Soiling accumulation impact on PV modules installed at different tilted angles in São Paulo, Brazil

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Abstract. The present study was carried out at the University of São Paulo (USP), in the capital campus, in Butantã, São Paulo. On the rooftop of the Photovoltaic Systems Laboratory (LSF). This study used twenty photovoltaic modules with a unit power of 20 Wp. Before the beginning of the study, the modules were exposed to natural light so that they would suffer the LID effect. Subsequently, all modules were calibrated to measure the solar irradiance, using IEC 60904-2 using a pyranometer as a secondary reference sensor. After calibration, the modules were arranged in pairs, with angles ranging from 0 to 45° as reference to the surface, with a difference between pairs of 5°. To evaluate the influence of rainfall, which is the main responsible for the natural cleaning of the modules. The pluviometric values were obtained from the meteorological station of the Institute of Astronomy, Geophysics and Atmospheric Sciences of the USP. The module allocated at 0°, "Dirty" was used as reference and all the results obtained were calculated in relation to it. The results for the 18 months of experiment showed the non-linear influence of soiling, acting in a stronger way for the less inclined angles, and after 10°, this influence, became less relevant, in comparison to the previous angle. The largest losses were found for 0° and 5°, the losses exclusively to soiling were 8.16 % and 6.82 % respectively. For angles greater than 10°, the soiling effect was attenuated, which resulted in less significant losses, for 15° the difference between the impact of dirt compared to 10° was only 0.1%. Rainfall also had a very relevant impact on the experiment. This study concluded that the optimal angle, where dirt accumulation was reduced, the rainfall cleaning and relative gains were optimized is in the range between 20° and 30°.

1. Introduction
Brazil has enormous potential for the use of solar energy since it counts with very high irradiation values ranging from 3,500 to 6,250 Wh.m⁻². Even with this potential, energy from this renewable resource represents only 1.7 % of the Brazilian energy offer [1].

The Brazilian Photovoltaic Solar Energy Association (ABSOLAR) indicated significant growth in the installed photovoltaic (PV) systems since 2012, going from 0.4 MW to 12.19 GW of accumulated installed power in December of 2021. The state of São Paulo outstands with 985.2 MW as the second place regarding installed photovoltaic power in Brazil, which corresponded to 12.9 % of the total installed in the country as of December 2021 [2]. In this context, following the growth of small
photovoltaic systems, the factors that can reduce the PV energy generation became a focus of several studies, including the tilt angle and soiling.

Soiling is the accumulation of material on the surface of the PV module, where this material acts as an obstacle to the solar irradiance, preventing part of it from being converted through photovoltaic conversion [3-6]. This reduction of energy generation has been estimated to vary in a range from 5 up to 15 % of the nominal capacity [7]. The economic losses associated with soiling worldwide were estimated to reach 3-4 % of nominal power. In addition, the financial impact of such losses was calculated considering 0.03 €/kWh. Thus, without proper handling, soiling has caused losses between 3-5 billion euros in the energy sector only in 2018 [8].

In that sense, one of the main strategies to reduce soiling accumulation and consequent losses consists of tilting the PV modules. The tilt angle not only influences the cleaning of the modules by the action of occasional rainfall but also the accumulation of dirt. This variation of the angle has a strong influence on the cleaning of the modules by natural factors such as rain and wind, at 0° the cleaning by rain is minimized, and at 90° this is maximized. This phenomenon is explained by the action of gravity, where the larger diameter particles move to the lower parts of the module and may even leave its surface, as the tilt angle increases [3-6].

Another strategy to prevent the losses caused by the effect of soiling consists on a regular cleaning of the PV modules. Depending on the purpose and size of the application, it may also become economically feasible to clean at regular intervals, whether it is manually or mechanized performed [9-10]. Considering these two strategies, the present work has quantified the values of losses caused by soiling deposition in association with different tilt and how this angulation influences the natural cleaning of the modules by rainfall.

2. Methodology
The study was carried out on the rooftop of the Photovoltaic Systems Laboratory (LSF) at the Institute of Energy and Environment (IEE), University of São Paulo (USP) (-23.559148 S, -46.735124 W), where 20 photovoltaic modules with a unit power of 20 W, model KM(P)20 Komaes Solar all from the same batch, were installed as presented in figure 1. The modules were exposed to natural sunlight right before the start of the experiment in order to cause the light-induced degradation (LID) effect. This effect normally occurs with new modules, causing a relevant efficiency loss in the first hours of its productive life. The irradiance that reached the module was monitored by using a pyranometer installed at the same angle as the modules until its value was equal to or greater than 60 kWh.m² [11].

