Estimation Model of Soiling Based on Environmental Parameters

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Abstract

Soiling is one of the most important problems that affect the performance of photovoltaic panels in desert areas. Although several models have been proposed to predict its evolution, a model that considers the thickness of the dust layer accumulated in the panel is yet to be proposed. The model proposed in this article manages to estimate that value and obtain results based on the days of accumulation and the angle of inclination of the panel, considering the change of wind velocity over time. From the results obtained, a thicker dust layer is expected as the angle of inclination of the panel approaches 0 °.

Keywords: Soiling, accumulation model, thickness.

1. Introduction

Soiling estimation has received much attention in recent years in the photovoltaic community due to its high impact in the performance of photovoltaic panels. Roughly speaking, soiling is the accumulation of dust on the panels in photovoltaic power plants (Syed and Ghassan, 2018). Such accumulation depends upon both weather conditions (like wind and humidity) and the chemical composition of the dust. Given its characteristics, soiling has been found to be one of the main sources of energy yield reduction in photovoltaic panels. In fact, in (Paudyal, 2016) if a solar panel was exposed for just 5 months, the output energy decreases by 29.76%. Other authors reported performance is reduced by about 32% in 8 months, as reported in (Ghazi, 2014). Thus, the estimation of soiling (dust deposition rate and thickness of the dust layer) is being investigated as a potential solution to overcome the associated performance reduction of photovoltaic panels.

However, it has been found that the estimation of soiling requires to (partially) account for the interaction between dust and the panel. In order to deal with this challenge, indoor and outdoor experiments are performed to understand how particle size, wind speed, humidity, chemical composition and panel inclination affect the soiling in a photovoltaic panel (Burton, Boyle, Griego and King, 2015; Burton and King, 2014; Lorenz, Klimm, Weiss, 2014; El-Shobokshy and Hussein,1994; El-SHobokshy and Hussein 1993; Ilse, 2018; Ilse, Werner, Naumann, Figgis, 2016). These experiments are performed directly in photovoltaic panels (El-Shobokshy and Hussein,1994; El-SHobokshy and Hussein 1993; Olivares,2017), or by using mirrors or other similar less expensive materials (Burton and King, 2014; Lorenz, Klimm, Weiss, 2014; Ilse, Werner, Naumann, Figgis, 2016; Klimm and Köhl,2016; Burton and King, 2014) to determine the density of the accumulated dust (Lorenz, Klimm, Weiss, 2014; El-Shobokshy and Hussein,1994; El-SHobokshy and Hussein 1993; Ilse, 2018; Ilse, Werner, Naumann, Figgis, 2016; Klimm and Köhl,2016; Burton and King, 2014; Elminir and Ghitas, 2006; Burton and King, 2014) and/or the expected distribution of the particle sizes over the surface of the panel (El-Shobokshy and Hussein,1994; El-SHobokshy and Hussein 1993; Ilse, 2018). In some cases, the results obtained from the experiments are also used to determine the relationship between the soiling and the loss of energy yield ((Burton, Boyle, Griego and King, 2015; Burton and King, 2014; El-Shobokshy and Hussein,1994; El-SHobokshy and Hussein 1993; Ilse, 2018). However, performing these experiments is not always feasible, and therefore other alternatives have been developed to estimate the soiling.

In the literature, different mathematical models have been reported. For example, in (Alnaser, 2018; Gholami and Khazaee, 2018) exponential models were adjusted to real data in order to estimate how a fixed angle panel output

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decreased due to soiling accumulation. The input of the models is the number of exposure days. In (Darwish, Kasem 2015) the same idea is implemented, but it considered how the output decreases depending on the pollutant type. Further in (Kaldellis, 2011) experimental measurements in a fixed angle panel were used for an adjusted model that predicts soiling density based on the area (g/m^2). In (Ketjoy and Konyu, 2014) actual data is adjusted for a linear model that predicted soil accumulation in milligrams in function of exposure days. Another linear model using actual data considered soiling accumulation as a function of many factors such as humidity, temperature and inclination is reported in (Paudyal, 2016). These models have been widely used due to their simplicity and because of their accurate hit rate, but the principal disadvantage is that the models obtained are just valid for a specific location. In (Hao and Wenjun, 2019), a model for the soiling of a panel was derived assuming that the air is a fluid full of dust particles of different sizes. This model uses CFD simulations, requiring a high computational cost. Although is very precise, the problem is that for new environmental conditions a new simulation shall be run, therefore it is not an economic tool in reality. In the same way, in (Wolfertstetter, 2018) analytical approaches for the solution of fluid dynamics of a panel were proposed and validated in a mirror.

