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EFFECTS OF SOILING OF PHOTOVOLTAIC MODULES AND SYSTEMS IN BRAZIL'S CLIMATE ZONES

Suellen Caroline Silva Costa[1], Antônia Sonia Alves Cardoso Diniz[1], Daniel Sena Braga[1], Vinicius Camatta[1], Tulio Duarte[1], Lawrence Lee Kazmerski[2]

1 Pontifícia Universidade Católica de Minas Gerais (PUCMinas)/Grupo de Estudos em Energia (GREEN-IPUC), Belo Horizonte (Brazil)

2 University of Colorado Boulder and National Renewable Energy Laboratory, Golden (USA)

Summary

This work reports a methodology for quantifying soiling loss in photovoltaic (PV) modules. We use measurements from c-Si and thin-film CdTe soiling stations installed in Belo Horizonte (19.92° S, 43.99° W), Porto Alegre (30.05° S, 51.17° W), and Brotas de Macaúbas (12.0011° S, 42.6303° W) in Brazil to example and validate this analytical approach. The measured PV module electrical parameters are compared with precipitation data collected in the same location, with the objective of evaluating the behavior of the soiling ratio during the dry periods. Mathematical models determined the soiling ratio (SRatio) and soiling rate (SRate) for each site (in compliance with the IEC-61724-1 monitoring standard [1]). The SRatio for short-circuit current and maximum power data from the modules were evaluated and compared, characterizing the potential effects of uniform and non-uniform soiling. The SRate defines the fraction of the ratio of soiling per day during the dry period (no rainfall). In addition, a method for analyzing energy-production data of PV systems in order to extract the soiling rate was developed and used to compare with monitoring system data. The soiling gravimetric densities (g/m²) were determined using the modeling by Coello and Boyle [2] and Hegazy [3] and these are compared to data collected using the Figgis soiling microscope [4].

Keywords: PV Modules, Soiling Ratio, Soiling Rate, Climate Zone, Gravimetric Densities.

1. Introduction

The accumulation of atmospheric particulates and other contaminants on the surface of a photovoltaic (PV) module has a potentially high negative impact on the energy output of PV systems. This, in turn, can result in greater system costs (loss of produced power, O&M) and reduced reliability of the power plant. The challenge is that the soiling accumulation can be more severe in regions where the installation of this PV technology has advantages, in locations normally possessing high incident solar radiation ("sun-belt areas"). Adding to the problem is that these areas are defined by high temperatures (enhanced soiling conditions) and long dry periods (less rainfall or availability of water to clean module surfaces). The particulates deposited on the photovoltaic modules reduce the cover glass or other front surface material transmittance, decreasing the solar radiation reaching the solar-cell converters. Soiling deposition is usually on uniform, causing different transmittances over the same surface of a module (influencing by tilt, wind direction, installation, and other factors) and associated partial shading of incident solar irradiance in areas with higher concentrations of dust.

To evaluate the photovoltaic soiling losses, soiling monitoring stations are being used in many world locations with the objective to quantify the soiling rates (Gostein, Duster, and Thuman [5]; International Standard IEC 61724-1 [1]; Bhattacharya, Chakraborty, Pal [6]). The impact of soiling on the performance of photovoltaic systems was evaluated by Hickel et al. [7]; Gostein et al. [8]; Dunn et al. [9]; Qasem et al. [10] who observed that short-circuit current data can generate erroneous results if the deposition is non-uniform. The accurate determination of this parameter for a PV power plant provides valuable information, including the required or optimum frequency of cleaning. R&D dealing with these important issues and related ones has been growing, with 400% growth in journal and conference publications over the past three years [11].

