Validation of the Optimal Performance Assessment Methodology for Photovoltaic Plants in the Context of EPC Contracts in Colombia

Ingenieria Creativa S.A.S presented for 2024 European PVPMC Workshop

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Abstract—*This study addresses the underperformance of photovoltaic solar plants in Colombia's Engineering Construction & Procurement (EPC) contracts, identifying causes and proposing solutions. Simulations of operational and pre-operational plants revealed that performance expectations depend on the meteorological databases used, with significant differences between on-site measured data and satellite image-based data. An evaluation of the Performance Ratio (PR) and weather-corrected PR showed decreased performance with on-site data and increased variables like module temperature and irradiance. The study highlights the inadequacy of the TMY PR metric in capturing curtailment and clipping phenomena, observing discrepancies of up to 10% when evaluated with on-site data. To address these nonlinear behaviors, the research suggests incorporating a new methodology for calculating the guaranteed PR which is calculated by sub-hourly on site data simulation for the periods where the saturation of the plant is bigger than the expected with the reference TMY simulation.*

The proposed methodology emphasizes using the PR under the conditions for which it is valid and correctly represents the non-linear conditions to which the plant to be evaluated is exposed in reality. This approach aims to improve performance evaluation practices, ensuring accurate and fair assessments, and maintaining transparency and trust among all parties in EPC contracts.

Key words: **Performance Ratio, Energy Performance Index, Weather Correction, Module Average Temperature, Satellite Data, Curtailment, Typical Meteorological Year, EPC.**

I. INTRODUCTION

The Performance Ratio, hereinafter referred to as PR, is the most widely used solar plant performance indicator in Colombia, as well as in much of the solar industry. Its methodology is formulated in IEC 61724 [1]. This indicator is the main tool used in Engineering Construction & Procurement contracts, hereinafter EPC, to establish the performance guarantees that a plant must meet and that investors expect to obtain from the project. However, the fulfillment of a guaranteed PR established in a contract by the company in charge of the EPC has meant in recent years a problem of uncertainty that translates into disbursements of high sums of money from builders due to the penalties that not reaching the commitment represents, as well as for investors it means a poor estimate of the available energy. It has been experienced that in Colombia there have been few plants capable of meeting the PR goals established in the contracts and this has led to both contractors having to disburse large sums of money and investors not obtaining the expected results of performance in their plants. However, everything seems to indicate that the plants are built in the right way and although there are no accentuated failures in the operation, the performance index is almost always below the expected goals.

This phenomenon of low performance in solar plants has led to the development of this study aiming to validate the PR performance index use and/or propose a more appropriate methodology in the context of EPC contracts in Colombia.

The PR is a dimensionless performance index that is currently applied by companies in several countries, including those belonging to the European Union, Australia, the United States and, in our case, Colombia.

According to EU PERFORMANCE [2], a PR above 0.8 is an indicator that you have a system that works correctly, but in EPC contracts the minimum limit depends on what has been agreed between the parties and can be greater than 0.8.

NREL's document "Weather-Corrected Performance Ratio" [10] suggests that an adequate tolerance value to agree on in EPC contracts corresponds to 95% of the guaranteed PR value, but this may vary depending on the parties involved and it has been seen that this tolerance may go up to 98% of the guaranteed PR.

As set out in IEC 61724, the PR is defined as:

$$PR = \frac{\sum_k P_{out,k} \cdot \tau_k}{\sum_k \frac{P_0 \cdot G_{i,k} \cdot \tau_k}{G_{i,ref}}}$$

Equation 1. Performance Ratio [1].

Where:

- $\sum_k P_{out,k} \times \tau_k$ corresponds to the output energy of the plant for a period τ.
- P_0 corresponds to the DC peak power of the solar plant.
- $G_{i,k}$ corresponds to the array plane irradiance (POA) for a time stamp. k
- $G_{i,ref}$ corresponds to the array plane irradiance (POA) for which it is obtained. P_0

The PR allows a linear relationship to be established between the irradiance received by the solar park (Input) and the energy generated and injected to the grid (Output), taking into account the efficiency and losses of the system. The standard has also established a correction factor that is applied to include the impact of temperature on the behavior of the solar park and that is of great importance to evaluate it precisely under weather conditions outside the expected ranges and shown in equation 2.

$$PR = \frac{\sum_k P_{out,k} \cdot \tau_k}{\sum_k \frac{(P_0 \cdot C_k) \cdot G_{i,k} \cdot \tau_k}{G_{i,ref}}}$$
$$C_k = 1 + \gamma \cdot (T_{mod,k} - T_{mod,avg,TMY})$$

Equation 2. Performance Ratio Weather Corrected [1].

Where:

- γ is the temperature coefficient of the modules in $°C^{-1}$
- $T_{mod,k}$ is the modulus temperature in the time stamp.k
- $T_{mod,avg}$ is the irradiance-weighted average annual module temperature of the Typical Meteorological Year (TMY) used in the contract.

