the works compared to the one performed during the works. These differences are related to pronounced gypsum peaks in the sample taken during the work that are not observed in the other two diffractograms. In addition, it can be observed that there is a similarity between the diffractograms of the samples taken before and after the work.

A semi-quantitative analysis by TOPAS showed that the difference observed in the diffractograms is related to the amount of crystalline species deposited on the surface of PV modules. The analysis showed that before the earthworks, quartz was the major compound with a 36% presence. During the work, the presence of quartz decreased to 11% but the amount of gypsum increased to 60%. Finally, for the analyses carried out after the work was completed, quartz again became the main compound with 27%. For these reasons, there is a similarity in the diffractograms performed on the samples before and after the earthworks, since quartz is the major compound. While in the diffractogram during the earthworks, the characteristic peaks of gypsum predominate, this is not the case in the other diffractograms where its presence is 2% and 5%.

Soluble salts, such as gypsum, are abundant in the area where the PSDA is located (Fig. 2.a). Ground presents a hard and compact type of substrate where, in a few decimetres below the surface, a layer of salt is easily distinguishable. This characteristic means that in the presence of water, e.g. light drizzle, these salts appear on the surface of the soil forming a hard white crust (Fig 2. b)(Berger and Cooke, 1997).

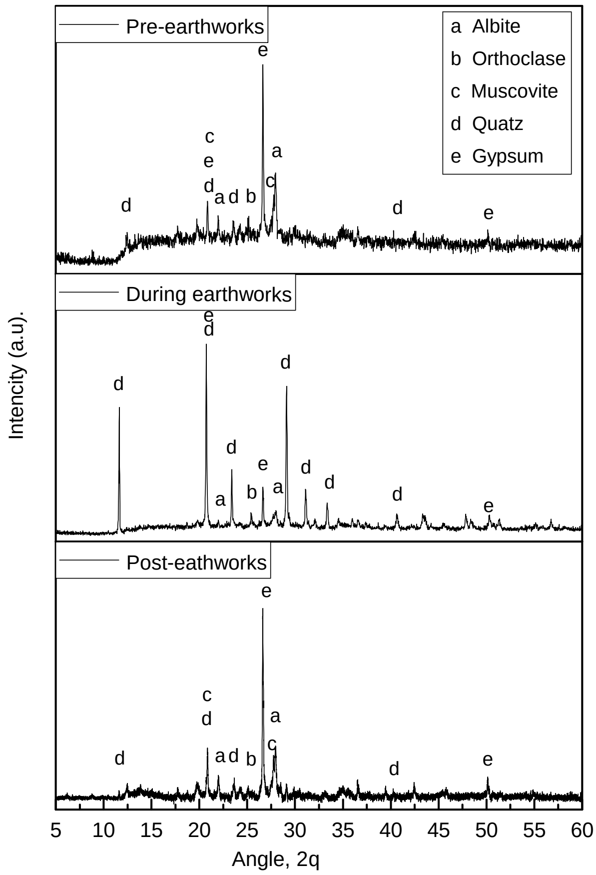

Fig. 1: XRD for soiling samples deposited on a string of PV modules at PSDA (pre-earthwork, during earthworks and post-earthworks).

These characteristics explain, for example, why dust deposition in the Atacama Desert is lower than in other deserts where the soil is not so compact. When groundworks are performed, the substrate becomes loose and is more easily moved by the wind, causing an increase in the rate of soiling. In the same way, deepening in layers below the surface, salt residues are exposed to the elements, which are deposited on the modules when airborne, leading to an increase in the presence of salts such as gypsum. The increased presence of gypsum changes the shape of the deposited material and further promotes soiling cementation on PV modules. The earthwork caused a disturbance which consisted of an increase in sedimentary material (gypsum). This disturbance tended to equilibrate over time, returning to quartz as the predominant depositional material.

Fig. 2: a) Soil of the PSDA on which the PV plant is installed. b) Formation of crusts caused by artificial watering and the solubilization and subsequent crystallization of gypsum.