Brazil's principally southern-hemisphere geographic location represents interesting, complex, and comparative opportunities for soiling studies, encompassing equatorial, temperate, and arid climate zones (defined in this paper). In this way, we present our evaluation and methodology to quantify soiling losses in photovoltaic modules of (frameless) thin-film cadmium telluride (CdTe) and (framed) polycrystalline silicon (p-Si) PV

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modules installed in 3-climate zone locations in Brazil. Results from monitoring stations are compared to PV systems data. The soiling ratios (SRatio) and soiling rates (SRate) were determined and evaluated. PV systems information associated with the accumulation of soiling during the dry season, during which SRate is obtained through the estimation of the slope of the characteristic using the Theil-Sen estimator7. The gravimetric soiling densities are estimated using the modeling of Coello and Boyle [2] and directly measured using the Figgis soiling microscope [4].

2. Methodology

This paper presents a methodology to quantify the soiling ratio (SRatio) and the soiling rate (SRate) for p-Si and CdTe PV technologies installed in Brazil's diverse climate-zones. For this, the Brazil's climatic zones were determined according to the climate model propose by Köppen and Geiger [13] and study done by Peel, Finlayson and McMahon [14]. The Brazil is divided into three major climatic groups: (A) megathermic (Equatorial) climate (Belo Horizonte); (B) dry climate (Brotas de Macaúbas); and (C) mesothermic climate (Porto Alegre), being most of its territory dominated by the Equatorial climate, representative of ~60% all country [14].

Specifically, these analytic procedures have been validated for soiling monitoring stations (Fig. 1). Note that each location has both polycrystalline-Si and thin-film CdTe module stations, a meteorological station, and reference solar irradiance cells and pyranometers. The p-Si monitoring station is composed by one module of 265 Wp (left to soiling natural deposition) and reference cell, while, the CdTe station has two identical photovoltaic modules of 110 Wp. All PV technology used on the soiling station was installed directed to the solar north and with the tilt equal the latitude of the site (β=ϕ).

(a) (b)

Figure 1 - Soiling monitoring stations installed in Belo Horizonte: (a) cadmium telluride technology and (b) polycrystalline silicon technology

To calculate the soiling ratio (SRatio) and soiling rate (SRate), the collected data from soiling stations were mathematically cross-examined and filtered, with objective to reduce the influence of noise or interferences or inconsistencies during the process of measurement. After this initial treatment, the electrical parameters were corrected (normalized) in relation ambient temperature and solar irradiance. Thus, the meteorological data, electrical, and thermal parameters can be analyzed and correlated. The soiling ratios were quantified using short-circuit data ($SR_{I_{sc}}$) and power data (SR_{P_m}) measured in the clean and soiled cells/modules.

$$SR_{I_{sc}} = \left(\frac{I_{sc_{dust}}}{I_{sc_{clean}}}\right) \quad (1)$$

$$SR_{P_m} = \left(\frac{P_{m_{dust}}}{P_{m_{clean}}}\right) \quad (2)$$

where $I_{sc_{dust}}$ and $P_{m_{dust}}$ are short-circuit current and power measurements from dust PV device, and $I_{sc_{clean}}$ and $P_{m_{clean}}$ are short-circuit current and power measurement clean PV device.

These two electrical parameters can identify the whether the soiling is uniform or non-uniform. The soiling ratio from power presents a higher correlation with the real operating data compared to the short-circuit current, due to the bypass diode, used particularly for the silicon module. Mathematical models were used to determinate the SRatio and SRate for each site (in compliance with the IEC-61324-1 monitoring standard [1]). The SRate is determined through the estimation of the SRatio slope of the characteristic using the Theil-Sen estimator [15]-[16]. The SRatio data were used to determine the gravimetric soiling densities (g/m^2) based on the methodology proposed by Coello and Boyle [2] and Hegazy [3]. In [2]-[3], the transmittance loss is correlation with gravimetric density through by the relationship:

$$\left(1-\frac{\tau}{\tau_{Clean}}\right)\% = 34.37\,\mathrm{erf}(0.17\ \omega^{0.8473}) \tag{3}$$