Several studies such as "*Comparison of normal and weather corrected performance ratio of photovoltaic solar plants in hot and cold climates*" [3] have shown that the temperature-corrected PR is an adequate index to relate the irradiance and power output of a plant when the temperature conditions are different from those proposed as original conditions in the project evaluation. For this reason, most EPC contracts in Colombia take into account the result of the temperature correction as established by the IEC in the evaluation of the guaranteed PR.
. However, there are several cases in which external factors that affect plant performance are not only related to temperature and despite the fact that the weather corrections are made to the PR, but the plants are also below the expected performance and it is in these cases where it is necessary to make the disbursement of penalties. The standard establishes a recommendation to guarantee 95% of the calculated PR in contracts, however, it is also common to see in Colombia a guarantee of 98%, which is above of what is recommended in the NREL[10].
It has also been evaluated in other studies such as [4] that the PR may have complications when evaluating the performance of a plant if the conditions under which the evaluation is carried out do not start from certain assumptions and conditions established by the standard. Specifically, the study carried out by Darío Brivio found that one out of every 10 solar plants that were in perfect condition did not pass the PAC test due to external conditions that are not considered within the PR methodology.
One of the main reasons why the PR does not coincide with what is guaranteed in the contracts is the influence of non-linear behaviors of the solar plant that are not able to be represented in the PR equation. Specifically, the conditions of Clipping and Curtailment represent non-linear states of the plant that, if evaluated in the PR equation, will deliver results that are not representative of the reality of the plant, leading to unfair fines for non-compliance, as suggested by A. Mohd in "*Performance ratio – Crucial parameter for grid connected PV plants*" [6].

In addition to the PR methodology, there are other indices that are used in the industry to measure the performance of a plant, mainly the Capacity Test and the Energy Performance Index (EPI). The Capacity Test arises from the ASTM E2848 standard [5] and evaluates the behavior of irradiation and power from the drawing of a linear regression line by filtering the nonlinear data of the plant (Clipping and Curtailment Exclusion). For the linear regression equation, the parameters of wind speed, irradiance and ambient temperature are taken into account to model the plant as a linear regression shown in equation 3.

$$P = E \cdot (a_1 + a_2 \cdot E + a_3 \cdot T_a + a_4 \cdot v)$$

Equation 3. Capacity Test Linear Regression [5].

Where:

- a_1, a_2, and $a_3 a_4$ are the coefficients resulting from the linear regression.
- E is the array plane irradiance (POA).
- T_a is the ambient temperature.
- v is the wind speed.

The use of the Capacity Test as a plant performance index in EPC contracts in Colombia is practically nil due to the complexity that it entails, as well as it is a methodology that takes only less than one week of measurements per month and filters the Clipping-Curtailment events that occur when the plant operates at maximum capacity and that investors request to visualize. For this reason, its deep use is not contemplated in this study more than to perform an evaluation of the capacity curve graph in the analysis section.

On the other hand, the IEC TS 61724-3 standard establishes another performance index for solar plants known as the Energy Performance Index (EPI) which is a dimensionless index that measures the ratio between the expected energy of a simulation model and the actual measured energy. In the case of Colombia, the most widely used simulation tool is PVsyst and it is through its use that energy prediction is made based on meteorological data measured on site. Equation 4 represents how EPI is obtained according to the standard.

$$Energy\ Performance\ Index = \frac{E_{measured,k}}{E_{expected,k}}$$

Equation 4. Energy Performance Index [7].

Where:

- $E_{measured,k}$ corresponds to the energy measured at the injection point during a window of time.k

- $E_{expected,k}$ corresponds to the energy simulated during a window of time using the same measured weather data.k

The use of the EPI in contracts in Colombia is more widespread than the Capacity Test due to the ease of mathematical expression and the inclusion of nonlinear phenomena in the calculation. The IEC TS 61724-3 standard [7] states that the phenomena of Clipping and Curtailment should not be excluded since the simulation model on which it is compared considers such behavior both for EPI and for the calculation of the guaranteed PR. Despite this, there are cases in Colombia where the evaluation of EPI in young plants does not reach the minimum limits (0.95) and as with PR, penalties must be paid.

The performance of the plants in Colombia and the difficulty of complying with the contractual indicators has led the company Ingeniería Creativa S.A.S. to develop this study to identify the root of the problem and in turn propose a fair methodology for the parties within an EPC contract.

II. Methodology

A. *Methodology*

The methodology adopted for the study aims to carry out a broad comparative analysis of the behavior of the expected and actual performance indices for solar plants are already built and are in the development phase. The simulations will be performed introducing meteorological data obtained from Satellite Data into the PVsyst tool from which the data to execute equations 1, 2 and 4 is obtained.

The methodology contemplates two types of plants, the first corresponds to a plant not built yet where there is a Satellite Data meteorological database that will be used to calculate the TMY from which the contractual PR expectations will be derived. The second plant, built and in operation, accounts with information from satellite based meteorological databases, which was used in the TMY calculation and PR expectations establishment. Additionally, it accounts with measurements of a meteorological station on site and energy injected into the grid..

In both cases, PVsyst will be used to calculate the TMY based on the Sandia methodology offered by the simulation software and which establishes the highest weight of the calculation to the daily global irradiance [8]. Subsequently, the TMY obtained will be used to run an annual simulation in the program to obtain the results of module temperature, irradiance in the plane of array and energy, required to calculate the expected PR for the plant each month. The calculation of the annual average module temperature weighted by irradiance continues following the methodology proposed by IEC 61724 [1] and which will be the reference temperature $\mathrm{T_{mod,avg}}$ with which the PR temperature corrections will be made.

