Impact of Calculation Assumptions on the Performance Ratio of Photovoltaic Power Plants: Influence of Discarding the Night Period and the Period of External Limitations

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Abstract

The Performance Ratio (PR) measures the performance of photovoltaic plants by the ratio between the actual AC (alternating current) energy generated and the theoretical DC (direct current) energy, based on the influence of irradiation. This calculation can also be adjusted for temperature to better approximate reality. However, as it involves summarizing variables in averages and sums for a given period, the PR is the result of all the factors that can impact the period considered. Therefore, the purpose of this work is to demonstrate how the choice of assumptions for calculating the PR, especially those related to disposal periods such as: average night-time temperature, imported energy for night-time operation of absorption or injection of reactive power by inverters and power limitation by external requests can distort the actual performance of the photovoltaic system. This impact can generate misinterpretation of results when the objective is to obtain: a trend throughout the month, improvement of results after actions, achievement of a result target or comparison between two different plants.

Keywords: Photovoltaic Plant, Performance Ratio, Influence of Temperature, Power Limitation Period, Night Operation, Photovoltaic System Performance, Key Performance Indicator

1. Introduction

The (IEC 61724, 2021) “Photovoltaic system performance” series of standards is the best available source that defines parameters such as the Performance Ratio (PR). This indicator portrays the performance of photovoltaic systems by comparing the actual result of AC (alternating current) energy and theoretical DC (direct current) energy. In short, the variation in the numerator reflects the high or low performance in relation to the same meteorological condition determined by the denominator. For this work, the influences of: consideration of the night period (for average temperature or sum of imported energy) and request for external limitation will be explored.

For the night period, what happens is that since there is no irradiance during the night, the sum of 24h or just the system operation period results in the same total. However, temperature is a variable present in 24h, with a profile that tends to present higher values during the day and lower values at night. Therefore, when the 24-hour average is calculated, it returns a lower average temperature value than during the period of irradiance. Thus, it does not reflect the real impact at the time of operation of a photovoltaic system.

In addition, some photovoltaic plants can operate 24 hours a day, injecting active power during the production period and, in the absence of irradiance, absorbing or injecting reactive power into the electrical grid in order to guarantee the stability of the system. In these cases, as the inverters need to operate at night, there is an increase in the consumption of energy imported from the grid to supply the auxiliary service of the inverters. Depending on the level of imported energy, when the 24-hour sum of energy from the system is calculated, there is a drop in relation to only the energy exported by the system. The balance of exported energy minus imported energy may result in a PR numerator that does not reflect the real performance during the period of operation.

In the case of discarding the night-time period, the focus is on the calculation method, including the sequence of calculation steps, the period considered, and the filters applied in the SCADA system to retrieve the assumptions used as inputs for the PR formula. Accordingly, this study presents PR results using two distinct methodologies. The first is the Direct Calculation (DC), which may lead to misinterpretations as it does not

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discard the night-time period. The second is the Aggregated Calculation (AC), which discards periods without valid denominators, including the night-time period, providing a more representative assessment of the photovoltaic system's actual performance.

Another scenario that impacts the PR result is the request for limitation of power exported to the grid, usually carried out to ensure the momentary stability of the electrical system. In such cases, since the numerator is reduced by external request, the corresponding period should be discarded, allowing for a fair comparison and an appropriate analysis of system performance during intervals without restrictions. However, it is important to note that the result obtained only from unrestricted periods may not faithfully represent the overall performance of the system, especially when these intervals coincide with conditions of low irradiance.

The results of this study illustrate how the methodology used to perform the same calculation, in this case, the PR, whether using the tradicional PR formula or the Temperature-Corrected PR STC can yield different outcomes. This variation may lead to the failure to meet reference targets under ideal conditions and result in misguided decision-making, potentially causing significant financial costs without a real return on investment.