where τ/τ_{Clean} is a transmittance loss, ω is a gravimetric density given in (g/m^2) and erf is Gauss error function. The transmittance loss varies from 0 to 100%, being that for ideal operating conditions of a photovoltaic module, the transmittance loss must be equal to 0%, while the soiling ratio will be equal to 1 or 100% (without soiling deposition). Thus, the soiling ratio can be obtained by subtracting an ideal condition (SRatio = 100%) by transmittance loss [2]:

$$(S_{Ratio})\% = 100\% - 34.37\,erf(0.17\ \omega^{0.8473}) \tag{4}$$

The gravimetric densities (estimated using SRatio data obtained from soiling monitoring station as input data), were compared with an inverse methodology, in such a way that, the SRatio was estimated considering data collected from gravimetric density (as input data). In addition, data were collected using the Figgis soiling microscope—providing direct measurement of the accumulated soiling levels and the corresponding morphological representations. For this, an experiment was conducted in Belo Horizonte, 19,92° S, 43,99° W to determine the gravimetric densities accumulated on the module surfaces, similar to the methodology proposed previously [2]-[3]. Some module-glass samples, with known surface area and initial weight, were exposed to continuous environmental conditions (dry periods), and these are weighed and analyzed under an outdoor microscope over several days/weeks. Those data are collected and used as inputs to compare with the SRatio obtained from soiling stations.

The proposed experiment consists of two samples of glass, with a surface area of 0.0121m^2, maintained on a larger flat surface, with a tilt fixed to the region, β=Φ, of 20°, as seen in Figure 2. Each sample was initially weighed, marking the day 0 of the experiment. Then, it was positioned on the surface to start the deposition.

Figure 2 - Arrangement of the samples on a reference surface

At each interval of 7 days, the samples were weighed, using a precision scale Shimadzu, model AUY220. Images of the surface were taken at different intervals of days to measure the evolution of dirt particles. The Celestron microscope, model Pro 44308, was used to take surface images with a magnification of 200x. The conditions for weighing it were constant, the same scale was used every time and the temperature and humidity of the place were kept at the same levels. Three measurements were made to each sample, following a period of five minutes to stabilize the weight of it. The values used for the calculation were the average of these three measurements. The gravimetric density (ω) is obtained by division of this average measured by the surface area. From the data obtained and the equations, (3) and (4), reached the results of the SRatio and transmittance loss for the conditions under study.

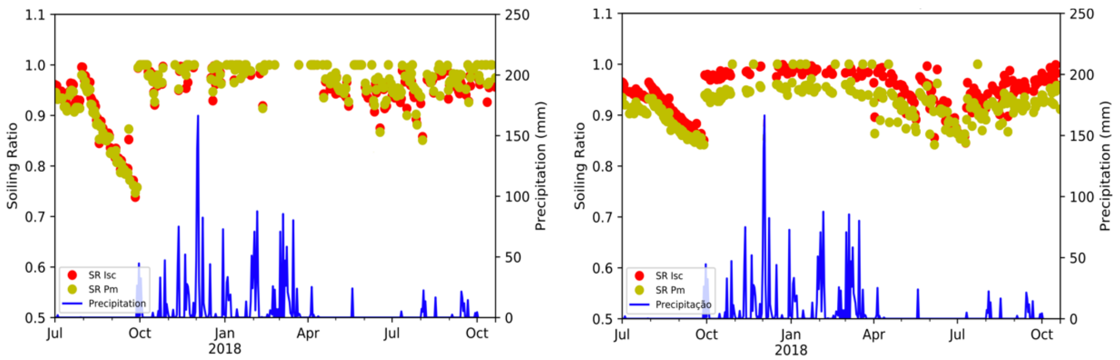
In addition, a method for analyzing energy-production data of PV systems in order to extract the soiling rate was developed and is presented. This method considers the change in energy production from the PV systems associated with the accumulation of soiling during the dry season, wherein SRate is obtained through the estimation of the power out slope of system using the Theil-Sen estimator [12].

The "monitoring station" and the "systems" methodologies are compared and discussed.