Notwithstanding foregoing efforts, so far the relationships taken from experimental results and the models proposed in the literature to estimate the soiling are highly dependent on local conditions and require a large amount of information for parameter identification. Furthermore, the estimation of the thickness of the dust layer on the panel has not been widely studied. It is worth mentioning that the thickness of the dust layer significantly affects the optical and thermal properties of the panel, which derive in a loss of energy yield. For instance, as the thickness of the dust layer increases the temperature of the panel also increases reducing its performance due to a loss in the heat transfer capability of the panel.

In this paper, a model to estimate the thickness of the dust layer accumulated over time in a panel is proposed. For this purpose, the model described in (Wolfertstetter, 2018) was taken as a reference. The proposed model was tested in a single panel assuming a fixed environmental temperature and variable wind speed. It is assumed that both wind speed and wind direction change hour by hour. A sensitivity analysis with respect to the angle of the panel was performed. In order to study the model performance, a computational simulation was run, using actual data of temperature and wind from the Atacama Desert. The simulation gives information of how the thickness evolve in time, day by day, according to the environmental inputs. This result is specified for every inclination angle.

The remainder of this paper is organized as follows: section 2 presents the proposed model for estimating the dust layer of soiling; section 3 sets out the results obtained using the proposed model to estimate the soiling of a panel under the Atacama Desert conditions; and finally, section 4 gathers the concluding remarks.

2. Proposed Model

In this section, a general model for predicted dust accumulation is described. The advantage of this model is that inputs can be modified to adapt to the actual condition for any location, by computing algebraic equations that can be easily solved, with a low computational cost. In that sense, this model may be used for operation.

The base model adapted is focused in dust accumulation on the frontal face. It is assumed that the contamination source is the air, full of dust particles, which travel with the wind. By using the model cited in (Wolferstetter, 2018) which describes the atmospheric dust transport (ADTM), the particle deposition on the floor can be described as a particle flux F, according to equation 1.

$$F(d_p) = V_D(d_p) \cdot C(d_p) \qquad \text{(eq.1)}$$

Where d_p is particle diameter, C is particles concentration in [1/m^3] and V_D is accumulation speed in [m/s]. So that the flux F has units of [1/m^{2}s].

Vd integrates the physical phenomena caused by environmental conditions and it is the linear sum of 3 velocities, representing 3 different effects that explain the accumulation of dust on a surface: Sedimentation, Brownian motion and impaction.

Sedimentation refers to dust fall caused by gravity. The model formula is for a horizontal surface, but it can be adapted to a surface with an inclination angle α. Then an expression for V_S, or sedimentation speed, is obtained as shown in equation 2. The symbol ρ is used for density and η represents dynamic viscosity.

$$V_S = \cos(\alpha) \cdot \frac{g \cdot {d_p}^2 \cdot (\rho_{aero} - \rho_{air})}{18 \cdot \eta_{air}} \qquad \text{(eq. 2)}$$

The Brownian motion refers to random particle motion in the air, caused by their impacts and the influence of other factors, producing an unpredicted movement. The best way to model this random nature is by applying the Brownian motion principles, which are summarized in equation 3. In this case, ν represents the kinetic viscosity and a_{brown} is an adjustable parameter to represent the contribution of Brownian motion.

$$V_B = a_{brown} \cdot v_{wind} \cdot \left(\frac{\nu_{air} \cdot 3 \cdot \pi \cdot \eta_{air} \cdot d_p}{\sigma \cdot T_{air}}\right)^{-0,667} \qquad \text{(eq. 3)}$$

On the other hand, impaction represents particles accumulation caused by the movement gained by wind speed in respect to panel position. Thus, when the wind faces an obstacle, such as a solar panel, it may change its direction violently. Small particles can follow this change, but the others cannot and eventually will fall onto panel surface. The expression for this phenomena is shown in equation 4. Note that f_{im} is an adjustable parameter which represents the contribution of impaction in accumulation speed.

$$V_{im} = \frac{\epsilon_{or} \cdot v_{wind}}{1 + \exp(-f_{im}(St - 1))} \qquad \text{(eq. 4)}$$