3.2. Particle size and morphology

The results of the SEM analysis show that the effect of the ground movements not only produced changes in the amount of crystalline species deposited, but also in the morphology of the material. For the particles analysed before the earthworks there is a predominance of spherical particles with a tendency to generate agglomerates as shown in Fig. 3.a). In addition, the presence of prismatic particles can be observed, but in smaller quantities, as can be identified in Fig. 3.b). Compared to the particles found at the end of the earthworks, defined prismatic particles are found as shown in Fig. 3 c) and d). These defined prismatic particles correspond to the mineral gypsum, which has a monoclinic crystalline structure. The implication of gypsum is its capacity to generate agglomerates as a result of cementation, which produces the so-called "desert rose"(Almohandis, 2002; Ilse et al., 2018). This phenomenon can be better appreciated in Fig. 3 d), in which a well-defined primary particle can be observed surrounded and encapsulated by smaller spherical particles, which have been trapped by the solubilization and recrystallization processes of this salt. For the analysis of the dust samples after the work (Fig. 3. f) and g)), it can be observed that the deposited material again has a predominance of spherical particles, in addition, the presence of clearly defined prismatic particles can be seen, but in smaller quantities.

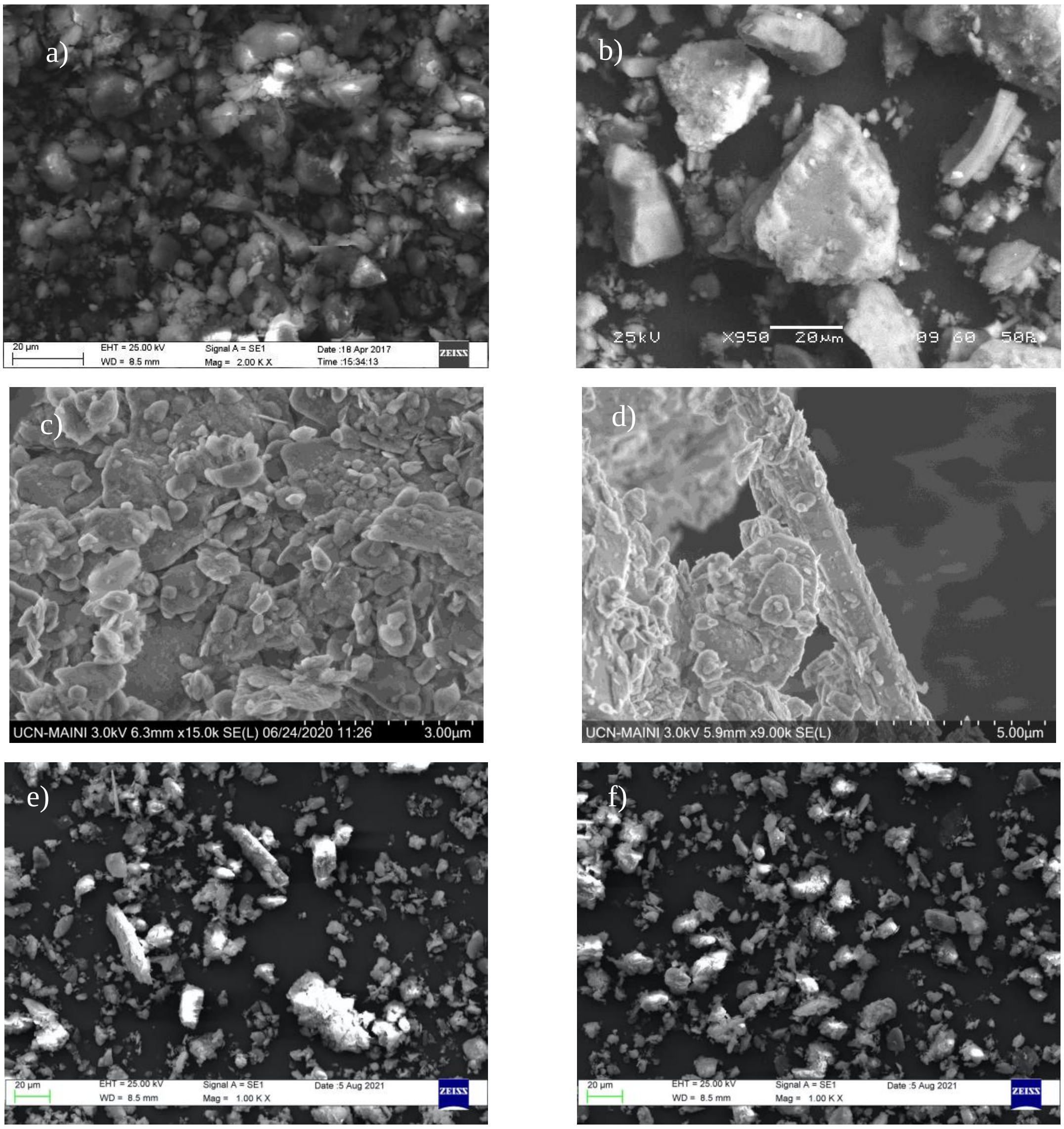

Fig. 3: Scanning electron microscopy of dust samples deposited on the surface of PV modules. (A) ,(B) Particles pre-earthworks; (C) , (D) Particles during earthworks ; and (E) , (F) particles post-earthworks.