3. Results

3.1. Soiling Monitoring Stations

Figure 3 presents the daily average soiling ratio ($SR_{I_{sc}}$ and SR_{P_m}) for the CdTe (Fig. 1a) and p-Si (Fig.1b) soiling stations, over one-year period, together with the cumulative daily precipitation measured at the meteorological station both installed in Belo Horizonte, Brazil (Tropical Climate). This analysis was realized for period May 2017 to October 2018. A soiling ratio is equal to "1" represents the clean state of the photovoltaic module, without losses due to deposition of particulate matter or any other contaminants. In other words, the lower the soiling ratio (i.e., less than unity), the greater will be the losses. In Figure 3, the soiling ratio decreased during the dry period, which indicates the accumulation of particulates on modules. After cumulative daily precipitations greater than 20 mm registered over the period September 28 to October 4, 2017, the soiling ratio increased to "1" representing in the natural cleaning of the module. The effects of "uniformity" or "non-uniformity" are most critical in crystalline modules, due the presence of the bypass diode and its physical structure (i.e., frame).



(a) **(b)**

Figure 3 - Average daily soiling ratio in relation cumulative daily precipitation for Belo Horizonte: (a) CdTe and (b) p-Si.

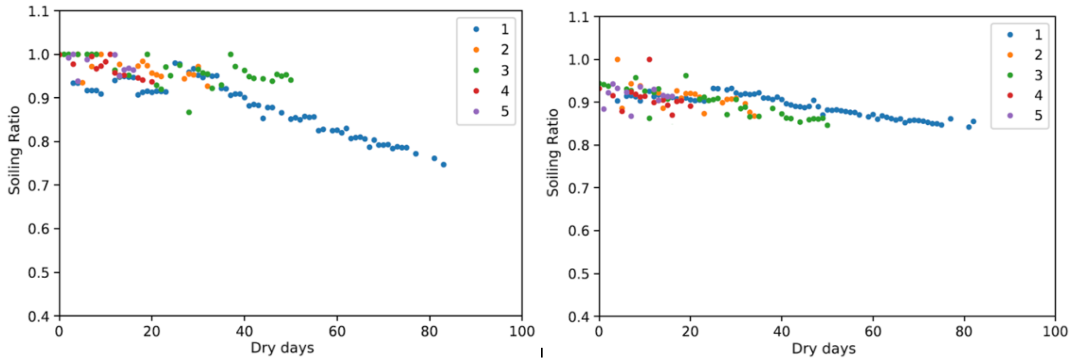
During all the data collection time, five-dry periods (no rain) longer than 14 days were recorded. Table 1 shows the soiling ratio for dry periods for p-Si and CdTe installed in Belo Horizonte.

Table 1 - Relation dry periods and daily average SR_{P_m} to CdTe and p-Si

Period	Season	Dry period	Length period (days)	Daily average SRatio	
				CdTe	p-Si
(1)	Autumn/winter	07/05/2017 – 09/27/2017	85	0,73	0,83
(2)	Autumn	04/13/2018 – 05/18/2018	36	0,92	0,88
(3)	Autumn/winter	05/21/2018 – 07/10/2018	51	0,88	0,84
(4)	Winter	07/12/2018 – 08/01/2018	21	0,92	0,91
(5)	Winter	08/18/2018 – 09/03/2018	17	0,96	0,93

The average SRatio for all period analyzed was 0.94 for CdTe and 0.92 for p-Si. But it was observed that during longer dry periods (as beginning of August and the end of September of 2017), the soiling ratio to CdTe was less than p-Si. This can be explained due to the different spectral responses for the technologies PV. The difference of semiconductor band gap (higher for CdTe) to the two technologies, presented different sensitivities for the incident radiation wavelength [17]-[18].

