Energy Conversion and Management: X 10 (2021) 100084

Contents lists available at ScienceDirect

Energy Conversion and Management: X

journal homepage: www.sciencedirect.com/journal/energy-conversion-and-management-x

Impact of soiling on Si and CdTe PV modules: Case study in different Brazil climate zones

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ARTICLE INFO

Keywords:
Climate
PV Modules
Soiling station
Soiling ratio
Soiling rate

ABSTRACT

Soiling, particulate accumulation on photovoltaic (PV) module surfaces, reduces the available solar resource and the resulting generated device power. This case-study summarizes initial results of 5-year research on the contrasting soiling conditions in the tropical, subtropical, and semi-arid climates in Brazil. A major objective is to present a case study of the effects of soiling on PV module performance in different Brazil climate zones that represent the primary areas for the current and expanding Brazil solar installations. For this, the paper presents methodologies to quantify the soiling ratio (SRatio) and soiling rate (SRate) for two representative commercial technologies, polycrystalline or multicrystalline silicon (mc-Si) and thin-film cadmium telluride (CdTe) modules, through soiling monitoring stations deployed in the selected climate regions. An aim is to add to the growing soiling-research knowledge base through addressing these key factors and their relationships to critical electrical, solar resource, thermal, and local meteorological and environmental parameters. This paper presents, evaluates, and compares soiling rates and losses in Belo Horizonte, Minas Gerais (Equatorial Tropical: 19.92° S, 43.99° W), Porto Alegre, Rio Grande do Sul (Humid-Subtropical: 30.05° S, 51.17° W), and Brotas de Macaúbas, Bahia (Semi-Arid: 12.00° S, 42.63° W). The results show that soiling is moderate in all 3-regions, for example with 0.1%/day $<$ SRate $<$ 0.2%/day for Belo Horizonte. Precipitation dominates the cleaning of the modules in the summertime in this climate zone, while it is the major factor year-round in Rio Grande do Sul. Wind is the major issue mitigating the soiling accumulation for the Bahia installation. The methodology incorporates several key refinements, including the normalization and adjustment for the meteorological parameters (temperature, irradiance, wind, precipitation). The evaluations include the region-specific differing effects of non-uniform soiling, natural cleaning, and ambient temperatures.

Introduction

PV shipments into world markets were nearly 125 GW in 2019, with an average 25%-growth/year over the past 5 years [1–3]. Reliability remains a principal concern for solar systems, ensuring installers, investors, financial institutions, and most importantly consumers of quality products that operate according to specifications during intended lifetimes and under the specific-site operating and environmental conditions [4–8]. Soiling, the accumulation of particulates on the surface of a PV module, can be a direct or indirect factor that affects the lifetime of that solar device or system. The literature has documented the various relationships between soiling and the performance of the PV module or system by limiting the photon flux that is available to the encapsulated solar cell [6,9–24]. One example on how the deposition of atmospheric dust, bird waste, urban effluents, and other contaminants deposited on the surface of PV module can adversely affect PV device reliability is the condition of non-uniform soiling [25–28].

This shading contributes to the generation of hot spots, with regions of the PV module sometimes reaching greater than 30 °C higher than the normal module operating temperatures [11,12,25,26,29,30]. The problem is primarily with framed Si-modules that use bypass diodes in the cell circuits. Thin-film modules avoid this type of hot-spot occurrence due to the integrated cell configuration, geometry of the cells, and absence of the bypass diodes, and frames [11–14].

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https://doi.org/10.1016/j.ecmx.2021.100084
Received 4 March 2021; Received in revised form 26 April 2021; Accepted 12 May 2021
Available online 23 May 2021

Research interest and growing concerns with the impact of solar-device soiling is reflected by the greater than 200% increase in publications and reports over the past 2-year period [31]. A growing volume of soiling monitoring stations [32–35] installed worldwide has provided information on regional soiling losses. Deceglie, Micheli and Muller [36,37] developed a foundational method to quantify soiling losses on PV-system performance using energy production data. Guo et al. [38] reported a wide-ranging multivariate regression model to quantitatively relate the daily variation of the cleaning index (CI) of photovoltaic modules to the concentration of dust, wind speed, and relative air humidity. The soiling losses have also been analyzed through related mass accumulation experiments, modeling, and simulations [39–41]. Additionally, Qasem et al. [26] verified the proportional relationship between the accumulated mass densities of the soiling layers and the losses.

The soiling losses from PV modules are location specific, depending on the local meteorological conditions, installation logistics (tilt, orientation, vegetation, etc.), characteristics of the site (proximity to highways, industrial effluents, urban/agricultural/desert, etc.), and technology type and module construction [42,43]. Annual losses in the performance of photovoltaic systems due soiling deposition can vary from 10 to 30% even under moderate dust conditions [10–12,38]. This loss can be even more significant when dust becomes caked or cement-like due to exposure to dew, precipitation, humidity, or UV, making removal difficult [44,45]. More severe dust conditions exist in desert regions with monthly power losses of 30% or more; ironically in these regions also having the highest solar resources [18,46,47]. Examples of research reports document the diversity and differences of soiling issues. Al-Ammri et al. [48] evaluated the losses of output power on mono-crystalline PV modules installed in Baghdad, Iraq, and observed annual energy losses around of 58.9%. Klugmann-Radziemska [49] evaluated the reduction of energy production from crystalline-Si photovoltaic modules due to soiling installed in Poland and reported the loss in efficiency was a linear function of the soiling layer gravimetric density, with mild annual maximum module power of ~ 3% in this northern climate. Cordero et al. [50] studied the effect of soiling on c-Si modules installed in the regions of Arica, Iquique, Calama, Copiapo, and La Serena in the Atacama Desert. The measured soiling losses varied from 0.6%/day in Arica and 0.31%/day in Iquique, to 0.16%/day in La Serena, and ~ 0.1%/day in Calama and Copiapo. Interestingly, though desert regions are considered heavy soiling areas, the daily soiling losses in the Atacama are moderate except near industrial mining operations [51,52]. Fraga et al. [53] evaluated the impact of soiling deposition on performance of a solar power plant (mc-Si) on a soccer stadium installed in Minas Gerais, Brazil. The soiling reduced the output power ~ 16.5% during the 6-month dry period, while during the summer rainy period, the reduction was about half that level. Kalogirou et al. [54] provided early identifications of the critical nature of seasonal effects, and particularly the unusual rain episodes, on the performance and cleaning of Si technologies under both artificial and natural soiling conditions in the Mediterranean climate. Saudi Arabia presents a range of soiling issues relating to the expanded use of solar in the region [55–58]. Micheli et al. [59] developed a soiling map at the National Renewable Energy Laboratory (NREL), providing data for 83 locations in the U.S. The daily soiling losses were determined from monitoring stations or photovoltaic systems. The greatest impact of soiling occurs in the southwestern U.S. region, with Southern California municipalities having the highest daily soiling losses indexes due to the high concentration of particulate matter, emissions, and long periods of drought.

Because the demonstrated energy losses associated with soiling lead to higher maintenance costs and diminished generated income, the determination of the effects of soiling on PV plants in Brazil is important, especially with the current expanding Brazil PV markets [60–62]. Solar-PV soiling research is still in its infancy in this largest, South American country. With its diverse climate zones, soiling information is important for location choice, proper sizing, estimation of anticipated maintenance costs, and participation in the Brazil electricity auctions [63–65]. The objective of this paper is to present a case study dealing with soiling issues in Brazil's climate zones, highlighting areas in which the major PV growth is taking place and being planned, as well as providing information on the diversity of these climate locations. We present a methodology to quantify and compare soiling losses in CdTe and Si PV modules installed in three states having diverse climates: (1) Rio Grande do Sul in the South; (2) Minas Gerais in the Southeast; and (3) Bahia in the Northeast (Fig. 1). In general, Brazil has favorable solar resource for PV operation with good return-on-investment [65]. However, these 3 states represent areas of various degrees of weather and soiling conditions. The south of Brazil has tropical conditions, with extended periods of precipitation. The hot and dry climate in the northeast have typically higher soiling conditions with mitigating wind levels. Currently, Minas Gerais has the highest PV power installations and planned power plants over the coming 5-year period—with the Northeast states positioned to be major areas of growth in the future [63]. This case study reports on the soiling conditions (soiling losses) in these three areas for which we have more than 1-year of monitoring periods. The methodology describes our monitoring stations and operation.

