Performance Degradation of Mono- and Multicrystalline Silicon PV Modules in Rural Grid-Connected Systems in Southern Brazil

Adriano Moehlecke, Izete Zanesco, João Victor Zanatta Brito, Taila Cristiane Policarpi, Moussa Ly, Felipe Chini de Freitas, and Lucas Teixeira Caçapietra Pires da Silva

Solar Energy Technology Nucleus (NT-Solar), School of Technology,

Pontifical Catholic University of Rio Grande do Sul (PUCRS), Porto Alegre (Brazil)

Abstract

The purpose of this paper is to compare the performance degradation of photovoltaic (PV) modules installed on three rural properties in southern Brazil. PV modules with mono- and multicrystalline Si solar cells from the same supplier were used. The power degradation rate (D_R) was determined from the temporal evolution of the temperature-corrected performance ratio (PR_{STC}) during the initial years of operation and from measurements of the I–V characteristics of reference PV modules under standard test conditions using a flash solar simulator. The monocrystalline silicon modules presented the lowest annual degradation rate, approximately 0.9% per year, whereas the multicrystalline Si modules presented an average degradation rate of 1.6% per year. The degradation rate determined for one PV system (system A) based on the temporal evolution of the PR_{STC} was consistent with the values obtained from electrical measurements of the PV modules. In two systems (B and C), the PR_{STC} method presented D_R values in the range of approximately 55%-70% higher than those obtained from the I–V curve measurements of the reference PV modules. Soiling ratio estimated by measuring the electrical parameters of the PV modules before and after cleaning yields average values of 1.3%, 2.0% and 4.0% for the reference modules installed in PV systems A, B and C, respectively. Applying a correction in the PR_{STC} to consider the average soiling reduced the difference between the D_R calculated using both methods by approximately 40% for systems B and C but still substantially differed from the degradation rates obtained via the measurement of the electrical parameters of the reference modules.

Keywords: PV degradation, crystalline silicon, performance ratio, rural grid-connected systems

1. Introduction

The power degradation rate (D_R) of photovoltaic modules is an important factor for the analysis of photovoltaic systems and the levelized cost of energy (Boretti and Castelletto, 2024; Ameur et al., 2022). Different methods can be employed to evaluate the degradation ratio of photovoltaic (PV) modules (Phinikarides et al., 2014; Lindig et al., 2022). One approach to assess the degradation of PV modules and systems is to perform electrical characterization of each module before and after the exposure period, which involves measuring the current–voltage characteristic curve (I–V curve) under standard test conditions (STC, i.e., irradiance of 1000 W/m^2, AM1.5G solar spectrum and 25 °C) (Sangpongsanmont et al., 2022; Zanesco et al., 2024; Moehlecke et al., 2025). However, for most photovoltaic systems, this is not feasible. Another approach involves the analysis of the behaviour of the performance ratio (PR) over months or years, enabling the estimation of the degradation rate of photovoltaic modules (Ameur et al., 2022; Isjii and Masuda, 2017). By measuring solar irradiation, the operating temperature of the photovoltaic module and the electrical energy produced over a period, the temperature-corrected PR can be calculated (PR_{STC}). However, the observed decrease in the performance ratio over time results from the combined effects of PV module degradation, soiling, increased ohmic losses in plant wiring, and the gradual decline in inverter efficiency.

In the literature, there are references comparing the methods mentioned above. For example, Isjii and Masuda (2017) investigated the degradation of PV systems composed of six types of crystalline silicon PV modules: two types composed of p-base, aluminum back surface field (Al-BSF) monocrystalline silicon solar cells; two types composed of multicrystalline silicon solar cells, p-base, with Al-BSF technology; one PV module composed of n-type crystalline silicon solar cells with heterojunction (SHJ); and another composed of n-type photovoltaic cells with interdigitated back contact (IBC). Module performance was assessed using both indoor

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and outdoor electrical measurements taken over three years. The degradation rate was also estimated by annual energy production and by the evolution of the performance ratio (corrected PR_{STC}) of the PV system. The experiments were carried out in an outdoor laboratory area. No comments were reported on the soiling or cleaning of the PV modules during the exposure period. The results obtained by the methods were consistent, showing that the Al-BSF PV modules did not present power degradation over the three years. The PV modules with SHJ and IBC solar cells presented annual degradation rates of 1.5% and 0.6%, respectively.