2. Calculation of the Performance Ratio - PR

According to (Hukseflux Thermal Sensors, 2024), thre forms of PR calculation formula can be observed, Tradicional PR (eq. 1), Temperature-Corrected PR STC (eq. 2) and Weather-Corrected Performance Ratio proposed by (NREL,2013). This last calculation method was not considered in the study in order to simplify the calculation and maintain the same reference values, regardless of the region.

$$PR = \frac{E\_OUT}{P0*(G\_POA/\ G\_STC)} \quad \text{(eq. 1)}$$

$$PR'\ STC = \frac{E\_OUT}{P0*(G\_POA/\ G\_STC)*[1+\gamma*(T\_MOD - T\_STC)]} \quad \text{(eq. 2)}$$

Where:

- E_OUT: [kWh] energy output from PV system (AC), so after the inverter;
- P0: [kW] array power rating (DC) the total DC power output of all installed PV modules;
- G_POA: [kWh/m2] in-plane irradiation;
- G_STC: [W/m2] 1000 W/m2 at Standard Test Conditions – STC;
- T_STC: [°C] 25 °C at Standard Test Conditions – STC;
- T_MOD: [°C] in-plane temperature;
- γ: [%/ºC] coefficient of negative effect of temperature on the power of photovoltaic modules;
- $[1 + \gamma \times (T\_MOD - T\_STC)]$: temperature factor.

3. Methodology

The methodology of this work consists of calculating the PR, Tradicional and Temperature-Corrected PR STC, for two real example days: one without restriction and another with an external restriction request. The purpose is to use actual measured data of G_POA, T_MOD, and E_OUT, considering as a case study a real grid-connected photovoltaic system with an installed capacity of 38.5 MWp and a negative temperature effect coefficient on the power of the photovoltaic modules, γ, of -0.4%/°C.

For the two example days, the data mentioned in item 2 as variables present in the PR formula were collected from the SCADA system of the photovoltaic plant in this case, in order to enable an objective calculation using Excel. For large volumes of data and routine application, it is recommended to use Python or another programming language to reproduce this analysis.
The (NREL, 2013) states that “The summations are over a defined period of time (days, weeks, months, years)“, to calculate PR using two different methods: the method outlined in IEC 61724, and a new method that corrects PR for site-dependent meteorological conditions. And acording to (Andy Walker; Jal Desai, 2021), “The performance metrics are calculated by aligning the measured production data with the model estimate on an hour-by-hour, day-by-day, or monthby-month basis (depending on the interval resolution of the production data)“.

These statements are correct when referring to possible analysis periods or periodicity for generating an indicator, in this case the PR. However, there is no clear order for applying the PR formula. This work highlights that the result can be influenced by the order of the chosen steps and by the data integration. It is worth noting that any data integration for calculations beyond hourly integration requires greater attention to points that may influence the result.

Therefore, this work will demonstrate results from calculations performed in two ways. The first is the calculation of PR directly after the integration of the period, such as using the sum or average of variables over a daily, monthly, or annual period included in the formula. This approach can be called CD, direct calculation. The second consists of performing the calculation so that each minimum analyzed period, such as 5 minutes or 1 hour, has its own numerator and denominator. In this case, the PR result would be the sum of the numerators divided by the sum of the denominators. This approach can be called AG, calculation grouping.

For the first day, to demonstrate the influence of discarding the nighttime period, it is noticeable that the direct calculation considers the nighttime period, resulting in lower average temperature and energy production values. In contrast, with the grouped calculation, these interferences are discarded and do not affect the PR outcome.

On the second day, the same calculations from the first day are repeated. The difference is that, since this is a day with an external restriction request, the calculation method with lower interference is separated into periods with and without restriction. It highlights how the period with restriction significantly lowers the PR result if the entire day is considered.

To complement the analysis, PR target scenarios are created to assess where each result from the different methodologies would fall, whether close to or far from the target, illustrating possible real-world comparisons with a plant’s historical data or between photovoltaic plants.

Finally, to confirm the Impact of Calculation Assumptions on the Performance Ratio regarding the Influence of Discarding the Night Period and the Period of External Limitations, the same detailed calculation used for the two example days was performed over 100 days for the same photovoltaic plant, in order to analyze trend curves of the results.

4. Results

4.1. Discarding the Night Period

The first example day for results demonstration, Day 1, will be used to explain the difference between Direct Calculation (DC) and Aggregated Calculation (AC). Below, it is possible to visualize each definition by topics. Table 1 summarizes the data of the example day to better assimilate the definitions.

- Direct Calculation (DC)

First, the desired period for calculating the PR is chosen (hour, day, month or year). Then, the average or sum information already calculated by SCADA is collected to include directly in the PR formula.