From the same simulation models for both cases, a simulation of the last 5 years of satellite meteorological data from Satellite Data was carried out, obtaining data on grid injection energy, irradiance in the plane of array, ambient temperature, module temperature, among others. A simulation for the plant in operation using the data that was measured on site was performed on a sub-hourly basis from 5-minute time stamps to account for intra-hourly effects that are overlooked by PVsyst when hourly simulations are performed to calculate the EPI.

In the case of the plant that has not yet been built, there are measurements for the year 2023 from a weather station that has horizontal global irradiance and ambient temperature data that were used to simulate the model of said plant, but with data measured on site obtaining the same variables as with satellite data simulations. In the case of the plant in operation, a simulation was carried out for the year 2023 with the data measured of the Plane of Irradiance and ambient temperature, obtaining the same variables as in the previous simulations.

The results obtained from the simulations in PVsyst were used to calculate the performance indices of equations 1 and 2 in both plants by applying the temperature correction using the TMY as a reference. For the plant already built, the validation of another performance index widely used in EPC contracts, the Energy Performance Index or EPI, was also carried out.

The calculated performance indices were compared with expectations from the TMY and the main differences were found as well as their causes. The evaluation of the change of parameters and graphical comparison between the simulated years as well as the input and output variables to find those factors that most affect the deviations between expectations and reality. The differences were quantified and a new evaluation methodology was proposed, taking into account the causes of the differences that were found, the evaluation methodology of each of the performance indices evaluated, and the interests of each of the parties within an EPC contract.

Figure one shows a diagram of the methodology used to come up with the performance evaluation methodology of a solar photovoltaic plant that will be explained in later sections.

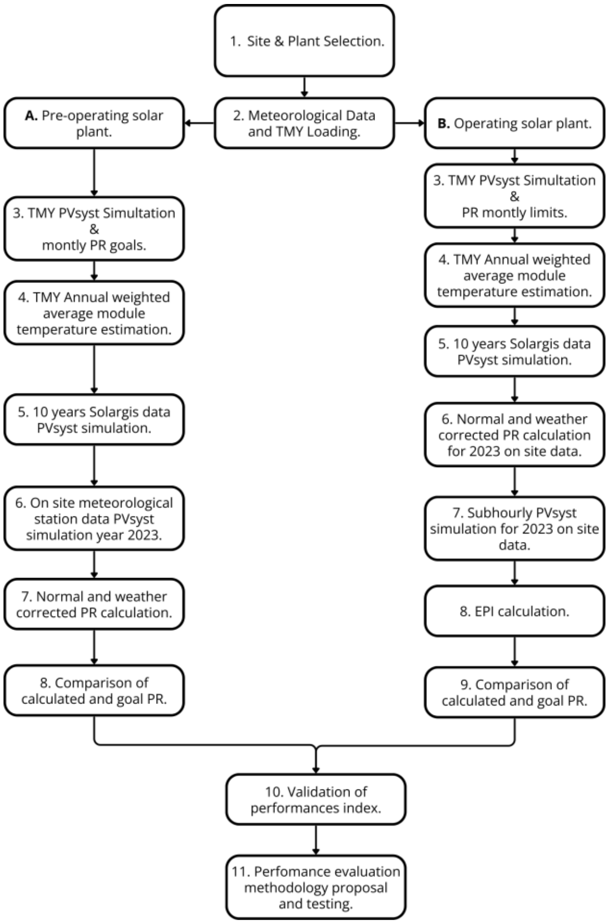

Figure 1. Methodology of the study.

B. Solar Plants Selection

For the development of this research, we worked with 2 plants that represent the 2 stages in which the evaluation of the performance of a plant and its expectations are carried out, which correspond to a pre-operational plant and an operational one. For the purposes of this article, the pre-operational plant shall be referred to as Solar Plant A and the plant in operation as Solar Plant B.

Solar Plant A

Solar plant A is a plant that is in the pre-operational stage, which means that it is not yet built and there is no actual production data for it. This plant would represent the characteristics of a project in the design and development stage, which is when performance expectations are agreed between the parties involved in the EPC contract. The characteristics shown in Table 1 correspond to the general parameters of the solar plant and which, in turn, are represented in the PVsyst simulation model.

Technical characteristics of the projects	
Climate Zone	Semiarid - Warm
Country	Colombia
Continent	South America
Temperature coefficient $[\frac{\%}{C}]$	-0,0034
DC capacity (MWp)	19,3
AC capacity (MWac)	18,2
AC capacity at point of interconnection (MWac)	16,0
DC/AC ratio at point of interconnection point	1,209
Modules (quantity)	585 W (32760)
Inverter (quantity)	200 kW(91)
Module Support Structure	Fix Structure

Table 1. Solar Plant A technical characteristics.

Solar Plant B

which means that it is built and there is data on its real production. This plant would represent the characteristics of a project in the operation and maintenance stage, which is where performance expectations are evaluated to meet what was agreed between the parties involved in the EPC contract. The characteristics shown in table 2 correspond to the general parameters of the solar plant and which in turn are represented in the PVsyst simulation model.

Technical characteristics of the projects	
Climate Zone	Tropical Dry
Country	Colombia
Continent	South America
Temperature coefficient $[\frac{\%}{C}]$	-0,00353
DC capacity (MWp)	27,39
AC capacity (MWac)	19,95
AC capacity at point of interconnection (MWac)	19,9
DC/AC ratio at point of interconnection point	1,377
Modules (quantity)	445 W (61560)
Inverter (quantity)	175kW (114)
Module Support Structure	Tracking plane N-S horizontal axis

Table 2. Solar Plant B technical characteristics.