In Sangpongsanont et al. (2022), the degradation rate of a PV system was assessed over four years using both performance ratio analysis and measurements of the standard test conditions power of the 32 PV modules in the array. For PR estimation, data were filtered on the basis of in-plane irradiance (900–950 W/m²) and module temperature (45–53 °C). Since all the PV modules were removed and cleaned prior to electrical characterization, the effect of soiling was partially excluded from the annual degradation estimate. The total array power was obtained by summing the individual module powers, and the I–V characteristics were corrected to 900 W/m² irradiance and 51 °C. The D_R values derived from electrical measurements and PR analysis were consistent, averaging approximately 1.4% per year over the four years. The degradation rate estimated from the PR_{SCT} was higher, at 1.7% per year, which may reflect differences in the applied irradiance and temperature corrections to the I–V curves.

Three different PV systems were evaluated to compute the degradation rate using four methods: I-V measurement, metered raw kWh, performance ratio, and performance index (PI) (Shrestha and Tamizhmani, 2015). Mono- and multicrystalline Al-BSF silicon solar cell modules, as well as heterojunction PV modules, were analysed. The raw kWh method uses only metered inverter data to compute the degradation rate, making this method simple and fast. To calculate the performance ratio, data were filtered by selecting periods with irradiance values exceeding 300 W/m². The performance index is an enhancement of the PR method that incorporates losses related to temperature (similar to the PR_{STC}), wiring, balance-of-system (BOS) components, and soiling (Townsend et al., 1994). Compared with the other methods, the I–V method was considered the ideal and most reliable for degradation comparison. For monocrystalline silicon Al-BSF PV modules, the D_R values were 0.96%, 1.11%, 0.84%, and 0.96% per year, as obtained from the I–V curves, raw kWh, PR, and PI, respectively. For the multicrystalline silicon PV modules, the D_R values were 1.38%, 1.45%, 0.96%, and 1.37% per year for the same methods. For the HJT PV modules, the D_R significantly varied among the methods. The PI method, which accounts for all relevant losses, was identified as the most accurate. The study did not report how soiling effects were addressed.

Carrigiet et al. (2021) presented a comparison of long-term degradation in crystalline silicon PV modules using both indoor and outdoor measurement techniques. Degradation data from 10 years were obtained from two PV systems: one comprising multicrystalline Al-BSF solar cells and the other based on heterojunction solar cells. The indoor measurements involved recording the I–V curve of a single reference PV module and of a string within the array, which was removed from the system to perform electrical characterization in a sun simulator. Outdoor measurements were conducted by obtaining I–V curves without removing the PV modules from the exposure area. The outdoor test field consists of a string and a single reference module for each technology. The reference modules were not connected to the string. For the HJT PV modules, the results were compared with the degradation rates estimated from the PR and PR_{STC} methods. For multicrystalline silicon PV modules, the values of D_R were 0.23%/year and 0.29%/year for the reference module and the string, respectively, according to indoor measurements. The outdoor measurements yielded linear degradation rates of 0.19%/year and 0.18%/year for the reference module and the string, respectively. For the HJT PV modules, the indoor measurements yielded an annual D_R of 0.29% for the single reference module and 0.26% for the string. The outdoor analysis resulted in degradation rates of 0.55%/year and 0.50%/year for the reference module and string, respectively. For the HJT modules, the PR_{STC} evaluation produced degradation rates of 0.29%/year for the reference module and 0.25%/year for the string, closely aligning with the indoor measurement results.

Soiling can cause power losses in a PV system and is difficult to estimate from PV power time series (Lindig et al., 2021; Costa et al., 2018; Sharma et al., 2023; Uykan, 2025; Agbogla et al., 2025). To obtain an unbiased performance assessment via linear methods based on the PR_{STC}, soiling events must be carefully removed from the time series data. This requires detailed information from a soiling monitoring station, where one module, for example, is allowed to accumulate natural soil while another is cleaned regularly (Jordan et al., 2018). Therefore, soiling contributes to the uncertainty in estimating PV module degradation from PR_{STC} data.