Methodology

The major technical contributions of this research include: (1) Development and validation of the methodology to estimate and compare soiling losses on PV-module performance using soiling monitoring stations data from sites in Brazil; (2) First-time acquisition and comparison of the annual soiling losses for locations in tropical, subtropical, and semi-arid zones in Brazil, based upon the developed climate zone map; and (3) Combined use of crystalline-Si and thin-film CdTe modules at the locations to compare and validate the effects of soiling and PV parameters, including the effects of non-uniform and uniform soiling on the IV characteristics and accuracy of soiling reporting; and (4) Providing initial evaluation and modeling of the spectral effects of the accumulated soiling layers on the relative responses on the two technology types. The impact and the novelty are that these investigations provide first-time reports specific to the Brazil situation.

The first requisite of this study was choice of appropriate locations for the monitoring station in different climatic zones in Brazil. The climatic zones designations were defined using the methodology proposed by Köppen and Geiger [66] and the base map available by Peel, Finlayson and McMahon [67]. Fig. 1 shows the climatic classification map developed on ArcGIS® software, version 10.2.2. As can be seen, the Brazil is divided into three major climatic groups: (A) on the influence of a tropical rainy (megathermic) climate; (B) dry climate (semi-arid); and (C) characterized by the temperate (mesothermic) climate. The cities of Belo Horizonte, Minas Gerais-MG (inside Aw-climatic zone, predominance equatorial climate with dry period during winter), Porto Alegre, Rio Grande do Sul-RS (inside Cfa, predominantly humid climate annually and high-temperature summers) and Brotas de Macaúbas, Bahia-BA (BSh-climate zone that presents dry summers with annual high temperatures) were selected, and soiling monitoring stations and meteorological stations were installed. Two of these three zones represent locations for major existing and planned PV installations.

Configuration of soiling monitoring stations

The soiling monitoring stations are the basic design, electronics, and controls of Atonometrics [68]. The general system (Fig. 2) is composed of one "clean" device (PV_{clean}) that can be a reference module or a solar cell, kept clean during the analysis, and one "dust or soiled" device (PV_{soiled}) that can be a photovoltaic module or solar cell exposed to the natural deposition soiling (not cleaned) [69]. The PV_{clean} and PV_{soiled} devices are connected to the control and measurement unit (RDE) and the collected data is transmitted (either over an internet connection or a

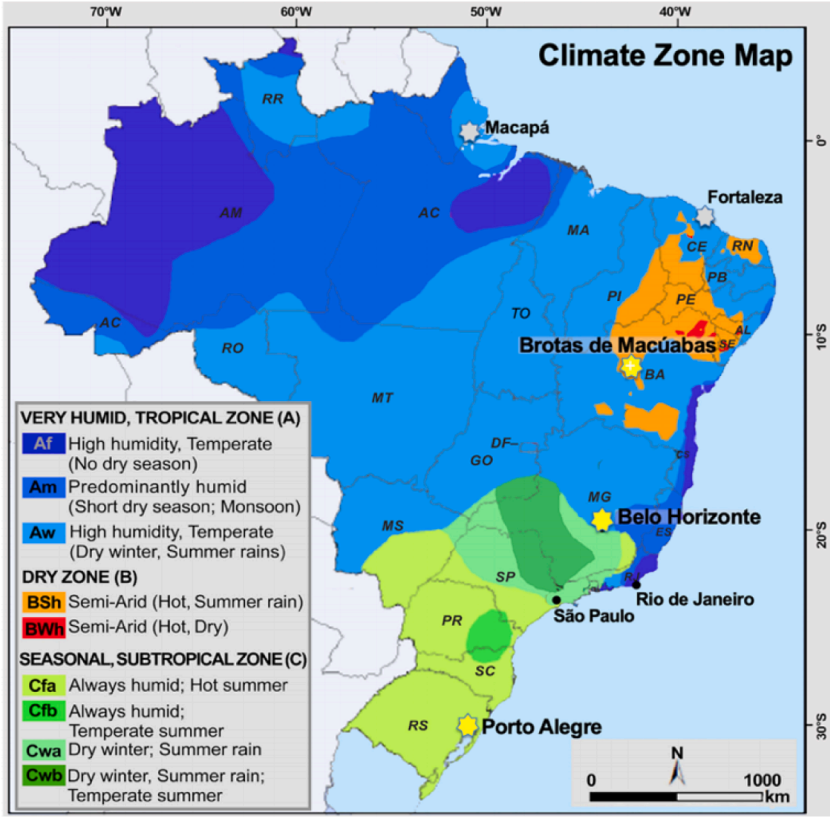

Fig. 1. Brazil climate-zone classification following Köppen-Geiger [66,67]. Note that (A) is also termed megathermic climate with high humidity; (B) semi-arid climate; and (C) mesothermic climate. Monitoring sites for this study are indicated by yellow suns.

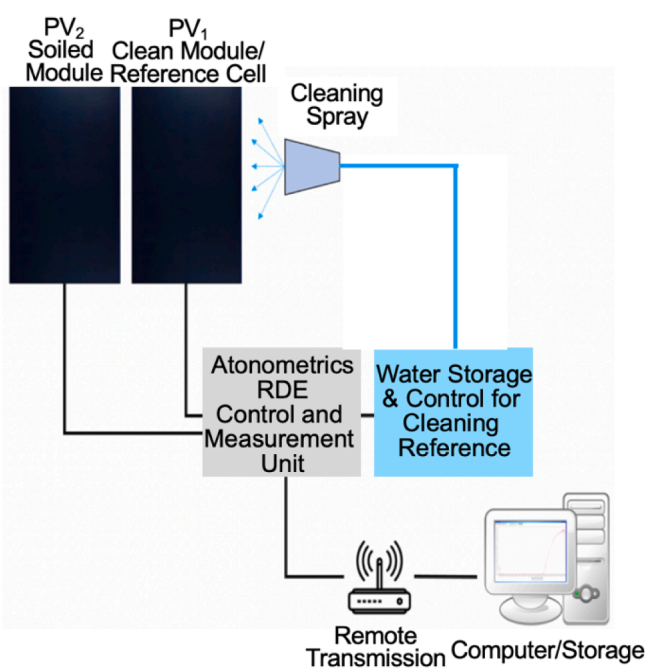

Fig. 2. Schematic of soiling monitoring station operations. Note that the reference (PV_{clean}) is either a module or a standard reference cell. PV_{soiled} is the soiling exposed module.

radio transmitter) and stored on the laboratory computer and the cloud. In addition, a remote washer unit is used for cleaning the PV_{clean} reference device with demineralized water. This wash unit has a sensor to measure the flow rate of the fluid, allowing the desired (measured) amount of fluid to be accurately dispensed at each wash. The soiled device (PV_{soiled}) is protected from the liquid spray.

In this study, the 3-soiling monitoring systems (each with a separate thin-film CdTe and mc-Si station) were installed at the Pontifical Catholic University of Minas Gerais in Belo Horizonte/MG, Pontifical Catholic University of Rio Grande do Sul in Porto Alegre/RS, and test site of Santa Catarina Federal University in Brotas de Macaúbas/BA. The soiling stations were installed on the ground (with elevations normally used for PV plants), in places without shading projection, away from high traffic and from potential polluting agents, such as industries. The soiling station installed in Brotas de Macaúbas/BA has a differential in relation to the others, as it is adjacent to a wind farm.