To confirm the results obtained it is necessary to perform morphology tests such as the shape factor. The histogram of the shape factor (A_{shape}) of the deposited material before, during and after the earthworks is shown in Fig. 4 left. It can be observed that before and after the earthworks there is a predominance of spherical particles with a frequency of over 40%. For the analyses carried out during the works, the opposite can be observed, the presence of spherical particles is low, less than 5% and 30% for particles far from the unit. These results confirm what was mentioned with the SEM images, showing that the presence of prismatic particles (gypsum) is a product of the earth movements, and that these altered the geology of the site. However, these disturbance will only be during the earthworks.

Particle size was also analysed, and the results are shown in Fig. 4 right. The frequency of fine particles predominates before and after the earthworks. In addition, it is shown that there are no particles larger than 50 µm for both analyses. In comparison with the analysis of the samples during the work, it is shown that larger particles are frequent, with the size between 20-30 µm presenting the highest frequency of 28%. In addition, it is observed that particle sizes above 100 µm were reached, which would be related to the works carried out at the site, as a result of the movements and excavations during the expansion of the PV plant.

The results of the physicochemical and morphological characterization of the deposited material show that the earth movements during the work affect the deposition of the material at the site. The effect is observed in the material chemistry, morphology and size. However, this disturbance that was generated does not last over time; on the contrary, the deposition of the material returns to the state it was in before the work.

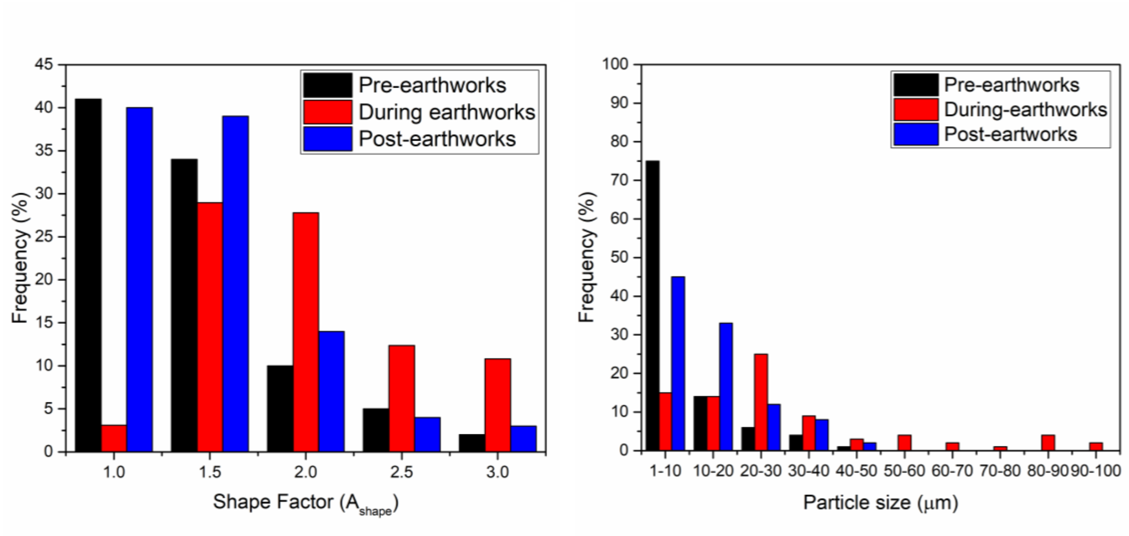

Fig. 4 Left: Shape factor pre-earthwork (black), during (red) and post earthworks (blue) at the PSDA. Right: Size particle pre-earthwork (black), during (red) and post earthworks (blue) at thePSDA