The aim of this work was to analyse three photovoltaic systems installed on rural properties in western Paraná, a state in southern Brazil, with a focus on PV module degradation during the initial lifetime. This article compares PV modules with multicrystalline and monocrystalline silicon solar cells. The degradation rate was determined using two methods: (i) characterization of the I–V curves of the reference PV modules under standard test conditions with a calibrated solar simulator, and (ii) analysis of the temporal evolution of the temperature-corrected performance ratio. The results obtained from both methods were compared and discussed. The reference PV modules were measured before cleaning to allow estimation of the soiling and to correct the degradation rate obtained from the PR_{STC} linear method.

2. Methodology

The PV systems were installed in the western region of Paraná State, Brazil, as shown in Figure 1, in three locations: Assis Chateaubriand (24°23′10″ S, 53°32′14″ W), Cafelândia (24°38′38″ S, 53°18′51″ W), and Medianeira (25°16′32″ S, 54°3′14″ W). The average annual global irradiation in the region is approximately 1744 kWh/m², and on a plane inclined at the latitude angle, it is 1825 kWh/m² (Tiepolo et al., 2018). A PV system installed at a tilt equal to the latitude yields approximately 1530 kWh/(kWp.year) (Tiepolo et al., 2015). According to the Köppen–Geiger photovoltaic climatic classification (Ascencio-Vásquez et al., 2019), the region is characterized by a temperate climate with high irradiation (DH).

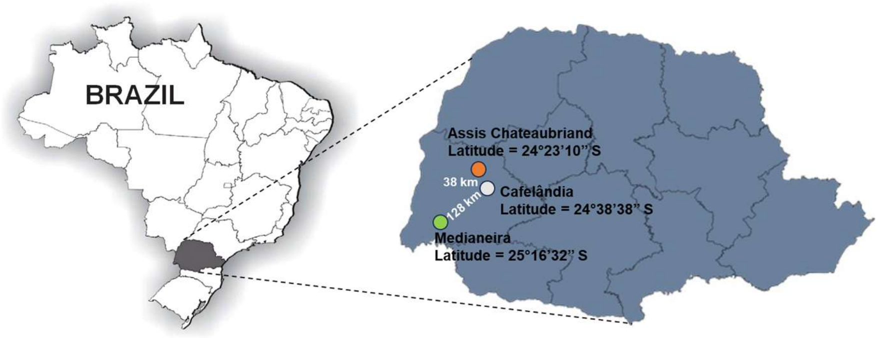


Figure 1: Geographical distribution of the PV systems in western Paraná, Brazil.

Moehlecke et al. (2019) presented a comprehensive description of the photovoltaic systems and the rural properties where the PV modules were installed. Figure 2 shows the 20 kWp systems, with 76 PV modules of 270 Wp (60 solar cells of 156 mm × 156 mm) and 72 modules of 325 Wp (72 cells of 156 mm × 156 mm), called systems A and B, respectively, with multicrystalline silicon solar cells produced with Al-BSF technology. In system C, 60 photovoltaic modules with 72 monocrystalline silicon solar cells (156 mm × 156 mm), also based on Al-BSF technology, were utilized, with each module having a nominal power of 340 Wp. The PV modules were from the same manufacturer. The arrays were installed as follows: (a) system A, on the rooftop of a cowshed, with a tilt angle of 18° and an azimuth of 9° NE; (b) system B, ground-mounted, inclined at 18° and facing north with an azimuth of 0°; and (c) system C, mounted on a roof with a 13° tilt and an azimuth of 52° NE. All the PV modules were installed in the portrait orientation. In addition to the modules connected to the arrays, four reference PV modules were also installed. These photovoltaic modules were measured prior to installation on the rural properties and subsequently removed and measured again to assess degradation after one, two, and three years of exposure for the Medianeira and Cafelândia PV systems and after two years for the Assis Chateaubriand system. During the exposure period, two PV modules were maintained under open-circuit conditions and two under short-circuit conditions. Although exposure at the maximum power point would be ideal, it was not feasible to install resistors or microinverters on the PV systems in rural areas. The open-circuit and short-circuit conditions expose the modules to extreme operating states that can reveal early signs of degradation. The potential-induced degradation (PID) was not considered in this study. A data acquisition system was installed in each rural property and consisted of a data logger, a pyranometer to measure the in-plane of the PV array solar irradiance, an anemometer, an ambient temperature sensor and a temperature sensor (PT100) installed on the rear face of a PV module. The data logger measured and stored the electrical parameters of the inverter (DC current, DC voltage, AC current, AC voltage, AC power, etc.) and the weather data to evaluate the performance of the PV system.