The *CdTe station* uses two identical PV modules of 110 Wp, both with the same tilt ($\beta = \phi$) that is determined by the latitude of the site. One module (the reference module) is cleaned daily, immediately before the period (11:00 am to 1:00 pm) for monitoring. Typically, the data are collected within 10 min of noon. The other module is exposed to natural soiling deposition. The control and data collection electronics also record the plane-of-array solar irradiation incident on the photovoltaic plane, the thermocouple-measured module temperature, and the module electrical parameters (short-circuit current, open circuit voltage, and maximum power) at one-minute interval.

The Si station is composed by a mc-Si photovoltaic module (265 Wp) and a calibrated Si-reference cell (0.0584 Wp). Both are oriented with the same tilt. The reference cell is cleaned daily by an automatic washing unit with demineralized water. The monitored-module (PV_{soiled}) is soiled naturally. As with the CdTe soiling station, the simultaneous measurements were recorded automatically every minute by a control system (RDE300), providing data of solar irradiance (POA), operating temperature and short-circuit current from the photovoltaic module and from the reference cell, as well as the power generated by the silicon

photovoltaic module.

For both stations, the entire current vs. voltage (I-V) characteristics are collected and archived. Meteorological stations are co-located and interfaced with the soiling stations, measuring and storing precipitation levels, wind velocity (speed and direction), ambient temperature, and humidity on one-minute intervals.

Our monitoring in all regions was delayed due to unanticipated equipment-importation issues and/or interrupted due to the pandemic. As a result, the soiling stations have different periods of operation, varying up to 5-years of data collection between the years 2017 and 2021. The longest periods are for Minas Gerais. In this paper, we present typical data for the three regions.

Methodology for soiling loss analysis: Soiling monitoring stations

To evaluate the PV performance soiling losses, a methodology to determine the soiling ratio (SRatio) and soiling rate (SRate) data was used, in accordance with the international standard IEC 61724-1/2017 [14,70–72].

Soiling ratio (SRatio)

SRatio is the ratio between the short-circuit current (I_{sc}) or maximum power point (P_{max}) from the soiled module or cell and the I_{sc} or P_{max} from the reference clean module or cell, under the same operating conditions. SRatio is a dimensionless parameter that varies between 1 (no soiling condition) to 0. The SRate represents the daily loss in I_{sc} or P_{max}, expressed as a negative percentage/day.

The soiling ratios are calculated and compared using both short-circuit current ($SRatio_{I_{sc}}$) and maximum power data ($SRatio_{P_m}$). The use of these two electrical parameters in this evaluation can be used to distinguish between uniform and non-uniform accumulations. The SRatio was calculated for each one-minute interval, and for analysis, daily SRatio was determined from the median value. The definitions and methodology for the determination of the SRatio compares the soiled and cleaned or reference device, and the analytical expressions depend on the "two-module" or "module and standard reference cell" for our stations.

(i) *Station with two modules*: With the soiling monitoring station composed by two identical PV modules or two identical solar cells, the soiling ratio is defined as:

$$SRatio_{I_{sc}} = \left(\frac{I_{sc\,dust}}{I_{sc\,clean}}\right) \tag{1}$$

$$SRatio_{P_{max}} = \left(\frac{P_{max\,dust}}{P_{max\,clean}}\right) \tag{2}$$

where $I_{sc\,dust}$ and $P_{max\,dust}$ are short-circuit current and power measurements from soiled or dust-accumulated PV device (PV_{soiled}), while $I_{sc\,clean}$ and $P_{max\,clean}$ are short-circuit current and maximum power measurements from clean reference PV device (PV_{clean}).

(ii) *Station with module and standard reference cell*: In this case, the soiling station compares the exposed module with a standard reference cell having different electrical parameters. The soiling ratio is determined by:

$$SRatio_{I_{sc}} = \left(\frac{I_{sc\,dust}}{I_{sc0}*(1+\alpha*(T_{c\,dust}-T_0))*\left(\frac{G_{POA}}{G_0}\right)}\right) \tag{3}$$

$$SRatio_{P_{max}} = \left(\frac{P_{max\,dust}}{P_{max0}*(1+\gamma*(T_{c\,dust}-T_0))*\left(\frac{G_{POA}}{G_0}\right)}\right) \tag{4}$$

where $I_{sc\,dust}$ and $P_{max\,dust}$ are short-circuit current and maximum power measurements from the soiled PV module (PV_{soiled}), I_{sc0} and P_{max0} are short-circuit current and at the maximum power of the module in Standard Test Condition (STC), α and γ are the temperature coefficients for short-circuit current and maximum power, respectively, $T_{c\,dust}$ is the soiled module temperature, T_0 and G_0 are temperature and solar irradiance in the normalized conditions (1000 W/m^2 and 25 °C), and G_{POA} is the solar plane-of-array irradiance measured by the reference cell.

The calculated SRatios were filtered to reduce the influence of noise or outliers with respect to acceptable solar irradiance, precipitation, or external interruptions. Only solar irradiance data that presented fluctuation<10% between maximum and minimum values for the 10-minutes intervals were considered in the calculations [36,37]. In addition, the data used were restricted to the period of highest incidence of solar (11 and 13 h) and taken near noon under clear-sky conditions and irradiance greater than 500 W/m^2 [13,14,18]. The data collection was restricted to the period close to noon to reduce the irradiation uncertainties and with smaller variation of the angle of incidence (AOI). All performance parameters are corrected to 1000 W/m^2 and temperature of 25 °C.

The calculated average daily SRatio was correlated with the cumulative daily precipitation data measured at the meteorological station installed near the soiling stations. Precipitation data were filtered to included accumulated daily rain greater than 0.3 mm. Below this value the rain has been reported to not have a sufficient cleaning effect on the photovoltaic modules [14].

Soiling rate (SRate)

The linear regression of Theil-Sen, commonly known as Theil-Sen estimator, is used to calculate the SRate. This algorithm was proposed by Theil and Sen [73,74] as a slope estimator, providing a more robust and efficient evaluation than the least squares calculation. The Theil-Sen linear regression is less influenced by anomalies. The regression of Theil-Sen is defined by [75]:

$$\beta_1 = \text{Mediana}\left\{b_{i,j} = \frac{t_i - t_j}{x_i - x_j} : x_i \neq x_j, 1 \leq i \leq j \leq n\right\} \tag{5}$$

The Theil-Sen estimator calculates the slope between all pairs of points (t, x), providing the median value of all slopes calculated. Thus, the Theil-Sen estimator was applied to calculate the median of slope of the SRatio curve during dry periods. Deceglie et al. [36] showed these dry periods have to be greater than 14 days to provide a valid evaluation photovoltaic performance. The median slope gives the value of the daily SRate.

Results

As noted, to calculate and compare the soiling ratios correctly, it is necessary to normalize the device parameters for irradiance and temperature. It is also advantageous (though not necessary) to know the measured performance (I_{sc}; open-circuit voltage, V_{oc}; P_{max}; I-V characteristics under standard conditions) of the modules involved with the monitoring stations. The "nameplate" values provide information—but these are provided with some ranges.

Even two modules of the same technology, same manufacturer, and same manufacturing run can have small differences. The modules were measured under standard simulator conditions to baseline them. With the monitoring station employing two modules, the "clean" module acts as a reference. Of course, the calibrated standard reference cell provides the require accuracy. We have also investigated using reference cell comparison for the CdTe modules (e.g., a calibrated Si cell with a KG-1 filter provides a good match), and this has provided confidence that our 2-module thin-film stations provide the same reliable measurements as our Si stations that directly use the clean reference cell directly. Additionally, the cleaned modules in the thin-film (2-module) station have

the same initial SRatio. The results will be presented by location, each of which represents a different climate zone in Brazil. Representative data periods are presented, but the soiling rates are consistent seasonally over the several years of monitoring. The Table 1 presents a summary of the general conditions of each site where the soiling monitoring stations were installed.

Soiling monitoring system: Belo Horizonte, Minas Gerais (Equatorial climate – Aw)

Belo Horizonte is located in the equatorial climate zone (Fig. 1), having high precipitation during summer season and long dry periods in winter season. Full operation was begun in July 2017. The delay provided time to calibrate and validate station operation and integrate the dedicated meteorological system.