C. Meteorological Data

For the development of the simulations of both plants, a satellite database from a well known Satellite Data company provider was used, which has irradiance and temperature information between the years 2000-2022 for plant A and 2000-2018 for plant B. This satellite database was entered into the PVsyst simulation program to calculate the corresponding Typical Meteorological Year (TMY) that will be used to obtain the plant's performance expectations for subsequent years. The methodology used to obtain this TMY was the one proposed by the Sandia laboratory and which is one of the automatic parameters in PVsyst, having only to enter the last 10 years of information on horizontal global irrandiance and ambient temperature so that the program automatically develops the typical meteorological year. The monthly horizontal global irradiance and ambient temperature data of the TMY of the two evaluated plants is condensed in tables 3 and 4 shown below.

Month	Horizontal global irradiation $[\frac{kWh}{m^2}]$	Ambient temperature [°C]
Jan	168.8	23.5
Feb	152.0	24.7
Mar	167.8	24.6
Apr	168.0	24.2
May	174.4	23.4
Jun	161.2	23.2
Jul	184.8	23.6
Aug	184.3	24.0
Sep	180.1	24.6
Oct	171.0	24.0
Nov	153.0	22.9
Dec	160.0	23.4
Average	169.6	23.8

Table 3. Solar Plant A Typical Meteorological Year.

Month	Horizontal global irradiation $[\frac{kWh}{m^2}]$	Ambient temperature [°C]
Jan	188,2	28,8
Feb	169,6	30,1
Mar	167,3	29,0
Apr	144,6	26,8
May	150,6	25,3
Jun	137,5	24,4
Jul	140,7	24,0
Aug	152,2	25,4
Sep	159,4	25,7
Oct	160,3	26,1
Nov	150,1	26,3
Dec	166,0	26,9
Average	157,2	26,9

Table 4. Solar Plant B Typical Meteorological Year.

III. Results and Analysis

A. TMY Simulation

EPC contracts must start from a basis on which the generation and performance expectations of the plant in future years are established. To do this, it is necessary to carry out forecasting processes based on historical data that can reflect as best as possible the weather conditions of the area where the solar plant will be built. For this, it is normal in the industry that the basis on which expectations are raised is a Typical Meteorological Year (TMY) which corresponds to the condensation of several years of meteorological measurements into a single year in which each month is the best representation of the typical behavior of the variables of interest. It is this TMY that functions as a basis to enter the simulation models and thus obtain the generation forecasts for years in the future, considering that reality is expected to behave similar to the TMY. For both plants of this study, a base simulation was carried out based on the TMY, obtaining as main variables the irradiance in the array plane, the module temperature that will be used as a reference for the necessary corrections of the PR and the PR of each month that will correspond to the objective set in the EPC contracts.

Tables 5 and 6 condense the general information of the simulation of plants A and B using the TMY of each one and which will be the one with which it will be established which are the performance gurarantees that each of the plants must have in the future entry into operation.

Month	Plane of Array Irradiation	Module temperature [°C]	Irradiance-weighted average annual module temperature [°C]	Performance Ratio
Jan	172.7	43.0882	43.4154	0.8316
Feb	155.3	44.1007		0.8344
Mar	167.3	44.1398		0.8354
Apr	164.9	43.3235		0.8377
May	168.2	42.3217		0.8418
Jun	164.7	42.0232		0.8422
Jul	177.1	42.8387		0.8395
Aug	187.6	44.7371		0.8319
Sep	183.7	46.2205		0.8279
Oct	173.1	43.5520		0.8352
Nov	157.1	42.1204		0.8341
Dec	165.7	42.0635		0.8366
Average	169.78	43.38		0.8357

Table 5. Solar Plant A TMY simulation results.

Month	Plane of Array Irradiation	Module temperature [°C]	Irradiance-weighted average annual module temperature [°C]	Performance Ratio
Jan	234,8	51,1137	46.7115	0,8316
Feb	206,2	52,1442		0,8344
Mar	188,3	50,9828		0,8354
Apr	159,6	46,6028		0,8377
May	169,3	43,7315		0,8418
Jun	155,8	41,3207		0,8422
Jul	156,8	41,2680		0,8395
Aug	172,4	43,7347		0,8319
Sep	186,6	46,5764		0,8279
Oct	182,9	46,5400		0,8352
Nov	175,9	45,3763		0,8341
Dec	202,5	47,0147		0,8366
Average	182.6	46.3671		0.8592

Table 6. Solar Plant B TMY simulation results.

B. 5 years Satellite Data Simulation

From the Satellite Data, simulations were carried out for the last 5 years of meteorological data from each of the plants to obtain the main variables to calculate the performance indices. The behavior of 3 main variables was graphed in Figure 2, the PR of the plant, the module temperature and the irradiation above the curtailment level. This last variable corresponds to the amount of irradiation in the plane of array that was above the level at which the plant generates its maximum limit of injection into the network (POI). This level of irradiation was calculated by applying the formula in equation 5.

$$\sum_{\substack{k \\ POA_k = POA \geq STC \cdot \frac{1}{DC/AC_{ratio} \cdot PR_k}}} POA_k \cdot \tau_k$$

Equation 5. POA over curtailment.