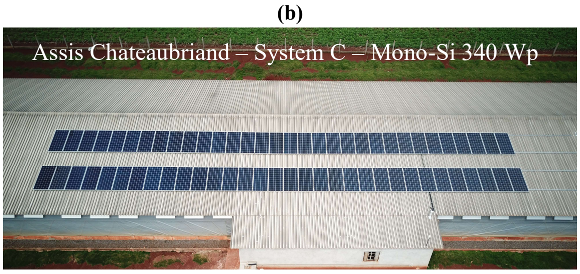
The final yield (Y_F) of the system was obtained by the ratio between the average value of the electric energy produced in a period and delivered to the load and the nominal power of the photovoltaic system. The reference yield (Y_R) was calculated by using the total in-plane solar irradiation divided by the reference irradiance (1 kW/m^2). The performance ratio (PR) is a key parameter used to evaluate the performance of PV systems and is defined as the ratio of the final yield to the reference yield. The PR is affected by temperature variations throughout the year (Gopi et al., 2021). To use the evolution of the performance ratio over time as an indicator of the degradation rate, the PR was normalized to a module temperature of 25 °C using Eq. (1) (Ameur et al., 2022; IEC 61724-1, 2017):

$$PR_{STC} = \frac{Y_F}{Y_R(1+\gamma(T_{mod}-25))} \times 100\% \qquad \text{(eq. 1)}$$

where T_{mod} and γ are the PV module temperature in °C and the maximum power temperature coefficient in %/°C, respectively. From the monthly PR_{STC} data, the degradation rate of the system in %/year was estimated. No filter was used for the data collected regarding the irradiance or operating temperature of the PV modules.

(a)

(b)



(c)

Figure 2: The 20 kWp PV systems installed and analysed: (a) system A, with 270 Wp multicrystalline silicon PV modules; system B, with 325 Wp multicrystalline silicon PV modules; and (c) system C, with 340 Wp monocrystalline silicon PV modules.

A linear regression of the time series of the PR_{STC} was used to obtain the following expression (Eq. 2) (Ameur et al., 2022):

$$PR_{STC} = \alpha t + \beta \qquad \text{(eq. 2)}$$

where α and β are the regression parameters, which are used to calculate the power degradation rate in %/year, as shown in Eq. (3):

$$D_R = \frac{\beta-(PR_{STC})t}{\beta}\ \frac{12}{t}\ x\ 100 \quad \left(\frac{\%}{year}\right) \qquad \text{(eq. 3)}$$

where t is the number of months of outdoor operation.

The degradation of the PV modules was also estimated by measuring the I–V characteristics of the reference PV modules. The PV modules were characterized under standard test conditions (STC, 1000 W/m^2, AM1.5G spectrum and 25°) by using a PSS8 Bergerlichttechnik sun simulator to obtain the actual power. The measurements were initially conducted on the soiled PV modules, followed by thorough cleaning of the modules. A visual inspection and a new I–V curve characterization were subsequently performed. This procedure enables the estimation of the soiling adjustment ratio (SA) (Townsend et al., 1994), which is defined by Eq. (4):

$$SA = \frac{P_{MP-soile}}{P_{MP-clean}} \quad \text{(eq. 4)}$$

where $P_{MP\text{-soiled}}$ and $P_{MP\text{-clean}}$ are the maximum power outputs of the soiled and clean PV modules, respectively, under standard test conditions.

Using the SA, a correction was applied to the PR_{STC} to compensate for soiling effects in the degradation analysis on the basis of the temporal behaviour of the PR_{STC}, as Eq. (5) presents:

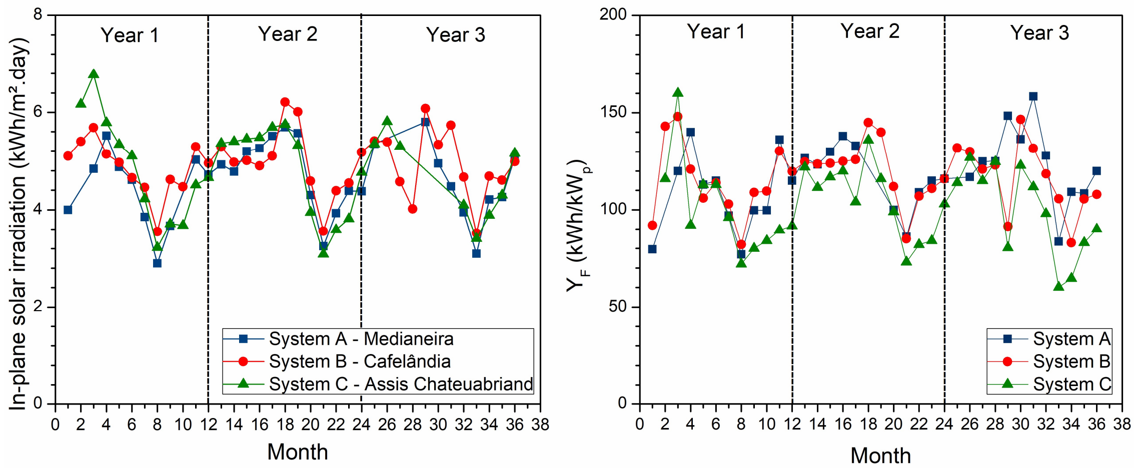
$$PR_{STC-Soiling} = \frac{Y_F}{Y_R(1+\gamma(T_{mod}-25))\times SA} \times 100\% \quad \text{(eq. 5)}$$

This compensation in the PR is similar to the performance index (PI) calculation proposed by Townsend et al., 1994.

3. Results and analysis

3.1 Reference and final yields of the PV systems

Figure 3(a) shows the monthly average daily total solar irradiation on the PV arrays. Considering all the months of operation, the values of average daily solar irradiation in the plan of the PV array were in the range of 4.4-5.0 kWh/(m^2.day). The measured average annual solar irradiance on the plane of the three PV arrays was 1674 kWh/m², representing an 18% reduction relative to the irradiance value commonly adopted in PV system simulations for western Paraná (Tiepolo, 2015). Figure 3(b) presents the monthly final yields of the three PV systems analysed. The first month of analysis was October 2018. The average final yield was 1358 kWh/kWp, 1419 kWh/kWp and 1182 kWh/kWp for the PV systems of Medianeira, Cafelândia and Assis Chateaubriand, respectively. The higher value obtained in Cafelândia (system B) can be attributed to the optimal slope and azimuth of the PV modules, along with a lower rate of inverter failure or power drop. In the case of the system in Medianeira (system A), an inverter failure caused a 45-day disconnection of the photovoltaic system, negatively affecting its electrical energy production. In Assis Chateaubriand (system C), power drops from the inverter resulted in a low final yield. The expected average daily final yield for PV systems in Paraná, which was based on simulation values and a PR of 75%, ranges from 94-125 kWh/kWp per month, or approximately 1128-1500 kWh/kWp per year. The average final yield over the three-year period remained within the expected range (Tiepolo et al., 2014).



(a) (b)

Figure 3: (a) Monthly average daily total in-plane solar irradiation; (b) monthly final yield (Y_F) for the three PV systems.

3.2 Degradation rates obtaining from indoor measurements

Table 1 summarizes the annual degradation rates estimated from the I–V curve measurements of the PV modules. The power degradation rate of multicrystalline silicon PV modules was approximately 1.6% per year, whereas for monocrystalline silicon PV modules, it was 0.9%. Compared with the degradation rates reported for PV systems installed in urban environments in Brazil over longer time periods, the PV modules with monocrystalline silicon solar cells and Al-BSF technology analysed in this study presented higher degradation rates. Specifically, degradation rates of 0.20%/year and 0.29%/year were reported for systems installed in Porto Alegre and Rio de Janeiro, respectively (Moehlecke et al., 2025; Zanesco et al., 2024). In those previous studies, the PV modules incorporated SiO_2 and TiO_2 as passivation and antireflection layers, respectively. Conventional PV modules typically employ silicon nitride (SiN_x) for these functions. The datasheet of the PV modules manufactured using multicrystalline silicon solar cells with Al-BSF technology indicates an expected power degradation of 2.5% during the first year of operation. Between years two and five, the degradation rate is estimated to be approximately 0.62% per year. Therefore, after three years of operation, the manufacturer anticipates an average power loss of approximately 3.7%. However, experimental measurements for systems A and B revealed greater power reductions, reaching 4.8% after three years of exposure. For PV modules with monocrystalline silicon solar cells, the manufacturer predicts a power drop of 3% in the first year, followed by a degradation rate of approximately 0.5% per year from years two to five. Consequently, a power loss of approximately 3.5% is expected after two years of operation. In contrast, the present study revealed a decrease in power of 1.7% over the same period.