Soiling ratio evaluations

Fig. 3a presents the daily-average $SRatio_{Isc}$ (using I_{sc}) and $SRatio_{Pmax}$ (using P_{max}) and the precipitation for the thin-film cadmium telluride (CdTe) modules over the representative

period July 2017 through April 2019. The long dry period July-October 2017 is typical for this location, and the soiling rates are consistent for year-to-year. The 2-year period is shown because it has an outlier second year in which the normal dry period (April-September) had unusual high levels of precipitation with shorter dry intervals (Table 2). The modules were configured with tilt of 20°, the latitude of the Minas Gerais site (Fig. 4).

SRatio equal to "1" represents the clean state of the photovoltaic module, without losses due to deposition of particulate matter or any other contaminant. SRatio with less than unity indicates greater soiling and greater performance losses. The initial period of data collection was during the dry winter season (the best time to monitor soiling at this location). Over this long, dry 85-day period, SRatio reached ~ 0.73. The SRatio using I_{sc} and P_{max} are the same because the thin-film modules used in these studies have no frames (and no bypass diodes). We have never measured (e.g., by IR-camera mapping) any significant non-uniform heating effects on the thin-film modules. The modules are mounted with the cells oriented to minimize the potential of such effects [76].

Periods without data in Fig. 3 reflect insertion of the filters to include measured data near noon, conditions of clear sky (high atmospheric clarity), and irradiance greater than 500 W/m^2. Some dispersion of the points on the curve to soiling ratio for the CdTe station is attributed to the dew deposited on the photovoltaic modules during the night and early morning when the relative humidity is high. In some cases, it is due to light rain leaving drops of precipitated water, as shown in Fig. 5. If this is detected prior to the data acquisition period, those data points or measurements are removed by the filter.

Table 1
Summary of the conditions for each analyzed site [12,66].

Site	General conditions
Belo Horizonte, Minas Gerais/ MG	Tropical (Equatorial) Climate Zone Dry winter; Rain/Humidity summer Low wind conditions Solar resource: 1500–1550 kWh/KWp/year (Very good)
Porto Alegre, Rio Grande do Sul/RS	Subtropical (Humid) Climate Zone High humidity, frequent precipitation year round Low wind conditions Solar resource: 1250–1400 kWh/KWp/year (Good)
Brotas de Macaúbas, Bahia/BA	Semi-Arid (Dry) Climate Zone Low precipitation summer; dry winter High persistent wind conditions Solar resource: 1600–1700 kWh/KWp/year (Excellent)

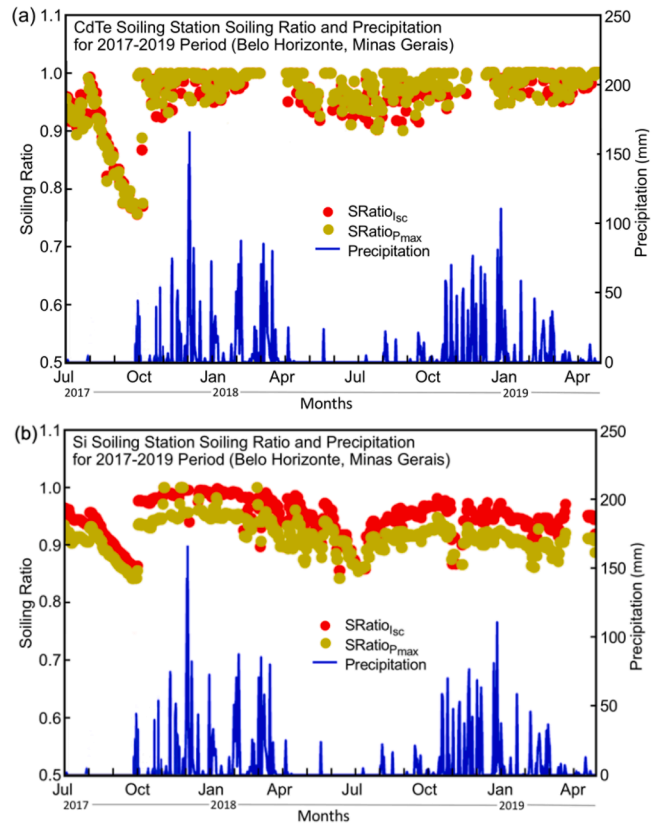

Fig. 3. Average daily soiling ratio (on left-hand axis) with $SRatio_{Pmax}$ - *yellow* and $SRatio_{Isc}$ - *red* as a function of exposure (days) in Belo Horizonte-Minas Gerais. Precipitation events are shown by blue characteristics (right-hand axis): (a) Thin-film CdTe module; and (b) Multicrystalline-Si module. The timeframe represents the usual winter dry period and summer rainy period.

Table 2
Summary of average SRatio at P_{max} in Belo Horizonte over defined dry periods and seasons from data provided in Fig. 3.

Period	Season	Dry Period	Period Length (days)	Minimum SRatio	
				CdTe	Si
(1)	Winter	07/05/2020–09/27/2020	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 typical period of daily precipitation greater than 20 mm occurred (September 28 to October 4), resulting in the natural cleaning of the module and restoration of the soiling ratio to near "1".

The same variations of SRatio occur in other dry periods, followed cleaning due to adequate rainfall. One example is shown in Fig. 4a with an accumulation of contaminants, including fairly substantial bird droppings after an extended dry period. Fig. 4b shows the same module immediately following 3 days of rain. (Note: Even with this extremely bad case with the bird droppings, the module did not exhibit any hot spots.)

The mc-Si technology daily average SRatio and precipitation is presented for the July 2017 through April 2019 period in Fig. 3b. This soiling monitoring station differs from the CdTe because it utilizes a

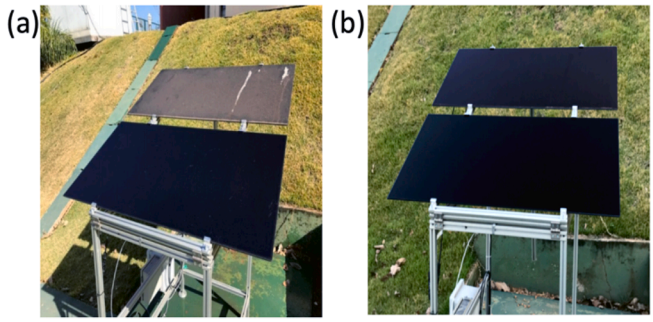

Fig. 4. Thin-film CdTe soiling station installed in Belo Horizonte: (a) during a dry period, and (b) after accumulated precipitation greater than 20 mm, indicating effectiveness of natural rain in cleaning the modules. Note that even with the bird droppings, no issues with hot spots were recorded.

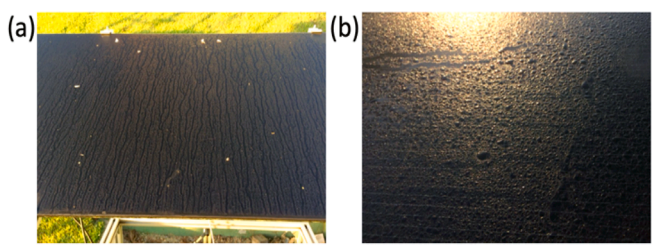

Fig. 5. Thin-film CdTe module (PV_{soiled} from Fig. 3) in Belo Horizonte: (a) with dew formation in early morning, and (b) with water drops formed after precipitation.

clean reference cell (PV_{clean}) that is cleaned automatically daily prior to the defined measurement period. The reference-cell (and reference module) characteristics are checked against calibrated conditions to ensure that the device is clean and the surface is dry (with module at operating temperature) before the measurements are accepted.