![Figure 1. The modules under the LID effect monitoring.](image)

After this procedure, the modules were calibrated following the IEC 60904-2 [12] with a pyranometer as a secondary reference sensor. The pyranometer used was an EKO-MS80 with a sensibility of 10.8μV/W.m². The calibration was performed on June 6th, a cloudless day to avoid shading the modules, and data was collected in the interval between 10:50 am and 1:40 pm, with an angle of 45°, for maximum irradiation capture. The modules and pyranometer were tilted at this angle and installed facing the geographic North, with their poles interconnected using a resistor of 0.27 Ω, as shown in figure 2.
Figure 2. Modules and pyranometer ready for calibration.

The datalogger Keysight model DAQ970A was used to store data during calibration, with two data acquisition boards model DAQM900A to connect the 20 modules plus the pyranometer. The calibrated modules were placed in pairs with angles from 0 to 45°, varying 5° between couples, as presented in figure 3. In which one module of the pair was cleaned weekly, and the other was kept dirty; both according to guidelines.

Figure 3. Modules calibrated and allocated at various tilted angles.

A Keysight 34970 A data logger was used to store data obtained from the experiment. The collection of seven days of the week, 24 hours a day with an interval of 1 minute between measurements, provided massive data, which led to the connection of the equipment to a desktop, as presented in figure 4.

Figure 4. Data acquisition and storage device.

The connection between the data logger to the desktop was made using the Benchlink Datalogger 3® software. To obtain the values of measured irradiance (I_{med}), equation 1 was used to get these measurements in W m². The calibration constant is a unique value for each of the used modules in the experiment due to the modules having slight constructive differences between each other. Therefore, the calibration constant is also a unique value, as observed in table 1.
\[ I_{med} = V_{med} \left( \frac{1}{C_{cal}} \right) \]  

- \( I_{med} \), measured irradiance, W/m\(^2\)
- \( V_{med} \), voltage measurement obtained in each of the modules, \( \mu \text{V} \)
- \( C_{cal} \), calibration constant of each of the modules, \( \mu \text{V/W m}^2 \)

**Table 1.** Values of the calibration obtained following the IEC 60904-2.

| Identification | Calibration constant (\( \mu \text{V/W m}^2 \)) |
|---------------|-----------------------------------------------|
| Module 1      | 343.70                                        |
| Module 2      | 332.42                                        |
| Module 3      | 330.99                                        |
| Module 4      | 336.63                                        |
| Module 5      | 332.53                                        |
| Module 6      | 333.40                                        |
| Module 7      | 336.86                                        |
| Module 8      | 337.43                                        |
| Module 9      | 338.01                                        |
| Module 10     | 341.05                                        |
| Module 11     | 336.31                                        |
| Module 12     | 321.42                                        |
| Module 13     | 335.63                                        |
| Module 14     | 337.27                                        |
| Module 15     | 333.32                                        |
| Module 16     | 333.46                                        |
| Module 17     | 345.68                                        |
| Module 18     | 338.47                                        |
| Module 19     | 339.50                                        |
| Module 20     | 332.71                                        |

Rainfall values were used to evaluate the influence of natural cleaning factor that can affect the soiling accumulation. Rain data was obtained from the weather station of the Institute of Astronomy, Geophysics and Atmospheric Sciences of the University of São Paulo, located at Parque Estadual das Fontes do Ipiranga, Água Funda district, São Paulo (-23,6512°S, -46,6224°W). The distance between the experiments and the weather station were estimated as 15,34 km.

Finally, the experimental data was compared to the dirty module allocated at 0º and the results were expressed as relative gain as a function of the title angle in relation to the horizontal position (R.G.). The results carried accumulated standard errors of the module calibration procedure (±2 %) and from the data acquisition set - Keysight datalogger 34970 A and the data acquisition boards model 34901A (±0.32 %). The equation 2 defines the relative uncertainty as the square root of the square sum of the relative uncertainties. Thus the calculated relative uncertainty for \( I_{med} \) was ±2.03 %.

\[
\left( \frac{\sigma_{I_{med}}}{I_{med}} \right)^2 = \left( \frac{\sigma_{V_{med}}}{V_{med}} \right)^2 + \left( \frac{\sigma_{C_{cal}}}{C_{cal}} \right)^2 
\]

- \( \frac{\sigma_{I_{med}}}{I_{med}} \), relative uncertainty for measured irradiance, W/m\(^2\)
- \( \frac{\sigma_{V_{med}}}{V_{med}} \), relative uncertainty of the voltage measurement (data acquisition system) obtained in each of the modules, \( \mu \text{V} \)
- \( \frac{\sigma_{C_{cal}}}{C_{cal}} \), accumulated standard errors of the module calibration procedure, \( \mu \text{V/W m}^2 \)