Some modifications were made to the original model equations; thus, the photovoltaic solar panel can be studied instead of the solar mirror. These modifications were made in the auxiliary functions used in equation 4 and are defined as follow. *St* is used for stokes' number, which quantifies how capable are dust particles to adapt to wind direction changes. It is shown in equation 5.

$$St = \frac{\rho_{aero}}{18 \cdot \eta_{air}} \cdot {d_p}^2 \cdot \left(\frac{v_{wind}}{D_{im}}\right) \qquad \text{(eq. 5)}$$

At the same time, D_{im} is defined as d_{im}/ϵ_{or} , where d_{im} is a free parameter used to represent the curvature diameter in wind direction change and ϵ_{or} is defined in equation 6. $\Delta\theta$ is the azimuthal angle difference between the panel and wind direction.

$$\epsilon_{or} = \begin{cases} 0 & if \quad \cos(\Delta\theta) \cdot \cos(\alpha) < 0 \\ \cos(\Delta\theta) \cdot \cos(\alpha) & if \quad \cos(\Delta\theta) \cdot \cos(\alpha) \geq 0 \end{cases} \qquad \text{(eq. 6)}$$

Finally, the sum of each of these defined speeds results in VD and with different parts of particles, the general expression shown in equation 7 can be achieved, therefore realizing that the accumulation of dust occurs with particles of all sizes for 1 second.

$$CR = \sum_{dp=0,25\mu m}^{dp=32\mu m} V_D \cdot C \cdot {d_p}^2 \cdot \frac{\pi}{4} \qquad \text{(eq. 7)}$$

It is worth considering that the model assumes a uniform accumulation, meaning that the soiling´s coat is the same on every part of the surface. This idea is an accurate approximation of what really happens on a soiled panel. Essentially, each particle that arrives to the surface is subdued to many forces, which determines whether the particle stays in the panel. The main force that tries to move the particle is gravity, but on the other hand, friction force and viscous rubbing force opposes to that movement. In that situation, it is logical to think that the wind could remove the soiling, but in most cases it cannot. The reason is that particles interact with the glass surface generating electro-chemical forces which, over time, become more relevant than mechanical friction forces. The interaction is demonstrated in (Cuddihy and Willis,1984).

In order to extend this model to a quasi-static method over time, it is enough to multiply it by the amount of time required, in seconds. As the model calculates the accumulation at every second, if there is wind speed information for every hour of a year, it is possible to considerer that if wind velocity (speed and direction) was constant for an hour, the accumulation rate is constant. The following hour, this rate can change as wind velocity changes. The calculation can be repeated for each inclination angle.

In order to calculate the thickness of a layer (T1) a uniform accumulation is considered. The thickness of the layer corresponds to the weighted average of each type of particle and its correspondent thickness d_{pi} in µm that can range from 0.25 to 32 µm. The expression is reflected in equation 8.

$T1 = \frac{\sum_{i=1}^{n} c_i \cdot d_{pi}}{\sum_{i=1}^{n} c_i}$ (eq. 8)

Unlike the base model, when CR>1, it means that a new layer is being formed uniformly. Thus, when CR=2 means there are exactly two layers formed on the panel and the thickness is the simple sum of each layer calculated with equation 8. In case of non-integer numbers, it is interpreted as if only a fraction of the panel was dirty. Finally, the expression for the total thickness (TT) is shown in equation 9.

$TT = T1 \cdot CR$ (eq. 9)

TT represents the thickness of a soiling uniform coat in the entire surface.

The methodology used was implemented through the equations in a software, introducing the necessary parameters such as numerical constants and vectors with actual information of climate conditions such as wind speed. Then, the results were plotted to understand how accumulation evolves.

The difficulty is that some conditions associated to equations, cannot be modified to consider different chemical species of pollutant. As described in (Darwish and kasem, 2015) different chemical properties imply different interaction forces between a particle and the surface. Thus, the accumulation rate could be different depending on that characteristic. This model considers an average type to describe the accumulation process.

3. Results

Different models reported that soiling accumulation increases over time for low inclination angles (Ghazi, 2014). On the other hand, in (Hao and Wenjun, 2019) it is reported that the more wind speed, the more accumulation.