3.3. Soiling deposition rates

Fig. 5 shows the surface dust density over time, during a 12-month exposure period. The glass samples were exposed to outdoor conditions in different one-month measurement campaigns. During each campaign, glass samples were collected each week to evaluate changes in their weight, until the period of exposure was completed. It can be observed that as exposure times increase, the density of cemented dust increases. It can be observed that there is a normality (months #1, #2 and #3), where it is shown that surface dust density does not exceed 0.05 mg cm^{-2}, with a temporal pattern that suggests an asymptotic behavior, at least in some cases. The disturbance of the works is shown during months #4 and #5, as the amount of cemented material in the samples increased dramatically to values of 0.65 mg cm^{-2}, i.e., 13 times larger or more than what was obtained during the months prior to the earthworks. During months #6 , #7 and #8 , the amount of cemented powder decreased progressively. This closely follows the construction activity, which ended in the middle of the 5th month,in which dirt levels clearly decreased and stabilized at their pre-work values. For the last four months of the measurement year, a similar behavior in deposition levels to the first three months can be observed. These values are related to the results of the physicochemical characterization, in which it is observed that the site affected by the works will tend to return to its initial state before the disturbance. In addition, month 11 shows the positive effect of the rain, which helped to reduce the amount of dust deposited, but its effect only allows to return to a density value similar to that of three weeks of exposure.

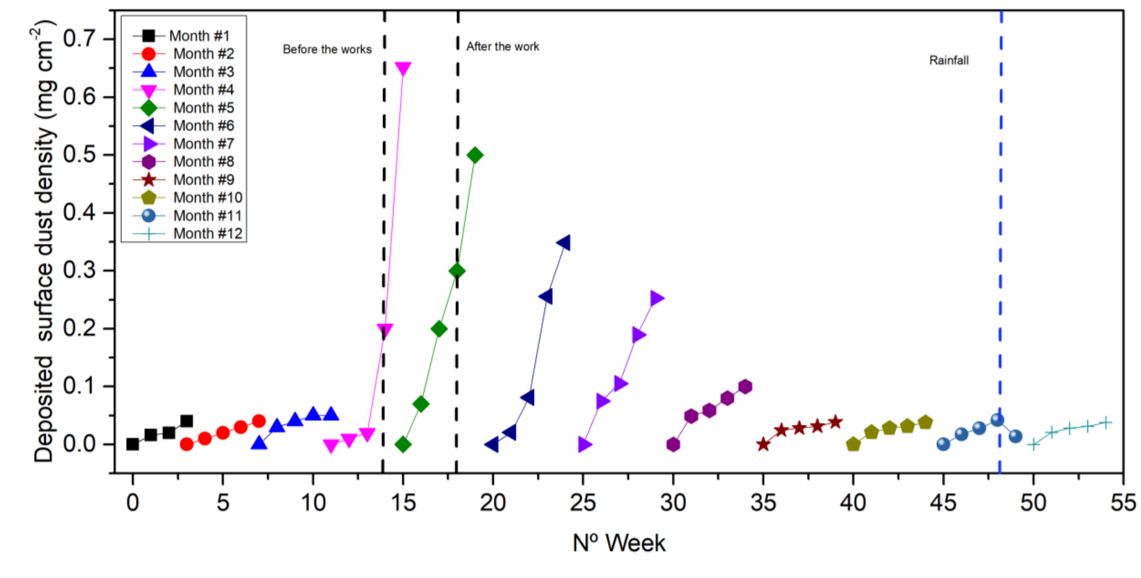

Fig. 5: Surface dust density of the samples over the 12 months of outdoor exposure. A slight increase in the deposited dust is observed as exposure time increases. This increase in the amount of deposited soiling occurs when earthworks begin. The vertical dotted lines delimit the period of earthworks for the installation of the nearby photovoltaic plant.

3.4 Effects of soiling

Fig. 6 left shows the measured transmittance of the photovoltaic glass samples exposed to the outdoor conditions in the PSDA. The dust density on the surface of the exposed glass reached 0.66 mg cm^{-2}. This value corresponds to a measured transmittance of 0.65, compared to a usual transmittance of 0.92 under clean conditions. This was the maximum transmittance loss for the exposure period of the samples, corresponding to a relative decay of about 29%. As shown in Fig. 6 left, the transmittance of the glass decreased linearly with increasing surface dust density. If a linear fit is used to describe the progressive loss of transmittance, the minimum transmittance of the glass at the end of the experiment would be 0.57, corresponding to a relative transmittance loss of 38%. However, in the case of deposited dirt without the disturbances from earthworks, maximum surface dust density reached 0.038 mg cm^{-2}, which lead to a transmittance decay of 3%.

The effects of soiling can be quantified in terms of photovoltaic power using an electrical spectral model (Ferrada et al., 2017). The model computed the photogenerated current density (J_{ph}) as a function of the solar spectral irradiance (F), the external quantum efficiency of a specific photovoltaic technology (EQE) and the experimental optical transmittance of the glass cover (τ).