During the longest dry period (July-September of 2017), the SRatio using either the I_{sc} or P_{max} decreases, reaching values ~ 0.83. (This is the typical dry annual dry period. The second "winter" in Fig. 3 had higher than usual precipitation.) After the extended precipitation period, the SRatio increases indicative of module cleaning, as shown in Fig. 6a,b. Three observations in the measurements of Fig. 3b need further explanation: (1) The Si-station operation began in the month before, and initially the SRatio using the I_{sc} or P_{max} were both initially equal to "1". This initial time was used to implement the data transfer system, and the module continued to be soiled. Thus at the initial recorded measurement time, the SRatio reflects the soiling condition at that time; (2) The initial interruption near the end of July 2017 corresponds to a short time there was light precipitation below 5 mm/day and some increased wind that limited the accumulation; and (3) The separation between the SRate determined by the P_{max} from that of I_{sc} (the yellow and red data points) is the result of non-uniform soiling, especially build-up near the module frame at the bottom and the corners as represented in Fig. 6. As the ambient temperature during the summer period (February 2019) increased, the non-uniformity caused a corresponding creation of non-uniform cell temperatures in the module, ranging from < 45 °C at the center up to 70 °C for some soiling-shaded cells measured by IR thermal scans–and eventually, the interruption in the recorded data.

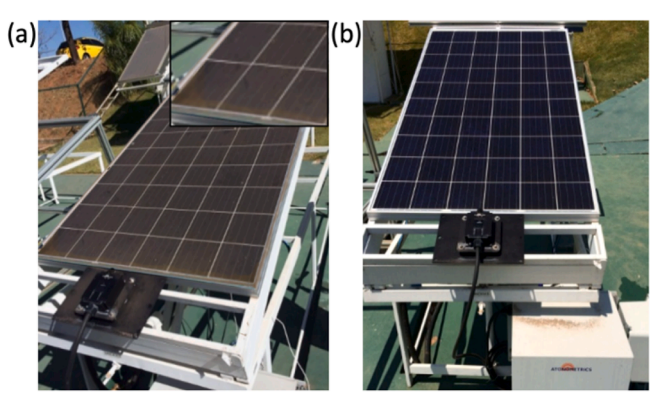

Fig. 6. Soiling station to mc-Si technology installed in Belo Horizonte: (a) during first dry period of 85 days, and (b) after measured precipitation greater than 20 mm, indicating effectiveness of rain in cleaning the soiled PV module. Inset shows accumulation (non-uniform soiling) with buildup along frame and extending from bottom portion.

During the first months of data collection (July to September 2017), the SRatio using I_{sc} and P_{max} characteristics are close, indicative of reasonably uniform soiling. However, the occurrence and severity of non-uniformity soiling are more of a concern for the crystalline-Si modules because of the electrical circuits (bypass diodes) and use of frames [71,77,78]. The frames tend to provide elevated boundaries above the glass where the particulates can collect. If the module is tilted, the collection tends to be greater at the bottom (Fig. 6a). The effect of non-uniform soiling on SRatio is observed in Fig. 3b with the start of the extended period of precipitation at the end of September 2017. The $SRatio_{Pmax}$ and $SRatio_{Isc}$ characteristics separate. This is due to the rain washing the module, but the soiling particles accumulate at the bottom along the frame.

This build-up continues through the rain events—causing the electrical response of the bypass diodes to affect the shapes and location of the P_{max} point as reported previously. This effect is the basis for using Pmax as a better indicator of the soiling process in these monitoring stations—though this measurement is far more sensitive to accounting for the module temperature [66,74,75]. The basis can be observed in the I-V characteristics of Fig. 7, which shows the evolution of the characteristics with soiling for a Si module. The change in I_{sc} is small, but the position of the P_{max} point changes due to the effect on the bypass diodes in the cell circuits [23].

Table 2 summarizes the $SRatio_{Pmax}$ for both the thin-film CdTe and mc-Si stations in (Belo Horizonte) for the seasonal dry periods with their length in days.

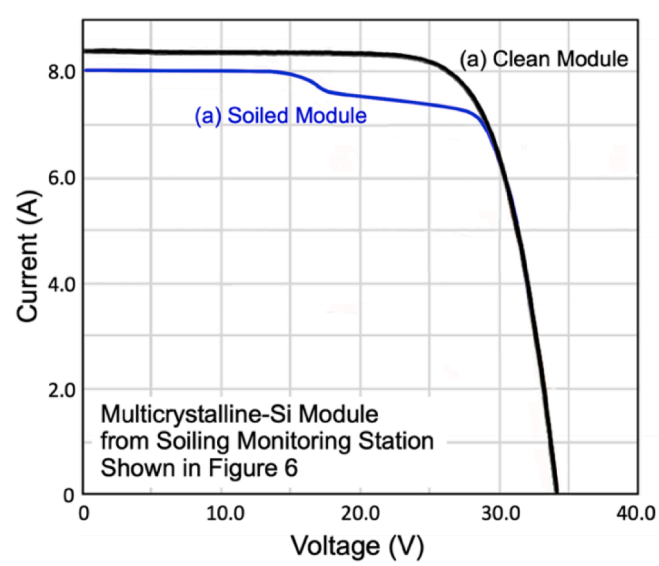

Fig. 7. Current-Voltage characteristics for modules indicating the change in output as function of soiling time for dry period in Figs. 3 and 6, indicating the potential preference in using P_{max} over I_{sc} in the case of non-uniform soiling conditions.

Soiling rates

The soiling rate is determined analytically from the measured SRatio. SRate is expressed in units of %/day, and a negative value indicates the module becomes more soiled. Table 2 shows the data from 5 partitioned dry periods of at least 14-consecutive rain-free days, the convention recommended by Deceglie et al. [36]. Fig. 8 presents the expanded portions of the SRatios for the CdTe and Si technologies. For each interval, the Theil-Sen estimator is used to extract the slope of the SRate [78–80]. Using the calculated angular coefficients, the average slopes of these coefficients give the average daily soiling rates. In this case, the data from Fig. 8a,b, SRate are −0.20%/day and −0.14%/day for the CdTe and mc-Si module, respectively.

Soiling monitoring system: Porto Alegre, Rio Grande do Sul (Humid climate – Cfa)

Subtropical regions with high humidity and higher precipitation levels have exposures to soiling from agricultural and industrial sources, and interestingly, biofilms that can be cultured on the module surfaces [81]. The soiling stations were commissioned in Porto Alegre, Rio Grande do Sul, at the end of May 2018, and data collection of electrical, thermal, and meteorological information was initiated at the beginning of June 2018 (Fig. 9a).

This sub-tropical region in the south of Brazil is characterized by frequent daily periods of precipitation throughout the year, unlike the case for Belo Horizonte in which the summer season is "wet" and winter is "dry". However, in Porto Alegre there are frequent daily clear periods with sunshine, permitting several hours of PV-power generation.

The average daily accumulated precipitation ranges from 0 to 86 mm. Because of the frequency of the rainfall, the measured SRatio for Porto Alegre is always close to "1". That is, the CdTe (Fig. 10a) and Si (Fig. 10b) modules remained consistently cleaned naturally by the precipitation. Because there were no extended dry periods greater than 14 consecutive days, the calculation of a SRate was not possible.

The longest dry period recorded was 12 days (October 14 to October 25, 2018), resulting in a decrease in the average daily soiling ratio to 0.95 and 0.97 for CdTe and mc-Si, respectively. In the other periods, the soiling ratio was equal to or relatively close to "1". The separation in the points between I_{sc} and P_{max} measurements is likely due to precipitation residue left on the glass surface, with insufficient time-to-dry during the data collection time.

In Fig. 10a,b, there is a region between January 16 and February 2 that appears to be "dry". However, there was a problem with the meteorological station data transfer line. The SRatio remained near "1" for this period consistent with the natural cleaning—and the local weather report confirmed precipitation continued during this period. Module glass coupons were also exposed mounted parallel to the Si module. These were examined for any possible biofilm growth as part of a collaboration with NREL, but only traces were in evidence. We had expected a greater presence of biofilms as reported by Shirakawa et al. [81] in their studies in this same climate zone, but we suspect our analysis methods are not adequately sensitive for this characterization. Over the period of the presented data in Fig. 10, the average SRatio was 0.98 for the CdTe module and 0.97 for the mc-Si module.