Where:

- DC/AC_{ratio} corresponds to the DC/AC ratio of the solar plant.
- POA_k corresponds to the irradiance in the array plane in $[\frac{W}{m^2}]$.
- STC corresponds to the irradiance of 1000 from the Standard Test Conditions $[\frac{W}{m^2}]$.
- PR_k corresponds to the performance ratio of the plant calculated for the timestamp k.

Equation 5 considers the DC/AC ratio as well as the PR of each data stamp in such a way that only the irradiance values for which the plant at a given time reaches its peak power are included.

Solar Plant A

The results of the simulations were graphically organized in such a way that the behavior over time of the PR performance index, the module temperature and the irradiation above the Curtailment level of the plant could be seen. The first graph called Figure 2 shows the behavior over time of the guaranteed PR in the EPC contract of Solar Plant A and that corresponds to the one obtained in the simulation of the TMY where it is evident that it depends on the month of the year that is being evaluated. In this same graph you can see the behavior of the PR calculated from the simulation and the temperature correction that reduces the peaks in its behavior. For Solar Plant A, it is evident that the simulated PR for the last 5 years of satellite data is above the guaranteed PR and this plant would comply with the obligations of the contract.

The module temperature graph shows that there is a tendency for the temperature of the simulated years to be higher than that of the TMY, which causes a lower PR and that a temperature correction must be applied to evaluate the plant in the right conditions. Finally, the irradiation graph above the Curtailment level shows that there was normally more plant saturation in the TMY than in the years evaluated.

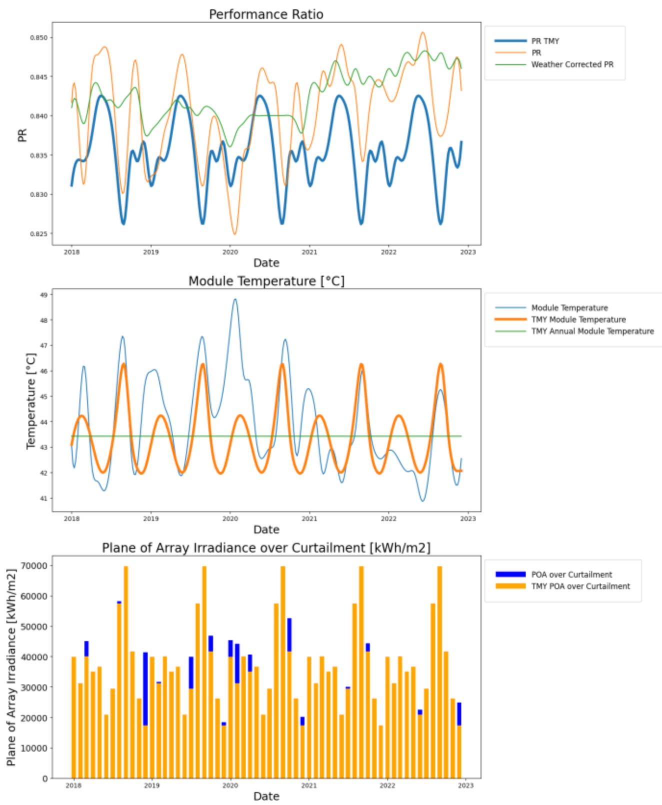

Figure 2. Solar Plant A 5 years simulation.

Solar Plant B

As for solar plant A, the calculated PR is within the tolerance limits established in the guaranteed PR, 0.95% of the TMY. Similarly, the module temperature variables have a similar behavior and the amount of irradiation above the Curtailment level presents a fairly equal behavior between the simulated for the years with satellite measurements and the TMY.

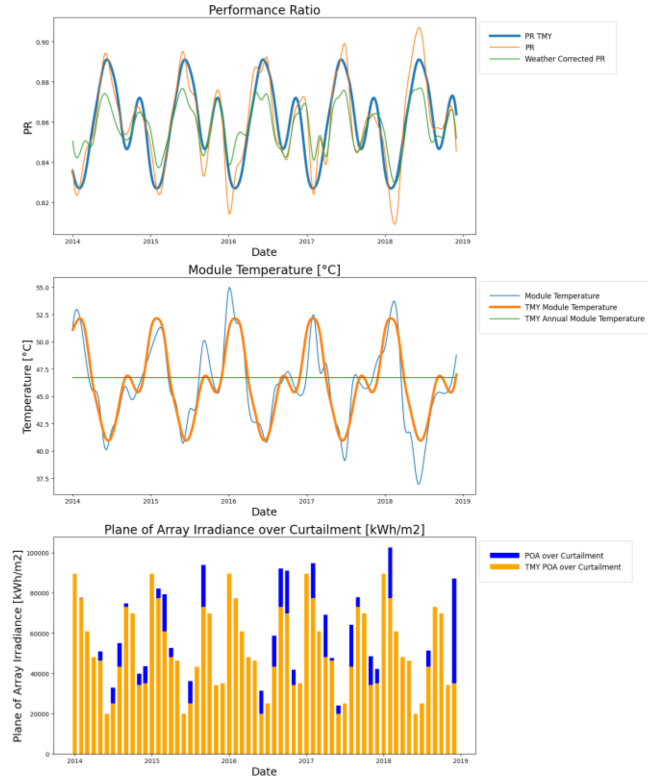

Figure 3. Solar Plant B 5 years simulation.