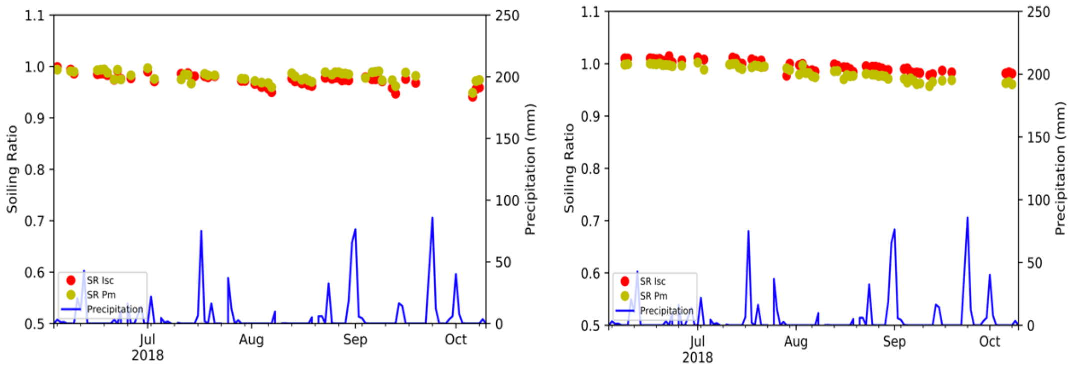
The average slopes SRatio observed on dry periods was estimated using Theil-Sen estimator in order to determine the SRate for the site. The Theil-Sen estimator calculates the slope between all pairs of points (t, x), providing the median value of all slopes calculated. The results show SRate around 0.20%/day to CdTe and 0.14%/day to p-Si considering the influence of climate variables from Belo Horizonte, Fig. 4.



(a) **(b)**

Figure 4 - Soiling ratio versus dry periods for (a) CdTe and (b) p-Si. The different colors representa different rainfall free periods. The Theil-Sen estimator identify the slope for each period, and median of all slopes indicate the soiling rate to site.

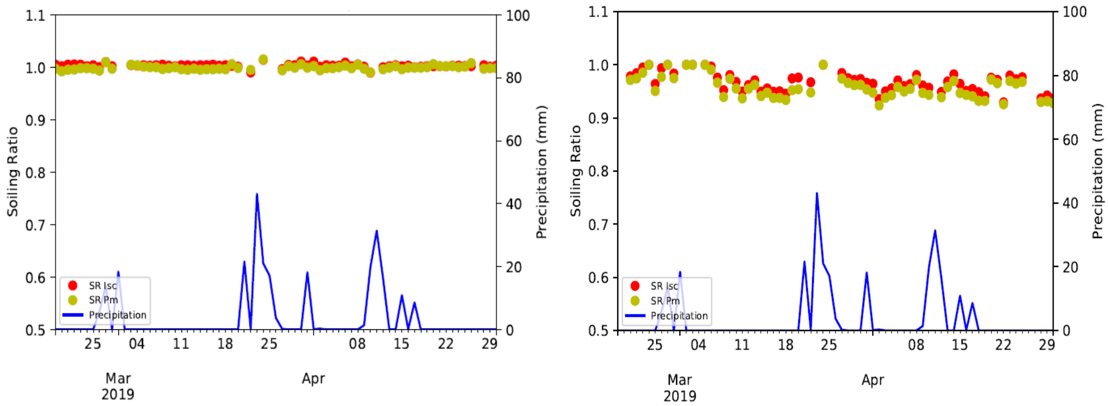
Figure 5 presents the daily average soiling ratio ($SR_{I_{sc}}$ and SR_{P_m}) for the CdTe (Fig. 7a) and p-Si (Fig. 7b) soiling stations over a 3-month period, together with the cumulative daily precipitation measured at the co-located meteorological station in Porto Alegre, Brazil (relatively high-moisture region – Temperate Climate). The results for this period indicate values to soiling ratio around of 0.98 for CdTe and 0.99 for p-Si. In addition, as well as observed in the data collected in Belo Horizonte, the soiling ratios comparing the measurement of short-circuit current and maximum power show that the soiling deposition is uniform.