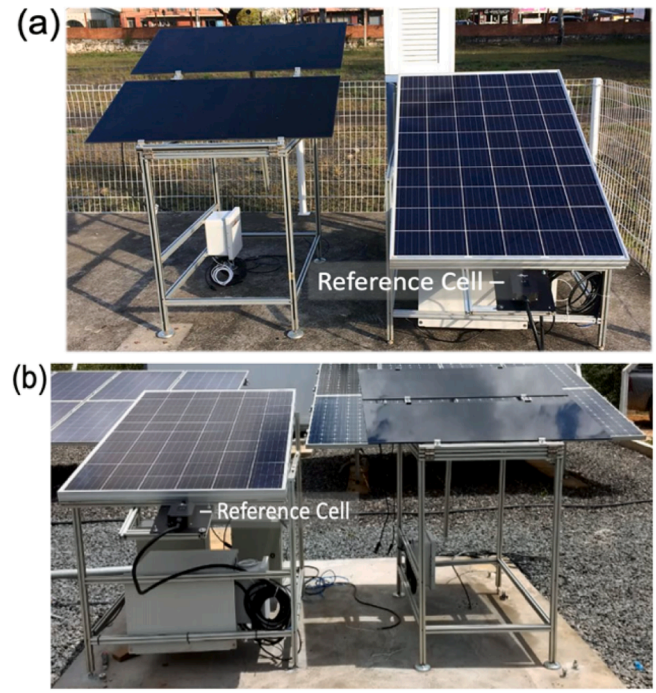

Fig. 9. Soiling monitoring system installations: (a) Porto Alegre-Rio Grande do Sul (south); and (b) Brotas de Macaúba, Bahia (northeast).

Soiling monitoring system: Brotas de Macaúbas, Bahia (Semi-arid climate – Cfa)

Brotas de Macaúbas, Bahia (northeast region of Brazil) resides in the semi-arid climate zone, with annual low-humidity and high-ambient temperatures. The PV and monitoring system location is also characterized by persistent higher wind levels, which our meteorological station recorded with average values of 6 m/s during June-July and greater than 8 m/s during August-September. This region is attractive for installation photovoltaic system because it has high solar irradiance throughout the year. Our measurements recorded values exceeding 1.0 kW/m^2 during March through May and August through November. The soiling monitoring stations (Fig. 9b) were commissioned at the end of February 2019. The modules were configured with tilt of 12°. The Federal University of Santa Catarina PV system is in the background.

Fig. 11a,b presents the typical and comparative SRatio (I_{sc} and P_{max}) for the thin-film CdTe and mc-Si soiling stations, respectively.

At this site, the SRatio has remained close to "1", due periodic precipitation (as for other sites), but more due to cleaning by the relatively

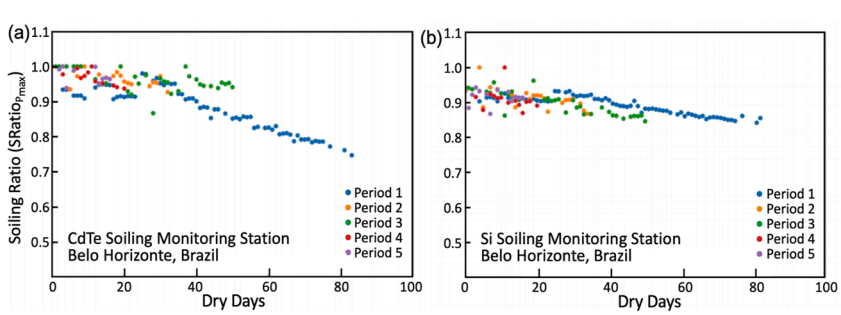

Fig. 8. SRatio versus dry periods (days) for (a) CdTe and (b) mc-Si modules. The selected dry periods (each more than the 14-day convention from Table 2) are represented by different colors. The Theil-Sen estimator identify the slope for each period, and median of all slopes indicate the soiling rate for the site.

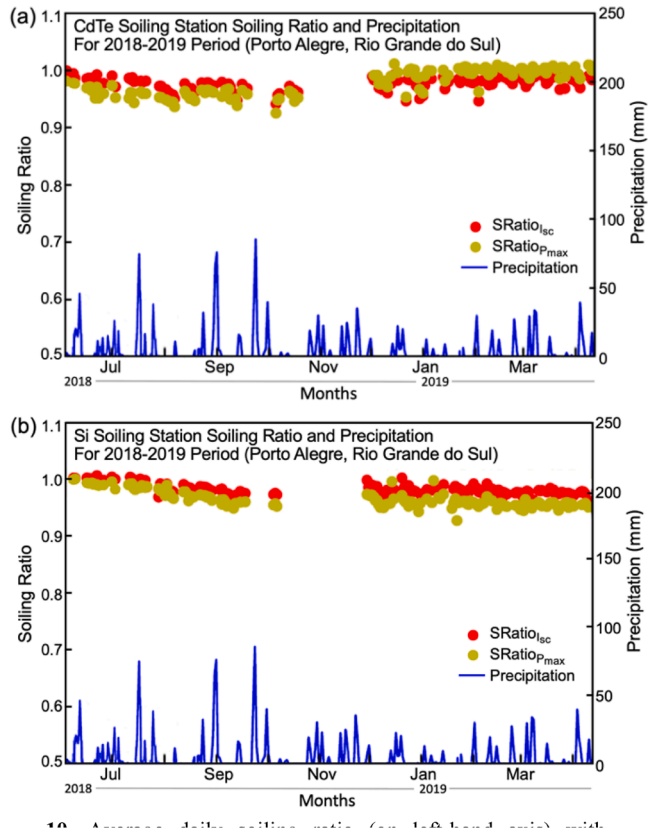

Fig. 10. Average daily soiling ratio (on left-hand axis) with SRatio$_{Pmax}$ - yellow and SRatio$_{Isc}$ - red as a function of exposure (days) in Porto Alegre, Rio Grande do Sul. Precipitation events are shown by blue characteristics (right-hand axis): (a) Thin-film CdTe module; and (b) Multicrystalline-Si module.

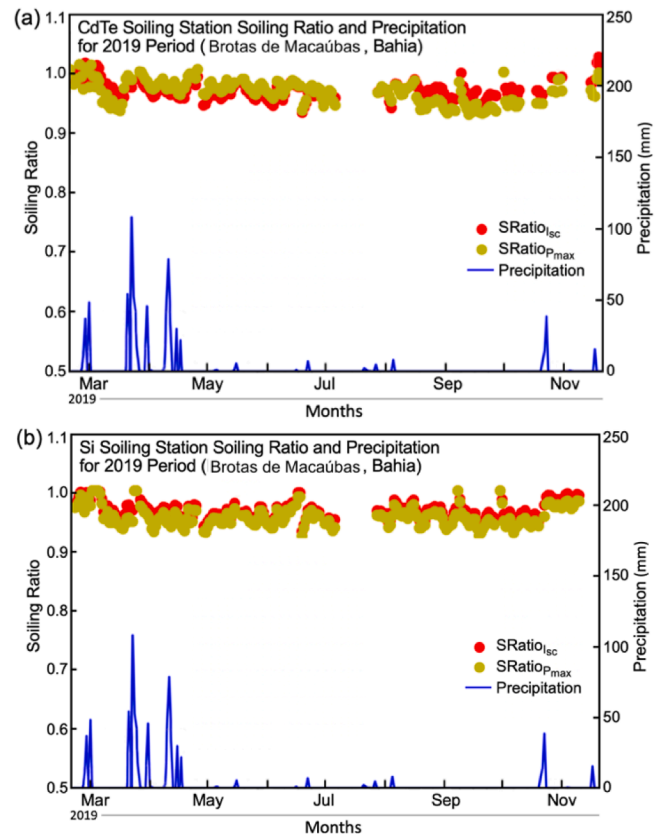

Fig. 11. Average daily soiling ratio (on left-hand axis) with SRatio$_{Pmax}$ - yellow and SRatio$_{Isc}$ - red as a function of exposure (days) in Brotas de Macaúbas, Bahia. Precipitation events are shown by blue characteristics (right-hand axis): (a) Thin-film CdTe module; and (b) Multicrystalline-Si module.

higher-wind levels. These significant effects of wind on the soiling accumulation have been reported in the literature [82–85]. Additionally, the site preparation minimizes soil (particulate) exposure and the surrounding area is very well cultivated and forested. Thus, the local source for dust particles is minimal.