- Aggregated Calculation (AC)

First, a numerator and denominator are calculated for each time step, in the smallest possible interval. Then, all numerators and all denominators are aggregated as a sum, to allow insertion into the formula and calculate the PR. In this case, aggregate the results of 1 hour to calculate the PR of the day.

Table 1: Summary of SCADA system data. measured hourly and aggregated daily

Times of Day	Average of T_MOD (°C)	Sum of G_POA (Wh/m²)
0	27.41	0.00
1	27.39	0.00
2	27.46	0.00
3	27.66	0.00
4	27.71	0.00
5	27.67	0.00
6	27.33	7.53
7	27.34	32.09
8	28.58	77.73
9	29.99	103.87
10	32.30	195.57
11	36.88	344.38
12	42.49	382.97
13	39.85	263.53
14	48.63	575.78
15	42.82	243.34
16	31.12	89.35
17	29.88	81.68
18	27.70	5.73
19	27.86	0.00
20	27.82	0.00
21	27.68	0.00
22	27.07	0.00
23	27.74	0.00
24h average	31.18	2,403.55

When an indicator, such as PR, is calculated on an hourly basis, there is no issue of nighttime interference, since it can only be calculated during periods with irradiance, that is, only during the day. When considering daily, monthly, or yearly integration, however, there is a difference between considering the integration of energy, temperature, or irradiance over these periods or simply discarding those periods. Table 2 below makes clear the difference in data integration: only during the day, only during the night, and considering 24 hours of a day.

Table 2: Difference between three periods of the day (Day Period, Night Period, and 24 Hours) for the calculation of Direct Calculation (DC) and Aggregated Calculation (AC).

Variable	Day Period (AC)	Day Period (DC)	Night Period (DC)	24 Hours (DC)
Sum of G_POA (kWh/m²)	2.40	2.40	2.40	2.40
Average of T_MOD (C°)	34.63	34.63	27.58	31.18
Temperature Factor	0.96	0.96	0.99	0.98
E_OUT (MWh)	79.99	79.99	-1.95	78.04
P0 (MWp)	38.50	38.50	38.50	38.50
Numerator	79.99	79.99	-	78.04
Denominator of Temperature-Corrected PR STC	86.70	88.85	-	90.25
Temperature-Corrected PR STC	0.92	0.90	-	0.86
Denominator of Traditional PR	92.54	92.41	-	92.54
Traditional PR	0.86	0.87	-	0.84

For the irradiation variable (kWh/m²), which is nothing more than the sum of irradiance over time (kW/m²), the result for daytime periods (AC or DC) or 24 hours is the same, since there is no irradiance during the night period.

For temperature, however, the form of integration is not the sum, but rather the average over the period. The average night period temperature tends to be lower due to the absence of irradiance. Thus, its negative impact from the temperature coefficient on generation is smaller if 24h is considered as the integration period, resulting in larger denominators as a possibility of achievement.

Therefore, it is not possible to calculate the PR denominator for the night period, since there is no irradiance. However, if the daily average is considered in the SCADA system, and no prior data treatment is applied, the night period ends up indirectly impacting the result, as it is not discarded.

Analyzing the calculations performed using the direct calculation method in the Table 1, it becomes evident how temperature influences the denominator through the temperature coefficient and, consequently, the PR result. The impact of the temperature coefficient during the night is imperceptible, since the value tends toward 1, indicating minimal losses. As the night period average is 27.58 °C and the loss is calculated proportionally to each degree above 25 °C, the small difference compared to the STC reference temperature explains this result.

When this portion is included in the 24-hour average, it distorts the actual impact that temperature has on energy generation, reducing its effect during periods of peak irradiance, with the daytime period being the one that best represents it. However, there is a subtle difference in the temperature impact when using direct calculation or grouped calculation. This can be observed through the temperature factor, which is the portion of the PR denominator that multiplies the difference between the actual module temperature (T_MOD) and the STC temperature (25 °C) by the module's power loss per temperature coefficient, as specified in the photovoltaic module datasheet. This occurs because the average loss impact, considering a temperature factor of 0.96, results from a range of values varying from 0.86 to 0.99, depending on the time of day. For the grouped calculation, each time step is multiplied by its respective temperature factor, which can be higher or lower than the daytime average.

And since, in this case study, the periods of highest irradiance also tend to be those of highest temperature, the impact of losses by temperature coefficient is greater when performing the grouped calculation, thus generating a lower denominator. In other words, this decreases the reference value of achievement and therefore increases the PR. Figure 1 below illustrates the difference in denominators per hour.