(a) **(b)**

Figure 5 - Average daily soiling ratio in relation cumulative daily precipitation for Porto Alegre: (a) CdTe and (b) p-Si.

Figure 6 shows the daily average soiling rate to CdTe (Fig. 8a) and p-Si (Fig. 8b) soiling station installed in Brotas de Macaúbas, localized in the semi-arid region of Brazil (Bahia). An first interesting observation is the difference in the SRatio between the two module technologies. The influence of the high ambient and module temperatures in Brotas de Macaúbas were higher than at the other monitoring station locations. At Brotas de Macaúbas, module temperatures rose above 60°C, while at the other locations the modules did not regularly reach 50°C. Thus, the SRatio was lower (the SRate, higher) due to the higher temperature. This is consistent with other reports that indicate that soiling is more severe on higher temperature surfaces [19]-[20]. Because these initial results corresponded to the rainy season, the soiling rates for Porto Alegre/RS and Brotas de Macaúbas/BH could not be accurately determined. These are currently being evaluated as the dry seasons begin.



(a) (b)

Figure 6 - Average daily soiling ratio in relation cumulative daily precipitation for Brotas de Macaúba: (a) CdTe and (b) p-Si.

SRate was not estimated for the sites of Porto Alegre and Brotas de Macaúbas, because during the data collection period was not identified dry period greater than 14 consecutive days. The typical dry period in Brazil, normally, it is registered during winter, as can be seen to Belo Horizonte site, with some exceptions as the climate zone where Porto Alegre is inserted, presenting high frequency of rain throughout the year.

3.2. PV System

The SRate was estimated using another, system-specific-metodology that uses a specific PV-system performance metric. For this example, the data are collected from a p-Si, 3.24-kWp PV system, installed at a distance within 2-km of the soiling monitoring station for comparison. The performance metric used in this methodology was performance ratio (PR), providing the relationship between the real yield-generated and the expected yield of the photovoltaic system. This is a dimensionless index, allowing to system performance comparisons regardless of geographic location, because the production is normalized with respect to the solar resource. When the overall performance is close to 1, the performance of the system is "as-designed", with no relevant or apparent losses.

Figure 7 shows the daily average PV syste performance ratio in relation to the cumulative daily precipitation measured by the meteorological station, for the interval between July 2017 and October 2018, the same evaluation period of the p-Si soiling monitoring station.

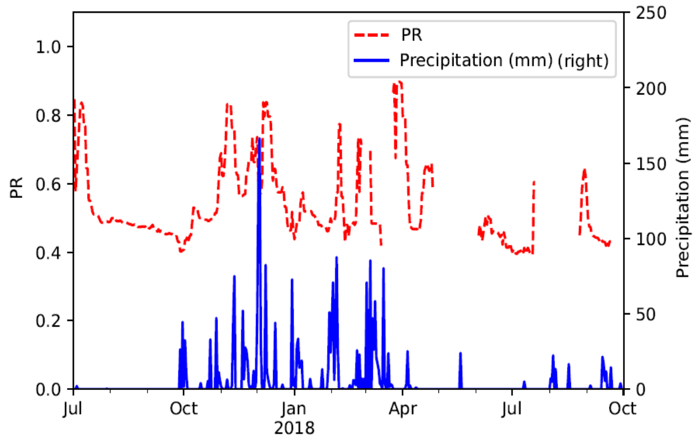


Figure 7 - Relation between Performance (PR) and accumulated precipitation for photovoltaic system installed in Belo Horizonte.

It is important point out that to estimated *PR* had a degradation ratio of 0.8%/year monitored over the period since its installation in 2007. The average of the slopes *PR* to dry periods identified to Belo Horizonte (same used on the soiling monitoring station methodology) indicated a SRate of about -0.18%/day, a value that is close to that found for the soiling monitoring station (i.e.,-0.14%/day). That divergence obtained through two methodology can be explained due to the locality of the system. The PV system is installed close to a high vehicular traffic and railway line, presenting high index of particulate matter suspended in the air (emissions from the vehicles) in comparison with soiling monitoring stations that are installed in more protected area. Additionally, the performance ratio for this system is low due the accumulation of organic matter, a high percentage of carbon. This is due both, the presence of biofilm formed by microorganisms difficult to remove by natural cleaning as rains and winds and vehicular emissions [21].