C. On Site Data Simulation

The simulations carried out for the satellite meteorological variables of previous years showed that before having on-site measurement data, the expectation of the plant's behavior in future years corresponds adequately to what is expected and represented in the TMY. However, it is necessary to evaluate the behavior of the plant and the model based on the use of data measured on site that represent the reality of the plant for both meteorological and electrical variables, depending on the case of a plant that is in a pre-operational or operational state.

Solar Plant A

A simulation was carried out for the year 2023 using on site data measured by a weather station at the location where the project is going to be built and which is the same location from where the satellite information from Satellite Data was obtained. Figure 4 shows how from 2023 on site data there is an abrupt change in the behavior of the evaluated variables, where it can be seen how the calculated PR decreases with respect to the PR guaranteed by the TMY, as well as how the module temperature increases significantly with respect to what is expected and the amount of irradiation above the Curtailment level is evidently higher than for the years evaluated with the satellite information. It should be noted that in the case of Solar Plant A, a plant that is not yet in operation is being evaluated, so it is assumed that the simulation model represents 100% faithfully the reality of what the plant will be. Even so, it is evident that the PR differs from the TMY in some months even a 2% showing the sensitive to changes in meteorological variables when compared with expectations that are based on different hypotheses of these variables, such as lower levels of module temperature and lower Curtailment. However, these changes in the PR allow the plant to still be within the 95% margin of the guaranteed PR, but knowing that the modeling of the plant is not perfect, when entering operation the level of difference with the guaranteed PR may increase and enter a state of Non-Compliance.

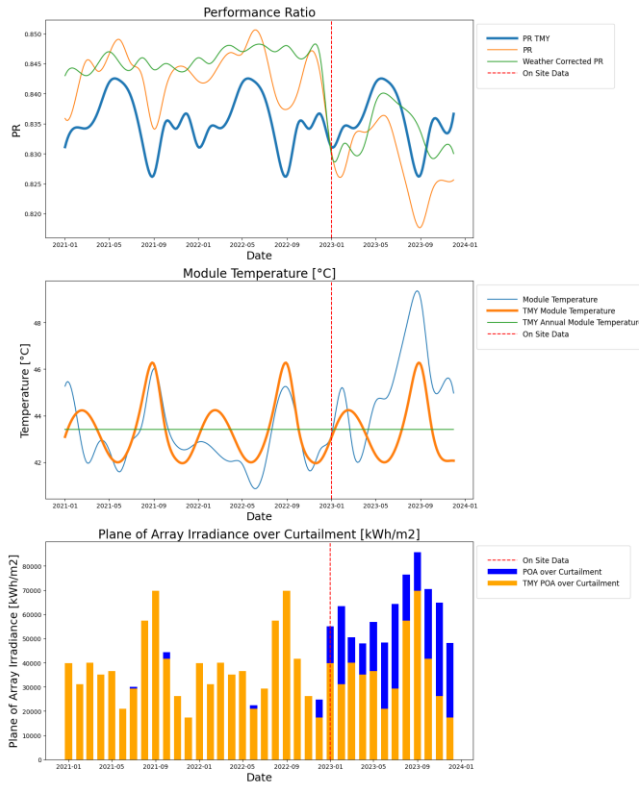

Figure 4. Solar Plant A on site data simulation.

Solar Plant B

For solar plant B, meteorological data from an on-site station and electrical data from generation injected to the grid from may 2023 to april 2024 at 5-minute time stamps are available. These data was used to calculate the PR for each of the months and a large difference between the expected PR in the TMY and the calculated one could be evidenced in Figure 5, reaching in some months up to 10 percentage points, as is the case of November 2023, which is completely out of the tolerance established in an EPC contract. The graph shows only for May, December, January, February and March are in a state of compliance, while the rest of the months are Non-Compliance, based on the 95% criteria suggest by NREL.

However, the module temperature does not have as significant a change as the plant's performance did, and as it can also be evidenced that the irradiation above the Curtailment level has, which for almost every month was higher than expected in the TMY. Another factor to highlight is that the temperature correction does not seem to alter the shape of the PR or improve its behavior since it simply changes the magnitude at certain points where the difference in module temperatures is greater, but in this case, it has not improved the performance of the plant. The external factor that has mostly presented a change is the amount of irradiance above the Curtailment level that exceeds what was predicted in the TMY. This increase also coincides with the months in which a state of Non-Compliance occurs, that is, those months where the saturation of the plant exceeds much more than expected in the TMY, the calculated PR is much lower than the expected that arises from the same TMY.

This case can be extrapolated to many others in Colombia where the plants do not meet the PR expectations agreed in the contracts even though there are no evident failures reported and the meteorological and electrical data presents an adequate quality. These underperformance behaviors in properly constructed plants are related to other external factors that are not taken into account when applying the PR equation that affect the way performance is measured and can be detrimental to the parties to the contract. In the following discussion section, we will describe what those external factors other than temperature are that greatly affect the performance index and why they should be taken into account when agreeing on the terms and conditions of EPC contracts.