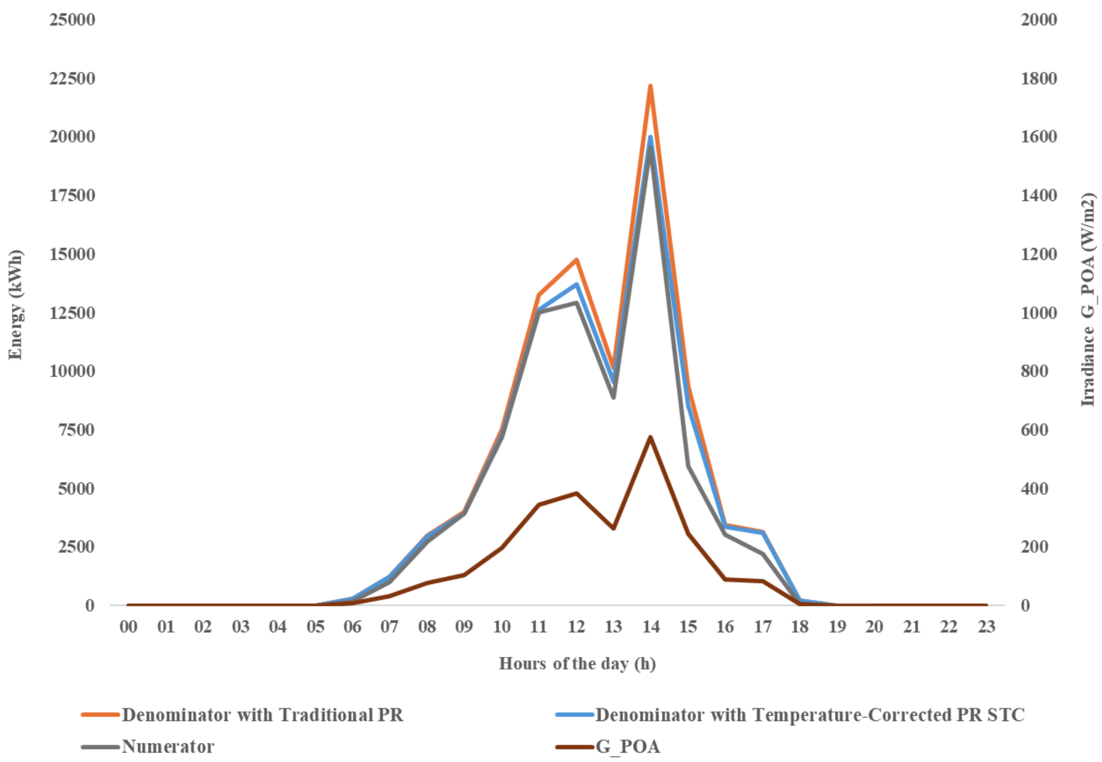

Figure 1: Curves of the main variables throughout the day

As illustrated in Figure 1, only to compare the curves of the variables without dimensions, the denominator curves follow the irradiance profile, as they are directly dependent on this variable. The divergence between the Denominator of Temperature-Corrected PR STC, which reflects temperature losses, and the Denominator of Traditional PR becomes more pronounced during peak irradiance hours, between 9:00 a.m. and 3:00 p.m. Moreover, the numerator curve, which represents the actual energy produced, aligns more closely with the Denominator of Temperature-Corrected PR STC.

In summary, the Denominator of Traditional PR would exhibit only negligible differences among the cases presented in Table 1. Conversely, the Denominator of Temperature-Corrected PR STC, which reflects temperature losses, is directly influenced by both the period of integration and the chosen calculation method, thereby propagating these differences into the final PR result.

The numerator, in contrast, depends solely on the energy measured downstream of the inverter. In large-scale power plants engaged in electricity trading, this measurement point may correspond to the grid connection point. In such cases, meters register the energy exported to the transmission network during the day, as well as the energy imported at night to supply auxiliary service equipment in the absence of generation. To ensure consistency in energy flow representation, exported energy is recorded as positive and imported energy as negative. Consequently, if the net daily measured energy is considered, the resulting value will be lower than the actual generation, due to the subtraction of night period imports. To accurately assess production efficiency, this period should be disregarded so as not to bias or distort the result with such variations.