The average SRatio for the CdTe and Si over the period February 19 to November 30 was 0.99 and 0.95, respectively. Additionally, some oscillations in the SRatio over time for Si (over that observed for the CdTe) are observed. In this case, the soiling ratio is influenced by non-uniform operation temperature of solar cells in the module circuits (see, for example, Fig. 12).

Several effects account for these differences between the two technologies. The module temperatures in this nearer-Equatorial location are higher because of the higher ambient temperatures and high solar irradiance. The modules routinely reach or exceed 60 °C.

The CdTe modules have a higher bandgap and correspondingly better temperature coefficient for P_{max} (−0.0034/°C) than for the temperature from Si, the cells in the Si module are not uniform in temperature and the higher the temperature, the more the non-uniformity differences.

This is illustrated in the temperature map of the Si module in Fig. 12, with cooler regions near the frame and some small variations due to cell mismatches. The CdTe modules are more uniform in temperature [86]. This is reflected in the SRatio, shown as a function of temperature two technologies measured at this Bahia location in Fig. 13. For Belo Horizonte and Porto Alegre, the modules rarely reach 50 °C operating temperatures (with lower ambient-T and irradiance), and these differences have less of an effect. The winds tend to be gusty and in excess of 6 m/s, causing the depositions to be sometimes observed as waves on the surfaces of the modules—with the majority of the surface relatively clean

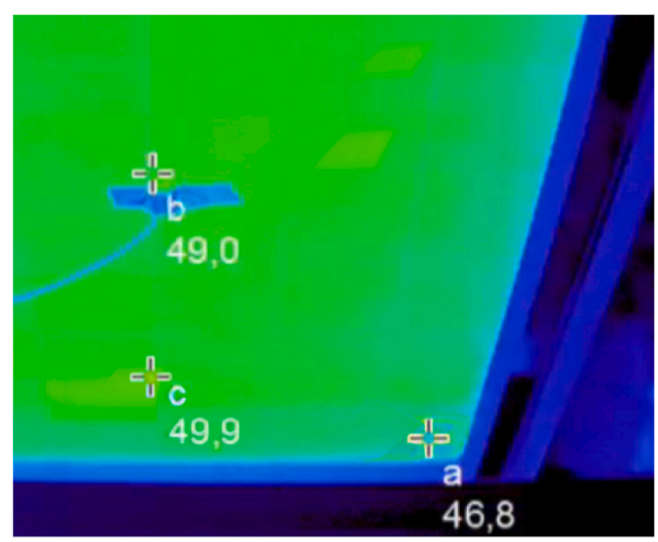

Fig. 12. Infrared temperature scan of Si module showing variations in temperatures over the displayed area for clean module (at Pmax, under 912 W/m^2 irradiance and ambient temperature of 20 °C). The aluminum frame causes some cooling at module edges and some cell areas are at slightly higher temperatures due to mismatches.

[38,85]. In this region, though the aerosol soil levels are higher, the wind tends to keep the module surfaces with relatively low, dry accumulations. Using the Theil-Sen methodology during the dry periods, preliminary SRate of −0.04%/day for mc-Si and −0.08%/day for CdTe

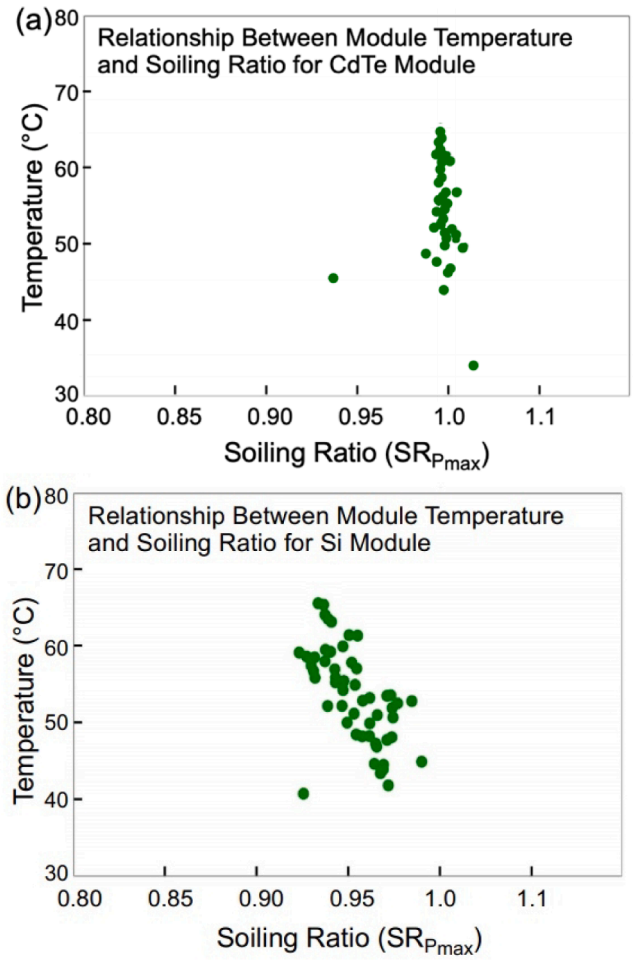

Fig. 13. Temperature as function of SRatio for soiled modules: (a) CdTe module and (b) mc-Si modules. This demonstrates the increase in scatter for the crystalline-Si module.

were calculated. However, it is necessary to have a longer monitoring period to gain a better evaluation of the soiling behavior.

Performance mc-Si versus CdTe: Notes on differences in soiling spectral effects

Some performance differences between the mc-Si and CdTe modules from the soiling monitoring stations for this case study in Belo Horizonte (with the longest monitoring periods) raised some additional questions. Since the stations are positioned side-by-side, what is the reason for the incremental differences in the SRate (Section "Soiling monitoring system: Belo Horizonte, Minas Gerais (Equatorial climate – Aw)")? The first suspicion was module temperature, with the Si modules operating at a slightly higher average temperature than the CdTe modules. But this is a small temperature difference (<0.5 °C-1.0 °C, within the uncertainty of the measurement), and a higher module surface temperature might result in a higher dry soiling rate [87]. This is the opposite case for our measurements (Section "Soiling monitoring system: Brotas de Macaúbas, Bahia (Semi-arid climate – Cfa)"). Second, could the glass surfaces be sufficiently different? Neither module surface has an anti-reflection coating (specified for our stations), with the glass having the same composition and general smoothness [90]. An independent investigation of the gravimetric densities of the accumulated soiling layers collected over the identical exposure times for glass samples of each module type has shown that in the collected gravimetric densities are the same [86,89,90].

Several previous investigations have reported that the absorption of light by the soiling layer controls not only limits the transmission of the sunlight but is also spectrally sensitive [25,89,91,92]. Specifically, the portion of the solar spectrum approximately between ~ 300 nm and ~ 600 nm exhibits enhanced absorption by the soiling layer. The added absorption in this lower wavelength region has a greater effect on the CdTe (E_g = 1.5 eV) than on the Si (E_g = 1.1 eV). The difference in the soiling rates can be attributed to the spectral effects, consistent with the previous literature [26,88,91,92]. The soiling particulates collected from the surface of the modules has been analyzed and have component constituents (specifically hematite and calcite) that are among those reported for the additional absorption [86]. Transmissions measurements on the layers collected confirm the additional absorption in the regions 300-nm to about 630-nm [89,92]. (Note: The soiling particles collected from modules in all three monitoring sites had very similar elemental compositions—rich in Fe and Ca. This is different than the differences in composition report by John [91] for India with more diverse climate and geographical regions.) These publications would indicate that the lower-bandgap absorber would be the better performance choice based upon the absorption properties of the soiling layers. This is the case for the normalized cases (temperature, irradiance) such as presented in this paperWe have previously confirmed this for Si and CdTe—and have recently shown the model and trends are the same for CIGSSe and a-Si:H [89,90]. However, it should be noted that for normal module-operation temperatures (e.g.,>50 °C), temperature dominates [90,92].