As a case study, it is assumed a north oriented panel subject to a fixed environmental temperature, a variable wind speed, using actual data from the Atacama Desert in Chile (Ministerio de Energía Chile, 2019) and the same number of particles of all sizes. It was processed to vary the number of days during which the panel is subject to the environment and the angle of inclination to assess the evolution of the thickness of the dust layer.

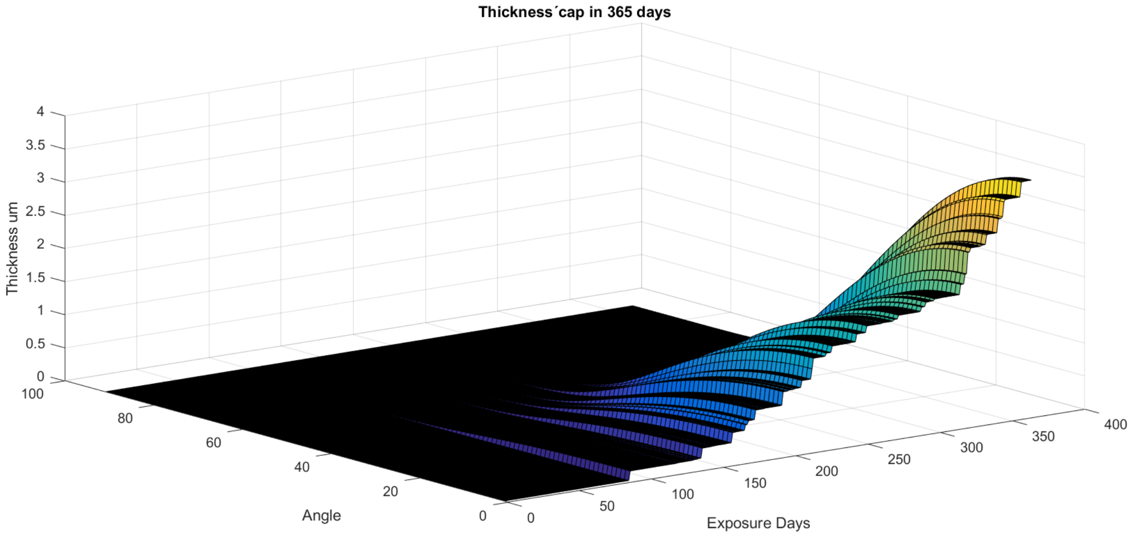

Fig. 1: Thickness of the layer in um, depending on the days of exposure and the angle of inclination, for the proposed study case.

Figure 1 shows the results of the virtual experiment performed, where it is appreciated that all the information for a number of days and 90 different inclination angles is summarized in just one image. This is actually an advantage because it can provide a good perspective of the situation to an operator. The graphic can be moved for a detailed observation.

For example, in figure 2 below, it can be appreciated that, as expected, the more days of exposure the thicker the layer. This increase is neither linear nor exponential, as there it is an important dependence on wind speed. As it can be seen, thickness growing does not follow a constant rate, which is explained by wind velocity changes. In this case, accumulation can change dramatically due wind direction. If the wind has a direction toward the panel, all the flux of particles can end up on the surface, but if not, the particles simply impact the side or the back of the structure. Accumulation is possible only when wind direction is between 0° and 90°. Thus, the increasing thickness between day 300 and 350 can be explained due to wind direction impacting the solar panel more frequently over that period.