4.2. Period of External Limitations or Restrictions

The PR result may also be distorted if periods of underperformance due to mandatory power limitations are not disregarded. This will be presented in the results for Day 2, which demonstrate the influence of externally imposed limitations on the calculation.

The purpose of a performance indicator is to enable comparison across different periods of the same photovoltaic system or among systems installed in different locations. Therefore, comparing a day with curtailment to a day without curtailment may lead to the interpretation that the unrestricted day performed better, which is not necessarily accurate.

Generation restrictions may occur in large-scale plants to ensure the stability of the power system, whether due to imbalances between generation and demand or transmission line capacity limits. Such restrictions typically occur during solar generation peaks, when irradiance levels are highest and photovoltaic plants connected to the grid tend to generate simultaneously.

The table below compares restricted and unrestricted data for the same day in which a power curtailment event occurred, highlighting this potential misinterpretation.

Table 3: Difference between three periods of the day (Day Period, Night Period, and 24 Hours) with and without a limitation period for the calculation of Direct Calculation (DC) and Aggregated Calculation (AC).

Variable	Day Period with External Limitations (AC)	Day Period without External Limitations (AC)	Day Period (AC)	Day Period (DC)	Night Period (DC)	24 Hours (DC)
Sum of G_POA (kWh/m²)	4.02	1.44	5.46	5.46	0.00	5.46
Maximum of G_POA (W/m²)	1017.16	697.33	1017.16	1017.16	0.00	1017.16
Average of T_MOD (C°)	47.23	36.60	41.94	41.94	26.84	34.39
Temperature Factor	0.91	0.95	0.93	0.93	0.99	0.96
E_OUT (MWh)	17.52	41.66	59.19	59.19	-2.00	57.18
P0 (MWp)	38.50	38.50	38.50	38.50	38.50	38.50
Numerator	17.52	41.66	59.19	59.19	NA	57.18
Denominator of Temperature-Corrected PR STC	140.45	52.16	192.61	195.94	-	202.29
Temperature-Corrected PR STC	0.12	0.80	0.31	0.30	-	0.28
Denominator of Traditional PR	154.80	55.38	210.18	210.18	-	210.18
Traditional PR	0.11	0.75	0.28	0.28	-	0.27

Table 3 replicates the differences in results for day period periods: day period in CD or AG, night period, and 24 hours, while also subdividing the day period AG column into two additional columns: one with calculations restricted to the curtailed period and another for the non-curtailed period.

It is evident that the result in the curtailed-period column yields a lower PR compared to the non-curtailed period. When analyzing the entire day, the final PR is also affected as a consequence of the curtailment. Thus, a low PR value may suggest poor performance, which is not an accurate representation, since it resulted from an imposed condition rather than an operational or maintenance issue.

When comparing only the PR of the curtailed period to that of the non-curtailed period within the same day, performance appears satisfactory during the non-curtailed period (PR of 0.8) and poor during the curtailed period (PR of 0.12).

On curtailment days, it is advisable to exclude the curtailed interval from performance assessment, as it represents an uncontrollable risk. This practice is widely adopted; however, it does not fully describe the plant's performance potential had curtailment not been imposed.

As observed in Figure 1, the impact on denominators is more pronounced during peak irradiance, which is also the ideal window for performance evaluation. A plant may reach expected levels under low irradiance yet fail to do so under high irradiance if the same operational issues persist.

Consequently, since curtailment is typically applied during periods of high irradiance and lifted during periods of low irradiance, it may become easier to achieve good performance under these conditions. However, there is no possibility of approaching peak production or testing whether the equipment reaches the expected limits, thus revealing hidden faults that may be imperceptible under average conditions or during generation restrictions, such as curtailment.

Figure 2 clearly illustrates the proximity between numerator and denominator in the non-curtailed period, as well as the divergence during the curtailed period, which coincides with peak irradiance.