Discussion

The climate-zone designations for Brazil to identify 3-primary climate zone groups (Fig. 1) were effective in selecting appropriate locations that represent different meteorological conditions and areas that correspond to existing or planned high PV-installations. The soiling monitoring systems, each consisting of a Si and a CdTe station, were used to gather data over a period of approximately 5 years and provided a consistent method to analyze the conditions. And the analytical technique developed provided the basis for determining the SRatio and SRate under standard IEC conditions. The comparisons of the SRatio and SRate show very different results for the tropical, subtropical, and semi-arid areas–under Brazil's moderate soiling conditions (≤0.25%/day) typical for all three regions.

The Minas Gerais tropical site had the longest period of monitoring, with five-dry periods of more than 14 days. Minas Gerais is the location with the largest current and planned PV power plant installations. The region has a low-moderate soiling location from these studies, with very good solar resource for photovoltaics (1500–1550 kWh/kWp/yr). The winter periods are the dry seasons—with extended periods (1–3 months) without rain; the summer periods are characterized by precipitation periods in the morning and late afternoon-evening, permitting adequate periods of solar resource for PV power production. SRatio was typically reaching 0.73 and 0.83 for CdTe and mc-Si technology, respectively. The mean SRatio for the two years of monitoring 0.94 for cadmium telluride, and 0.92 for the mc-Si (using Pmax). The average SRate for all 5-dry periods were −0.20%/day for CdTe and −0.14%/day for mc-Si. In addition, during the data collection period it was possible to identify the accumulation of soiling in the bottom area of the mc-Si modules because it has a metal frame that can act as a collection area for accumulating soiling non-uniform. These soiling rates complement and correspond to previous measurements on PV systems reported in Minas Gerais [93].

The Rio Grande do Sul sub-tropical location in the south of Brazil has consistent extended periods of precipitation year-round. The average SRatio was 0.98 for CdTe and 0.98 and 0.97 using both short-circuit current and maximum power for mc-Si. No dry periods more than 14 days occurred during the greater than 1 year of measurements. Thus, a soiling rate to this site was not able to be calculated. The annual solar resource in this region is low (1250–1400 kWh/kWp/yr).

Bahia (semi-Arid) is among the best PV regions with an annual solar resource (1600–1700 kWh/kWp/yr) and characterized by arid conditions in the autumn-winter-spring and intermittent rain in the summer. The commissioning of the monitoring equipment for this site was delayed due to import issues, so the data represented is for a shorter period of operation. The site has higher wind conditions that keep the soiling accumulation at low levels. Additionally, there has been higher than normal precipitation that also helped in naturally cleaning the modules. The average to soiling ratios were 0.99 and 0.95 to CdTe and mc-Si, respectively. However, more extensive monitoring is needed to evaluate the long dry periods and the periods that provide the best PV power production.

Conclusions

This case study has presented to evaluate and compare the SRatio and SRate for PV modules in three different climate zones in Brazil. The case study covers ~ 5-year periods, with typical data presented for each location. The rationale for these studies was based on the knowledge that while the solar resource information for Brazil has been well-documented over the past decade, other critical aspects that affect the sizing, maintenance, and potential of solar PV performance are only in the initial stages of being evaluated. This investigation has concluded for the following three areas, representing Tropical, Subtropical, and Semi-Arid climate zones, respectively:

A. Belo Horizonte (Minas Gerais):
   - The module soiling is consistent and in the moderate range (i.e., 0.1–0.2%/day) during the extended dry winter periods (April-October). Varying levels of non-uniform soiling encountered (module frame edges).
   - Soiling is significantly diminished during the shorter summer wet periods (November-March), but precipitation interaction with dust results in non-uniform, caked soiling buildup that can require cleaning.
   - Regular cleaning is required during the dry periods that can have power losses in the range of 5%-9%/month. During the shorter summer rainy season (e.g. January-March), cleaning is not required, except for non-uniform soiling with the framed modules which does require attention to avoid potential hot spot problems.
   - The annual solar PV output is very good both in dry and wet periods (precipitation occurs typically in late afternoon or early evening during summer season).
B. Porto Alegre (Rio Grande do Sul):
   - The module soiling rates are very low, <0.05%/day.
   - Frequent precipitation provides natural cleaning of the PV modules throughout the year.
   - The annual PV output is adequate because the rain is typically in the late afternoon and evening.
C. Brotas de Macaúbas (Bahia):
   - Module soiling rates are low, <0.1%/day.
   - Mitigating persistent winds (5–8 m/s).
   - High annual PV output due to excellent solar resource and natural cleaning of modules by wind year-round and by evening precipitation during Summer.

In general, the extended periods of measurements under dry conditions confirmed that the P_{max} measurement for determining SRatio and SRate are preferred to avoid issues of non-uniform soiling. However, P_{max} measurements are more temperature sensitive than the I_{sc} approach, so that extra care is required. Incremental differences in the soiling rates for the thin-film CdTe and the mc-Si modules determined under the same P_{max} methodology were noted. These were attributed to soiling layer spectral absorption, primarily in the low-wavelength 300-nm to ~ 600-nm region, as reported in the literature.

The continuation of these monitoring activities is needed to gain a more complete portfolio over several seasons for Bahia and other locations. This includes the deployment to other regions (e.g., Ceará and Amapá), where PV is also of high interest with planned installations. However, our current and planned activities have been interrupted for a temporary period because of the COVID-19 restrictions.

This report addresses the initial phase of this case study. Our discussions and interactions with Brazil developers/installers/users have indicated that the continuation of present monitoring sites and at specific additional locations being commissioned is necessary. They require these soiling data for multiple seasonal periods (2-years or more) to evaluate their maintenance and installation planning. It is also intended to correlate the monitoring station results with system soiling monitoring methodologies for larger operating systems to compare and demonstrate the feasibility of these two different evaluations approaches. Several system developers are anticipating use of other technologies (including CIGS and organic PV) and other installation types (floating-PV, agrivoltaics, and bifacial-module systems, with a number of bifacial systems currently being installed). These soiling monitoring studies will be extended for these applications. Finally, there is a growing interest in emerging tandem Si/hybrid perovskites. These variations in system types and technologies provide a research opportunity to work with prototype manufacturers to begin evaluation of early-stage approaches that holds high current interest and investment potential.

CRediT authorship contribution statement

Suellen C. Silva Costa: Methodology, Software, Visualization, Writing - original draft, Investigation. **Lawrence L. Kazmerski:** Conceptualization, Supervision, Validation, Visualization, Writing - review & editing. **Antônia Sônia A.C. Diniz:** Supervision, Conceptualization, Methodology, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors gratefully acknowledge CAPES ("Coordenação de Aperfeiçoamento de Pessoal de Nível Superior") for the support of this research program through "Pesquisa Visitante Estrangeiro" through Project Number 8881.068091/2014-01 and to Ciência sem Fronteiras that supported the student and postdocs working with this program. We also sincerely thank the international institutions, National Renewable Energy Laboratory (NREL) and the Renewable and Sustainable Energy Institute (RASEI) at the University of Colorado Boulder for sponsoring the research visit of Suellen Costa and providing extensive technical direction. We also acknowledge the help and *input* of Atonometrics, especially with the measurement science and technology base of this research. Finally, the collaboration of Dr. Izete Zanesco and Dr. Adriano Moehlecke, PUC Rio Grande do Sul and Dr. Ricardo Rüther, Universidade Federal Santa Catarina in implementation of soiling monitoring sites and providing important technical guidance and experience on PV technology, climate, and performance expectations.

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