Table 1: Annual power degradation rates obtained from PR_{STC} linear fitting and from I-V measurements of PV modules (four samples for each PV system). Initial years of operation.

	Annual power degradation rate (%/year)	
	Method – I-V curve of PV modules	**Method – PR_{STC} – Linear fitting**
System A - Multi-Si - 270 Wp	-1.7	-1.5
System B - Multi-Si - 325 Wp	-1.4	-3.1
System C - Mono-Si - 340 Wp	-0.9	-3.4

3.3. Degradation rates from PR_{STC} method

Figure 4 presents the evolution of the PR_{STC} over three years for the analysed PV systems. The observed decrease in the PR_{STC} is attributed to the degradation of the PV modules, which results in reduced electrical output. However, it could also be influenced by soiling on the PV modules and issues related to balance-of-system components. For example, problems with the inverter and the internal circuitry of the rural property were responsible for the lower PR_{STC} observed in system C. As mentioned above, the final yield of system C was 13% and 17% lower than that observed in systems A and B, respectively, owing to the inverter disconnections to the grid or the power reduction in several days. In this rural property, PV array and inverter were installed in the same building, far away from the main electrical input, where electrical noise (due to the fans, illuminating control system, etc.) can disable the inverter (Moehlecke et al., 2019).

Table 1 also shows the degradation rates obtained via linear fitting of the PR_{STC} data. In system A, the annual degradation rates obtained by both methods were similar. However, for systems B and C, the percentage differences between the annual degradation rates derived from the two methods were 55% and 74%, respectively. A probable cause of this discrepancy is soiling, as the photovoltaic modules on these farms were not cleaned throughout the operation period.

3.4. Degradation rates from PR_{STC} method and including soiling

Figure 5 shows images of the three reference PV modules after the first year of operation and prior to cleaning. The percentage power reduction for each PV module at each rural property after the first year of exposure is presented in Figure 6. During the first year of exposure, the PV modules installed in system C at Assis Chateaubriand (340 Wp modules) were the most affected by soiling, with an average power loss of 4.5%. This was attributed to their direct installation on the rooftop, which has a relatively low tilt angle of 13°.

Additionally, poultry farming operations and seasonal indoor cleaning activities in the farm contributed to elevated levels of airborne dust in the surrounding environment. In system A - Medianeira (270 Wp modules) and system B - Cafelândia (325 Wp modules), the soiling effects during the first year were similar, with average power losses of 1.8% and 2.0%, respectively. Overall, the reference PV modules installed in systems A, B, and C presented average power reductions due to soiling of 1.3%, 2.0%, and 4.0%, respectively.

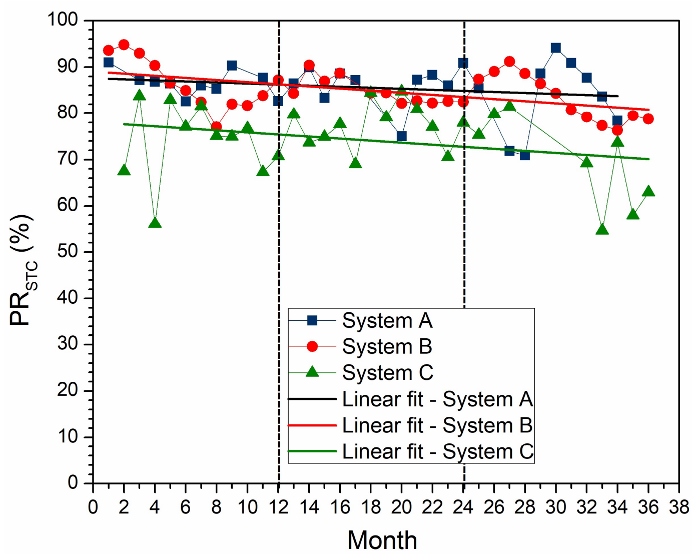


Figure 4: Temperature-corrected performance ratio (PR$_{STC}$) for the PV systems analysed.