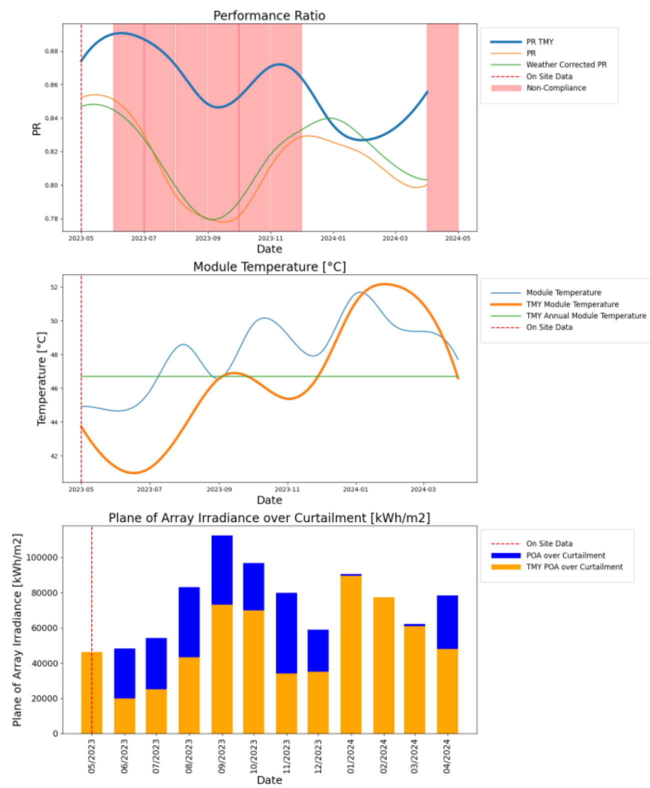

Figure 5. Solar Plant B on site data simulation.

D. Analysis

The results in the previous section showed that for both pre-operational and operational stages, the plants demonstrate a PR that is within the agreed ranges when the simulations are evaluated from satellite databases. However, when evaluating the behavior of the plant by simulating with meteorological data measured on site and calculating the PR from the real measurements, this same plant that previously seemed to have an expected behavior, goes beyond the limits established in the contracts and presents a behavior that could be classified as low performance.

It was also assessed that the drastic change in the behavior of the PR is accompanied by the change of another important variable that affects first-hand the equation with which the PR is calculated, the irradiation above the curtailment level. In cases where this irradiation is higher in the measured data than in the TMY, the greater the discrepancy in the calculated and guaranteed PR, making the result of the calculation of performance index lower. This makes sense since the PR equation is designed to work with variables that have a linear behavior and can therefore be represented from a function with a slope that represents the performance of that plant. As already mentioned in the study by A. Mohd [6], including non-linear external factors in the PR equation distorts the results and shows behaviors that do not correspond to the plant being evaluated.

To show this visually, a capacity curve of Plant B for the month of November was graphed in Figure 6, which is where it presents a greater discrepancy between the calculated PR and the objective.

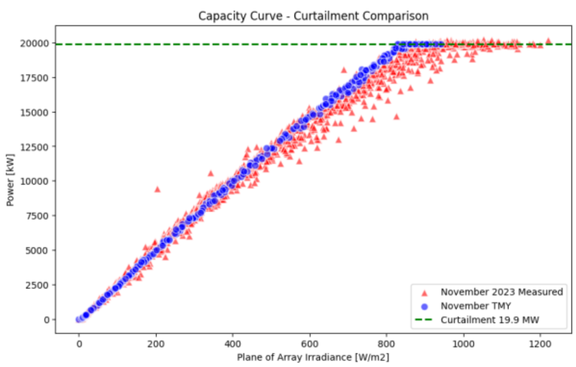

Figure 6. Solar Plant B curtailment comparison.

The graph shows how as the irradiance increases, the power increases in a linear way following the slope of a straight line corresponding to the quotient of the PR equation. Once the curtailment level (19.9 MW) is reached, an increase in irradiance does not represent an increase in power and therefore the plant is "Saturated" at this point. In the figure can be seen how this saturation is much greater than what was expected in the TMY. This means that the simulation that was used to establish the PR expectations considers the saturation behaviors of the plant, however, the saturation in real time operation is much higher than what was expected from the plant, creating a greater distortion of the plant's reality from expected initial TMY.

To corroborate that solar plant B does behave as expected and does not have an internal failure problem, the calculation of the Energy Performance Index (EPI) was carried out for the same months in which the simulation was evaluated with the on-site data.

In order to obtain a simulation that correctly represents the reality of the plant for the EPI, it is necessary that the simulation is performed in a sub-hourly way, i.e. the program does not average the intra-hourly data to hourly data, but that the intra-hourly time stamps are considered. This is very important because when the plant reaches its curtailment irradiance and it is not constant for a full hour, the PVsyst program averages the data, and the curtailment effect is not considered as shown in Figure 7.

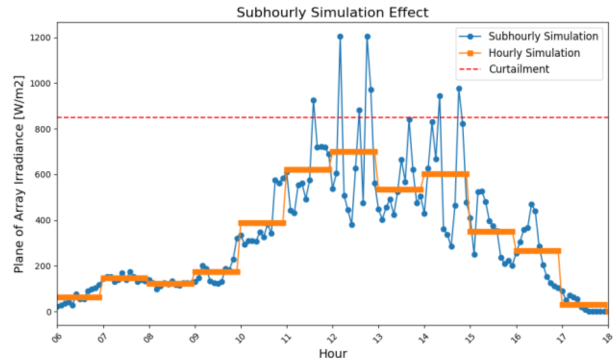

Figure 7. Subhourly Simulation Effect.