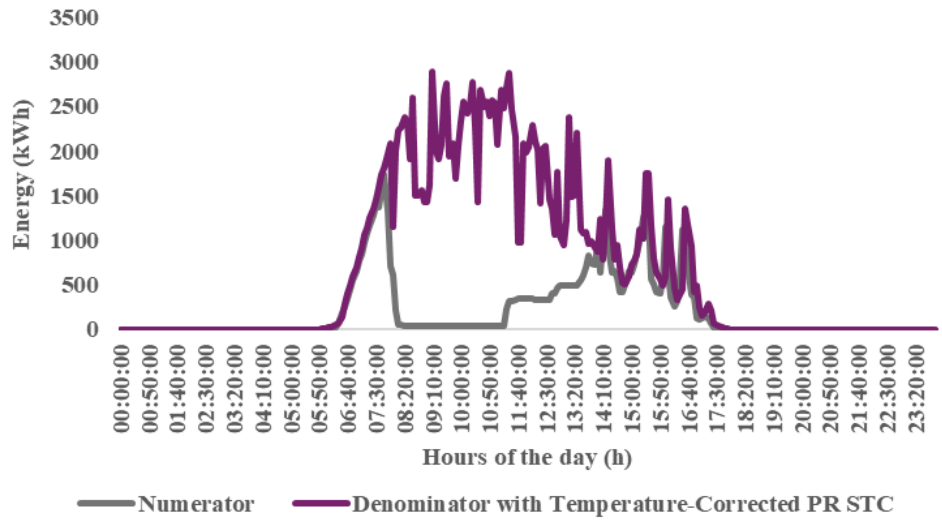

Figure 2: Curves of the numerator and denominator of the Temperature-Corrected PR STC throughout the day

This is clearly observable in Table 3, as the curtailed period presents a maximum irradiance of 1017.16 W/m², whereas the non-curtailed period reaches 697.33 W/m². It cannot be guaranteed that, on this same day, under identical irradiance and temperature conditions but without curtailment, the PR would still remain at 0.8. The value might decrease slightly due to the inclusion of peak irradiance in the analysis, but it is not possible to precisely estimate the extent of this reduction.

This highlights the need for caution when comparing days affected by curtailment, as the results are influenced both by the number of curtailed hours and the PR analysis window. Furthermore, comparing this indicator across different plants on curtailed days may also compromise interpretation, since curtailed plants may exhibit distinct profiles in terms of maximum power limits, irradiance, and timing of the cuts, particularly when comparing a curtailed plant to a non-curtailed one.

A possible alternative to address the challenge posed by external curtailment requests would be to perform performance assessment and PR calculation only on days without curtailment. However, curtailment has become so frequent in certain regions that this may not be a feasible option. Therefore, to maintain PR calculation, the alternative would be to disregard the curtailed intervals or to explore alternative indicators for performance evaluation.

4.3. Trend over 100 example days

Considering 100 days with different profiles as an example, in the case of the average module temperature, with 24h T_MOD defined as the 24-hour average (including the nighttime period) and Day T_MOD defined as the average only during the Day Period, operation period, it can be observed that the greater the difference between Day T_MOD and 24h T_MOD, the greater the percentage increase in the Temperature-Corrected PR STC calculated from Day T_MOD (Figure 3). Furthermore, it can be noted that the days with the largest temperature differences are also those with the highest G_POA values.

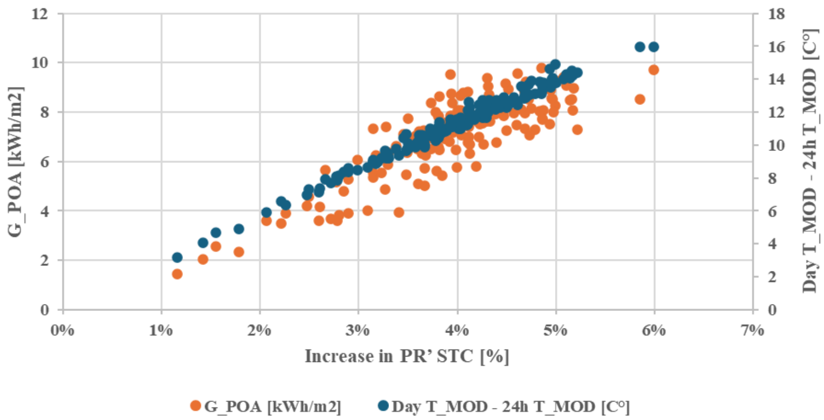

Figure 3: Increase in Temperature-Corrected PR STC according to the variation of the average temperature considered

With the aim of measuring the impact over 100 days of restriction, it is observed that the scenario of days in which it is necessary to limit the exported power due to an external request shows a more evident impact on the increase in PR. This impact is proportional both to the duration of the restriction and to the percentage of energy curtailed in relation to the installed power P0. The longer the restriction period, the greater the effect of excluding it from the PR calculation, and consequently, the higher the PR value when considering only the period without the influence of the restriction (Figure 4).