(a) (b) (c)

Figure 5: Soiling observed in the reference PV modules after the first year of operation in each PV system: (a) system A, Medianeira; (b) system B, Cafelândia; and (c) system C, Assis Chateaubriand. Letter and number correspond to module identification. The PV modules installed in the portrait orientation showed dust accumulation at the bottom.

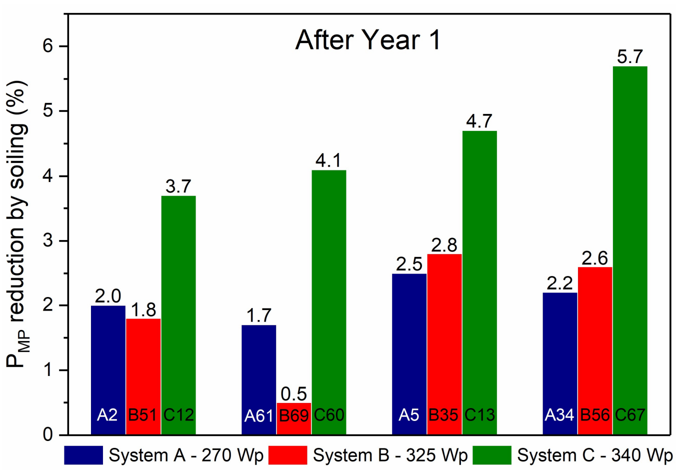


Figure 6: Effects of soiling on the P$_{MP}$ of the reference PV modules (measured under STC): system A, Medianeira; system B, Cafelândia; system C, Assis Chateaubriand. Letter and number correspond to the PV module identification.

Table 2 presents the degradation rate calculated via Eq. (5) (from $PR_{STC\text{-}soiling}$), with SA estimated from the comparison of the I-V characteristics of cleaned and uncleaned photovoltaic modules. For systems B and C, the introduction of a soiling adjustment ratio reduced the difference in degradation rate obtained by the temporal analysis of the PR_{STC} and the electrical characteristics of the PV modules to 42% and 40%, respectively. In the case of system A, the correction with SA reduced the D_R to values below those obtained with the characterization of the PV modules. These results indicate that estimating the degradation of PV modules via the temporal behaviour of the PR_{STC} has greater uncertainty regarding the soiling at the system installation as well as the problems of the inverter or the electrical installation of the building. These limitations have also been reported in the literature concerning soiling estimation methods (Agbogla et al., 2025; Kazem et al., 2020). For situations of low soiling, as was the case for Medianeira (system A), this methodology proved to be applicable.

Table 2: Annual degradation rates obtained from PR_{STC} linear fitting and considering the average soiling ratio for each PV system. Initial years of operation.

	Annual degradation rate (%/year)		
	Method – PR_{STC} – Linear fitting	Method $PR_{STC+Soiling}$ – Linear fitting	Method I-V curve of PV modules
System A - Multi-Si - 270 Wp	-1.5	-1.0	-1.7
System B - Multi-Si - 325 Wp	-3.1	-2.4	-1.4
System C - Mono-Si - 340 Wp	-3.4	-1.5	-0.9

4. Conclusion

The power degradation rate of multicrystalline silicon PV modules was approximately 1.6% per year during the initial years of operation, whereas for monocrystalline silicon PV modules, it was 0.9%. Compared with the manufacturer's predictions, the average D_R over three years for multicrystalline silicon photovoltaic modules was higher by approximately 0.4% (absolute). In contrast, the experimentally measured degradation rate for monocrystalline silicon modules was 0.9% (absolute) lower than the manufacturer's forecast. When comparing the methods used to estimate degradation, we observed that the evolution of the PR_{STC} resulted in values similar to those obtained from the measurement of the I–V curves of the reference PV modules under STC, particularly where soiling was not a significant factor in reducing performance. An approach to estimate soiling by measuring the I–V characteristics of reference PV modules before and after cleaning was insufficient to fully account for the observed degradation rates obtained by PR evaluation. Additional factors related to balance-of-system components may have contributed to the greater degradation rates obtained by the performance ratio method. Furthermore, potential-induced degradation losses may also have played a role in these discrepancies. The application of the performance ratio to estimate the power degradation rate of PV modules has several limitations when it is used in real-world conditions.

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