The global solar spectral irradiance in the air mass was considered to be 1.5 and is obtained from ASTM G173 -. For the quantum efficiency, a standard monocrystalline silicon solar cell was used as a reference (see Ferrada et al., 2017 for details). The decrease of photo-generated current with surface dust density is shown in Fig. 6 right. Since the transmittance of glass is determined experimentally in the field using silicon photocells, its value is representative of the spectral range and spectral response of each PV technology considered (300 -1200 nm). Thus, the transmittance (τ) is obtained over the entire wavelength range as a broadband value. It is found that the current density drops at a rate of 21 mA cm^{-2}, thus showing a behavior similar to that of the transmittance, this value corresponds to the point of maximum soiling caused by the work. For a normal month of exposure, the current density is 32 mA cm^{-2}, which corresponds to losses of 4%.

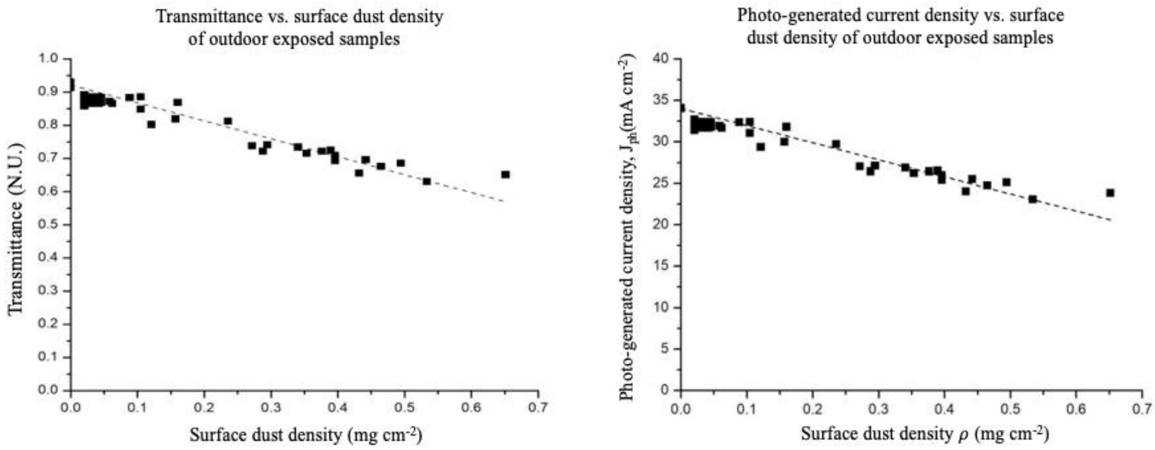

Fig. 6 Left: Measured transmittance of outdoor exposed PV glass versus surface dust density (Olivares et al., 2019)**. Right: Estimated photo-generated current density of outdoor exposed glass covers versus surface dust density of samples. Olivares et al., 2019)**

4. Conclusions

The impact of earth movements on the soiling properties for photovoltaic modules in the Atacama Desert has been analyzed. The results show that earth movements cause significant changes affecting the geology of the site. These changes are observed in the morphology, granulometry and density of the deposited material. The most significant change is related to the increase of gypsum deposited on the surface of the photovoltaic modules. This implies that processes such as cementation are favored in this period, possibly generating an impact on the way the affected modules must be cleaned. Due to the cementation process, the sand grains are trapped in this process, which implies that cleaning methods must be sought where this glue does not generate abrasion at the time of cleaning.

Another important aspect to consider is that earth movements also generate an increase in material deposition. This increment has a detrimental effect on the proper performance of the PV module. For one month of earthworks, optical losses of 40% were achieved, directly affecting the profitability and projection of a photovoltaic park.

Nevertheless, these disturbances caused by the earth movements were temporary and four months after the work, the original levels of soiling, chemical and morphological composition were found as before the disturbance. To address the negative effects of the construction, it is proposed to use the chemical properties of gypsum (abundant material during the earthworks) and to wet the rubble and the construction site to reduce the impact of dust. This would generate salt crusts that would prevent the increment of suspended material resulting from the earthworks.

This work provides information that allows operators of photovoltaic plants to take the necessary precautions to reduce the effect of soiling caused by artificially created soil movement. In addition, information is provided on how to mitigate the effect of earthworks. In this case, it is recommended to water the soil removed from the working area to achieve a cementation of the soil and not affect the performance of the surrounding PV modules.

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