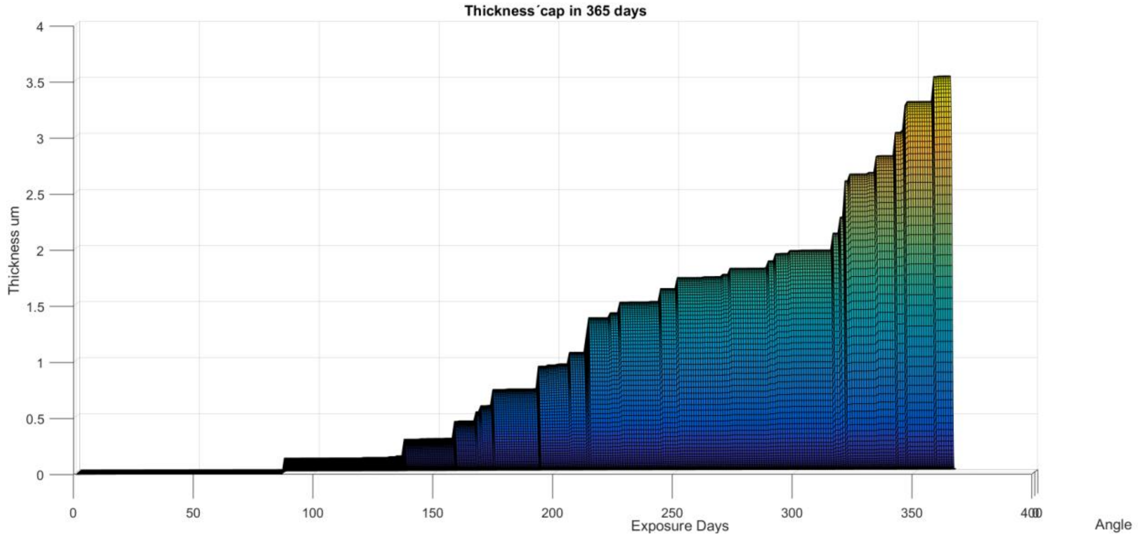

Fig. 2: Thickness of the layer in um, depending on the days of exposure

Similarly, if the panel has an angle closer to 0°, the soiling will become much more accelerated than when the angle is closer to 90°, which is explained because the particles have no possibility of rolling if the panel was completely horizontal (α=0), as it can be seen in figure 3. Accumulation depending on the angle evolves in a sinusoidal shape, according to equation 6.

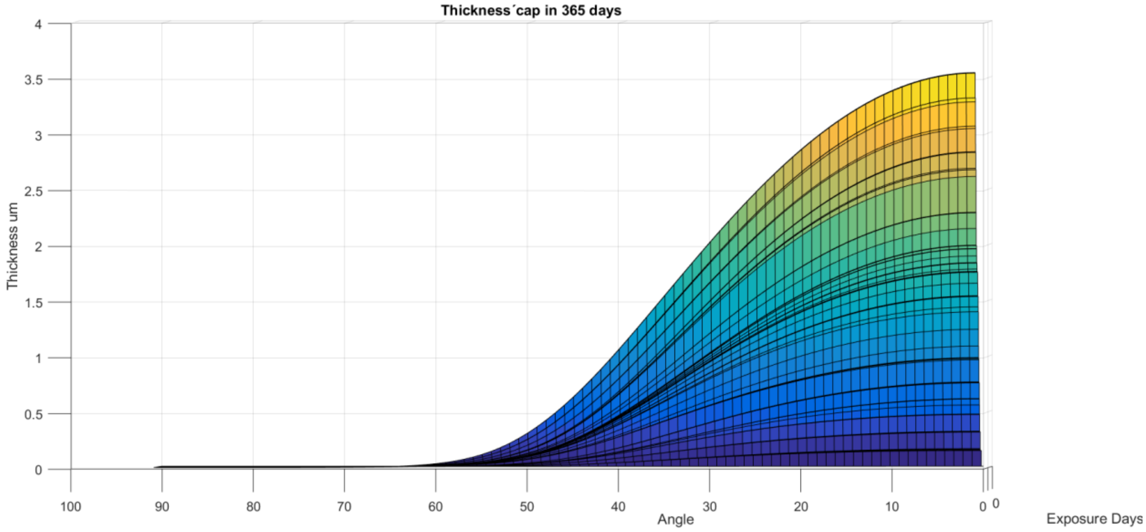

Fig. 3: Thickness of the layer in um, depending on the inclination angle

As thickness can be predicted, a relationship between this information and how temperature and transmittance changes may be described. Thus, it may be possible to predict the future output of solar panels to create an economic and convenient cleaning schedule.

4. Conclusions

In this article a model capable of estimating the thickness of a dust layer that accumulates on a solar panel is proposed under a number of environmental conditions. The model meets the expectations as the thickness increases with the number of days and this increase is higher for inclination angles closer to 0 °. The model can be adapted to different wind speeds by using actual data over a year, with hour by hour changes.

This model can predict at low computational costs how soiling accumulates in quasi-static environmental conditions on an accurate basis, by calculating a very relevant variable such as thickness, which may be related to temperature and transmittance, to then calculate the changes in performance.

For future research, the purpose is to study the effects of layer thickness on performance, in order to be able to quantify more accurately the performance evolution of the panel. The other idea is developing a model for an entire plant, considering that there is another kind of phenomena in fluid flux, and soiling impact is different for each panel depending on its position within the array.

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6. References

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