**3. Results and discussion**

The values presented for the relative gain variable (R.G.) were calculated using the module labeled “dirty” tilted at 0º as a standard, for the other calculations. That justifies the value presented in the figure 5 (0.00 %). The gains of the other angles were calculated relative to this standard, using equation 3.
\[
R.G. = \frac{\text{Imed}_{M,x} - \text{Imed}_{M,0^\circ}}{\text{Imed}_{MD,0^\circ}}
\]

(3)

**R.G.**, Relative gain

\(\text{Imed}_{MD,0^\circ}\), Measured Irradiance for the module tilted at 0° labelled as “dirty”

\(\text{Imed}_{M,x}^\circ\), Measured Irradiance for the modules tilted at X angle (for \(x\) ranging from 0-45°), labelled “dirty” or “clean.”

The values presented for the modules, “Dirty” label, represent the gains obtained by tilting the modules above 0°. For the modules, “Clean” label, the gains obtained by tilting the modules above 0° plus the gains from performing a regular cleaning routine are represented.

The tables also show the "Difference" value, which was calculated for each pair of modules allocated to each angle. This is the value of the "Clean" label subtracted from the "Dirty" label that allows the effect of dirt to be isolated. Finally, the variable "Rain" demonstrates the values of accumulated precipitation in the analyzed period. The experimental error for the R.G. variable was ±2.03 %.

**Figure 5.** Relative gain of the 12-month experiment, from July 2019 to June 2020.

The values at the table in figure 5 show that soiling was unevenly deposited at the tilted modules, being mainly influenced by how tilted were the angles. The values presented at the x axis “Difference” show that the soiling effect is very severe at the low angles (0 and 5°). For this parameter, a relevant influence can be noticed for all angles. The maximum value was 4.78 % for 0°, and it was reduced as the modules were tilted, reaching the lowest value of 0.14 % at 45°. For comparison, annual energy losses due to soiling measured worldwide are typically in the range of 1–7 % [5-10,13-15] These values can be compared with the “difference” line values at figure 5.

The recommendable tilt angle for maximal irradiation usually is the local latitude, for São Paulo this angle is 23°. Thus, the angles near 23°, are expected to present high R.G. values, as was the case for 20 and 25° with 14.19 % and 14.89 % respectively. At these angles the irradiation capture along with the cleaning performed by rain were maximized, the combination of these factors resulted in the highest experimental values. For the angles higher than these, especially 35° and above the cleaning by rain was maximized as can be observed at the difference line, but the irradiation capture was reduced, similar effect occurs for angles lower than 20°, but in these angles soiling is maximized resulting in low irradiation captured as can be observed at the difference line, where the highest values occurred at the lowest angles, remembering that these values represent the isolated soiling effect.

Also, it was observed that the cleaning caused by rainfall was strongly influenced by the inclination of the modules (fig 5). As the angle increased, the difference in irradiance between the dirty and clean
patterns became smaller and smaller, as can be seen in Figure 5 at the “difference” line. This can be observed in the “Difference” values between 0 and 5° to 10°, the discrepancy was equal to 2.39 and 1.78 % respectively. Also, the discrepancy between 10 and 15° was only 0.18%, that drastic difference occurs because when the tilt is less than 10°, the losses by the effect of dirt are greater than the energy gains obtained by the recommended angulation, this effect is explained in more details in paragraph 4 of this study introduction [4].

4. Conclusions
From the results obtained in the present work, soiling accumulation had a significant impact on the observed G.R., especially for the less inclined modules (0° and 5°). At angles of 10° and above, the observed loss was less significant, due to the gravity effect. Rain also played a significant role in cleaning the modules, reducing the accumulation of dirt in a natural way, especially for angles greater than 30°. Cleaning of the modules by rain was optimized for these angles, which resulted in the reduction of losses due to soiling as can be seen at the figure 5, “difference” line.

In general, the recommended angle for the urban environment of the city of São Paulo is between 20° and 30°. The highest values were observed near the local latitude, 23°. Similar results were previously reported in the literature [4-10,13].

Finally, it is concluded that a cleaning routine plays an important role in the control of dirt, corroborating the provisions in the literature [4-7,13]. This is because, despite the high incidence of precipitation, the observed losses due to soiling remain significant. With this, it is understood that performing a cleaning routine brings beneficial results, even during periods with high incidence of precipitation.

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