3.3. Gravimetric density

The gravimetric density was measured by determining the weight of the glass samples left by the natural deposition of soiling particles. Tables 2 and 3 summarize the values obtained over the analysis period in Belo Horizonte/MG for sample I and sample II, respectively

Table 2 – Data for Sample I, collected on 0, 7, 12 and 19 days

Period [Days]	Weight [g]	ΔW [10^{-3}g]	ω [g/m²]
0	2,8836	0,00	0,000
7	2,8868	0,32	0,2645
12	2,8887	0,51	0,4187
19	2,8920	0,84	0,6942

Table 3 – Data for Sample II, collected on 0, 7, 12 and 19 days

Period [Days]	Weight [g]	ΔW [10^{-3}g]	ω [g/m²]
0	2,9091	-	-
7	2,9122	0,31	0,2521
12	2,9141	0,50	0,4160
19	2,917	0,86	0,7080

From the input data in Eq. (3), it was possible to obtain the values for the SRatio and transmittance loss due to the gravimetric density, as summarized in Table 4.

Table 4 - Effects of the soiling deposition on the SRatio and transmittance loss of samples

Sample	I			II		
Period [Days]	ω [g/m²]	SRatio [%]	τ [%]	ωp [g/m²]	SRatio [%]	τ [%]
0	0,000	100,000	0,000	0,000	100,000	0,000
7	0,264	97,866	2,134	0,252	97,951	2,049
12	0,419	96,854	3,146	0,416	96,871	3,129
19	0,694	95,186	4,814	0,708	95,106	4,894

The increase of the surface soiling can be visualized from the images collected by microscope and summarized in the Figure 8.

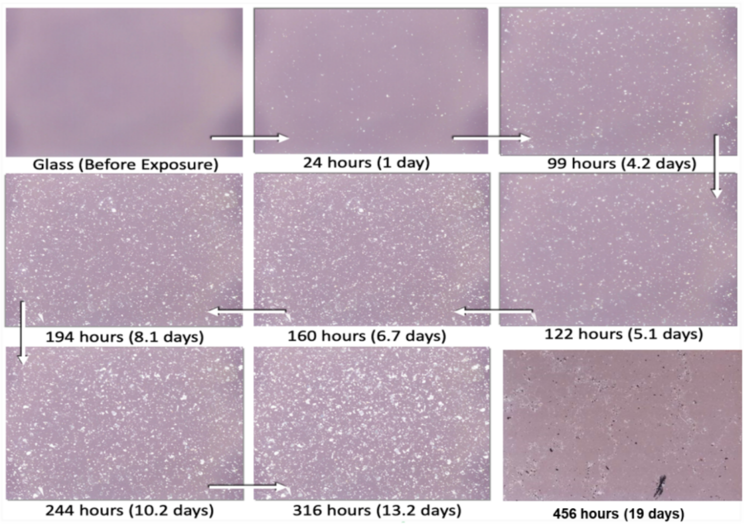


Figure 8 - Sequence of images of the exposure of the sample as a function of time, for Belo Horizonte / MG

The sequence of images, at Figure 6, shows the increased of soiling on the surface of the sample, prevailing small particles, up to 10µm, and uniform distribution. The accumulation results in less transmission of the incident solar light. The effect of dirt added to humidity causes greater adhesion layers, being harder to remove without a facilitating atmosphere, as the water itself, and favors the clustering of small particles, increasing the impact on transmittance of the sample, predicted by Figgis et al. [4].