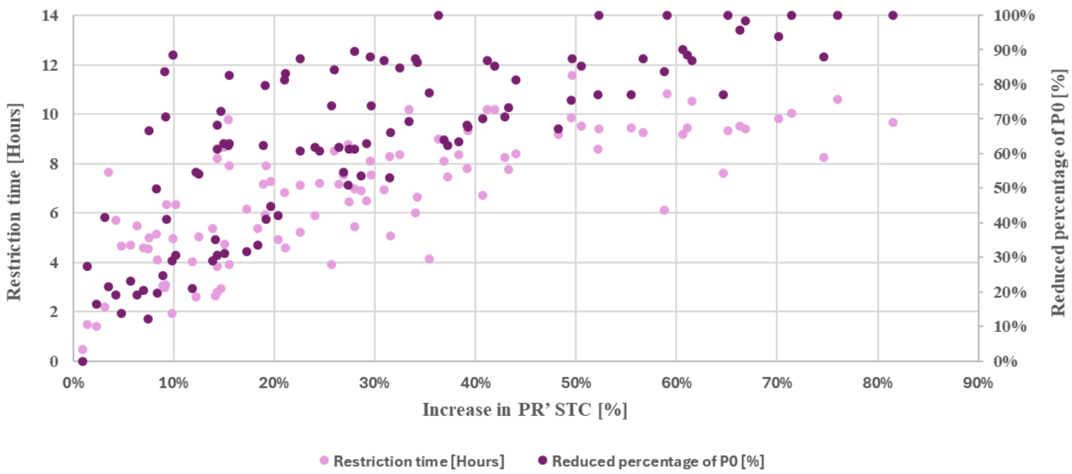

Figure 4: Increase in Temperature-Corrected PR STC according to the removal of the restriction period and proportional to the percentage of restricted power and hours of restriction

5. Conclusion

It is concluded that, in all cases analyzed, PR improves after adjusting the calculation assumptions. This demonstrates that the choice of calculation method can be decisive in achieving performance targets or accurately assessing the impact of improvement actions.

Tables 2 and 3 illustrate how methodology, analysis period, and calculation assumptions influence performance outcomes. For example, an PR target greater than 0.87 in Table 2 is achieved only for daily periods; a 24-hour calculation falls below the threshold. In Table 3, the same target is unattainable under any scenario, while a PR target of 0.80 is satisfied only by the daily grouped calculation excluding curtailed periods.

Based on the analysis of 100 days with different profiles, it can be concluded that the increase in PR' STC (Temperature-Corrected PR STC) consistently follows the same logic, regardless of the variability of the days considered. The results demonstrate that the improvement in performance is directly proportional to the factors analyzed: the difference between Day T_MOD and 24h T_MOD, as well as the magnitude and duration of power export restrictions. Consequently, as the number of days in the sampling increases, including days with diverse operating profiles, the observed trends remain valid, reinforcing the robustness of the analysis and confirming that the behavior of PR' STC is systematically governed by these parameters.

This study emphasizes the critical impact of calculation assumptions on the Performance Ratio of photovoltaic plants, particularly regarding night period periods and externally imposed power limitations. The choice of methodology direct or aggregated, Tradicional PR or Temperature-Corrected PR STC, can substantially alter PR results, potentially leading to misinterpretation of plant performance if not carefully considered.

For solar energy professionals, these findings fill a gap in the literature by providing guidance on practical PR calculation under real operational conditions. PR should not be treated as a mere formulaic metric; critical analysis of input variables, period selection, and external influences is necessary to accurately assess system performance.

The study also addresses the lack of clear guidance in existing standards, offering strategies to mitigate distortions caused by night period averaging, energy imports for auxiliary loads, and curtailment periods. By excluding non-representative intervals or adopting alternative performance indicators, practitioners can obtain more reliable metrics to support operational decisions, investment planning, and comparative analysis.

Ultimately, this work highlights the importance of a critical, informed approach to evaluating photovoltaic plant performance, promoting better decision-making and operational optimization beyond the mere application of standardized formulas.

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