Figure 9 correlates the modeled and measured gravimetric densities. The estimated (obtained through the mathematical model of Coello and Boyle [2] and Hegazy [3]) and measured SRatio (using the collected samples from the Figgis microscope, Fig. 6) show very good agreement for this experiment in Belo Horizonte/MG. It can be observed that, gravimetric density deposited on the photovoltaic module increases, while soiling ratio decreases, indicating losses in the performance of the module. These results show levels of soiling deposition around 3.0 g/m² at the end of dry period of 85 days. Again the experiment was conducted in region that is far from traffic routes, that is, far from regions where there may be high level of soot or other fuel emissions resulting from the vehicle combustion. The average measured $PM_{2.5}$ and PM_{10} for period analyzed was around 11.45 µg/m³ and 12.42 µg/m³, respectively, using air-quality sensor installed in the same site. It is possible to see that the use of measured SRatio or measured gravimetric density on Eq. (3) allows a convergence of the results, validating the two methodologies.

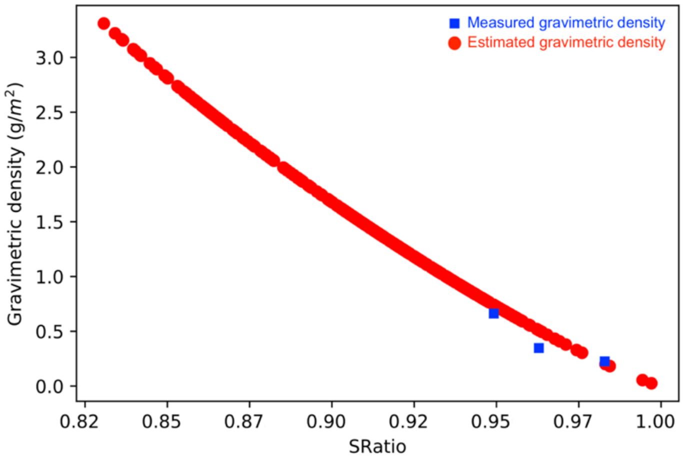


Figure 9 - Relation between gravimetric density and SRatio to Belo Horizonte/MG. The red mark is representing the estimated gravimetric density using SRatio from soiling monitoring as input to Eq. (3), and the blue mark is indicating the estimated SRatio through of measured gravimetric density as input.

4. Conclusions

Soiling studies reporting the soiling ratios (SRatio) and soiling rates (SRate) for 3-climate zones in Brazil have been presented with comparison of these parameters for the three areas. The methodology developed for these investigations was described and utilized with p-Si and thin-film CdTe soiling monitoring stations. The priority is the Tropical Zone data from Belo Horizonte, which has been monitored for more than 2.5 years. These data provide dry-season parameters, with soiling rates for Si modules (0.14%/day) and CdTe (0.20%/day), with the differences ascribed to spectral-response difference (band gaps) between the technologies. SRatio and SRate have also been initially determined for Temperate (mesothermic) Zone (Porto Alegre) and Semi-Arid Zone (Brotas de Macaúbas), but the monitoring time was primarily in the wet periods for each, which limited the rigorous determination of SRate.

The modeled (following Coello and Boyle [2] and Hegazy [3]) and measured (Figgis microscope [4]) gravimetric densities were correlated for Belo Horizonte/MG with good correspondence. It can be observed that, gravimetric density deposited on the photovoltaic module increases, while SRatio decreases, indicating losses in the performance of the module. These results reach levels of soiling deposition approximately 3.0 g/m² at the end of dry period monitoring of 85 days.

A crystalline-Si module system (2.24 kWp) in Belo Horizonte was also studied using the Theil-Sen estimator methodology. The SRate was found to be slightly higher than for the monitoring stations. This was found to be associated with the location of the system (near a highly trafficked highway)—with the soiling exhibiting compositions associated with carbon fuels and biofilms.

Finally, the relationships of the measured SRatio to the module temperature reflected information on the status of the modules themselves. Higher soiling rates were found to occur with higher module temperatures. The effects of non-uniform soiling were also observed—with some non-uniformities found to coincide with the differences in the individual Si cell temperatures.

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