The results of the subhourly simulation are presented in Figure 8 where, in addition to the EPI, a comparison was included between the real and weather-corrected PR of the plant for each month and the PR that was obtained from the simulation. The weather-corrected PR is obtained using the average irradiance-weighted module temperature of the measured months that are being evaluated. It has been seen in Colombia that the Energy Performance Index of the plant is normally accepted for the same tolerance suggested by IEC and NREL for the PR, a 95% [10] which would mean a range of $0.95 \leq EPI \leq 1.05$ which is the one where the evaluated plant is in.

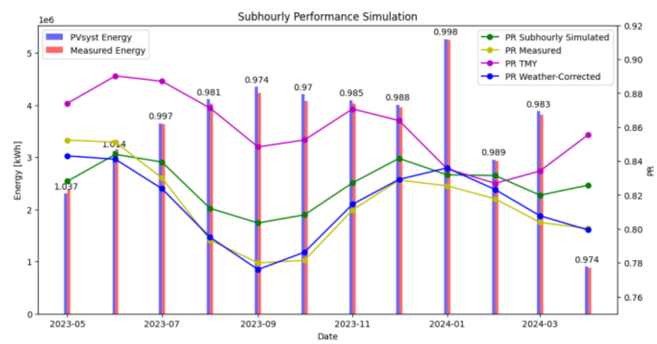

Figure 8. Subhourly Performance Simulation.

Figure 8 shows that the energy generated by the plant for the meteorological input data corresponds almost perfectly to that which would be obtained with the same data using the simulation model from which the plant performance targets were established. The largest energy difference does not exceed 3%, which is a value that is considered to be within the expected range of normal plant behavior, unlike the 10% discrepancy originally obtained with the TMY guaranteed PR analysis. This graph shows that the problem with solar plant B is not that it has a low performance as indicated by the PR set by TMY, but that this performance index does not adequately represent the plant's behavior under saturation conditions. But the PR obtained from the sub-hourly simulation does represent in a better way the real performance of the plant in these conditions, since the amount of saturation is being considered in the simulation in the same proportion as in the operation of the plant.

IV. PERFORMANCE EVALUATION PROPOSAL

The results obtained in the present research have shown that although the Performance Ratio is an index widely used in the industry and allows quantifying the performance of a plant, it is highly sensitive to nonlinear behaviors in the operation of a plant that usually occur when Curtailment and Clipping phenomena occur. Regarding these phenomena, IEC TS 61724-3:2016 [9] states the following:

"*6.5.12 Inverter clipping (constrained operation) – In the case of inverter clipping because the inverter has reached its output capability, it is assumed that the model originally quantified the output assuming this clipping. The expected energy should be calculated in the same way*" [9]

As the standard states, the non-linear effects of the plant should already be considered in the original modeling (TMY) so these phenomena should not have to be altered when evaluating plant performance. However, the standard indicates that this validity exists because the original model should already take these phenomena into account, but if these phenomena are much larger than in the reference simulation where the performance expectations were set, the number of discrepancies also increases.

Due to the sensitivity of the PR to changes in the number of non-linear phenomena, it is recommended to calculate a new guaranteed PR for the period being evaluated, which will be obtained from the sub-hourly simulation in PVsyst with the meteorological data measured in that period.

If the plant presents saturation levels equal to or lower than those in the reference period according to the TMY simulation, both periods are representative of each other and therefore the comparison of the PR obtained would comply with the guaranteed PR of the original TMY simulation. But if the saturation of the plant is higher in the period in which the performance is being evaluated than the saturation that existed in the reference period on which the performance commitments were established, the PR would not adequately represent the behavior of the plant for that period and a new guaranteed PR should then be calculated that is representative of the phenomena that occurred in the plant.

The criterion proposed to be used to discard the use of PR guaranteed by the reference is the comparison of the sum of the amount of irradiation above the saturation level between the measurements of the period to be evaluated and the reference. If in the period to be evaluated there is a higher irradiation above saturation than in the reference, a new guaranteed PR must be simulated.

To define the radiation value for which the curtailment level is exceeded, the Standard Test Condition [$1000 \frac{W}{m^2}$] is used as a reference and a multiplicative factor proportional to the DC/AC ratio and the PR of the plant is applied as shown in equation 6, similar to that previously used in equation 5.

$$\sum_{\substack{k \\ POA_k = POA \geq STC \cdot \frac{1}{DC/AC_{ratio} \cdot PR_k}}} POA_{measured,k} \cdot \tau_k > \sum_{\substack{k \\ POA_k = POA \geq STC \cdot \frac{1}{DC/AC_{ratio} \cdot PR_k}}} POA_{TMY,k} \cdot \tau_k$$

Equation 6. POA over curtailment.

Where:

- DC/AC_{ratio} corresponds to the DC/AC ratio of the solar plant.
- $POA_{measured}$ corresponds to the radiation in the array plane measured in the solar plant in $\frac{W}{m^2}$
- POA_{TMY} corresponds to the radiation in the array plane obtained in the TMY simulation for the solar plant in $\frac{W}{m^2}$
- PR_k corresponds to the performance ratio of the plant calculated for the timestamp k.

Once the above criterion has been evaluated, the calculation of the performance index is carried out as appropriate using the equations presented above and the methodology established in IEC 61724. If the corresponding index is above the guaranteed reference value in the EPC contract, there is a satisfactory test and a Compliance status. If, on the other hand, the index is below what is guaranteed in the EPC contract, there would be a Non-Compliance status and the plant would be below the expected performance for the evaluated period.

The methodology proposed by ICREA is visualized in Figure 9 below.

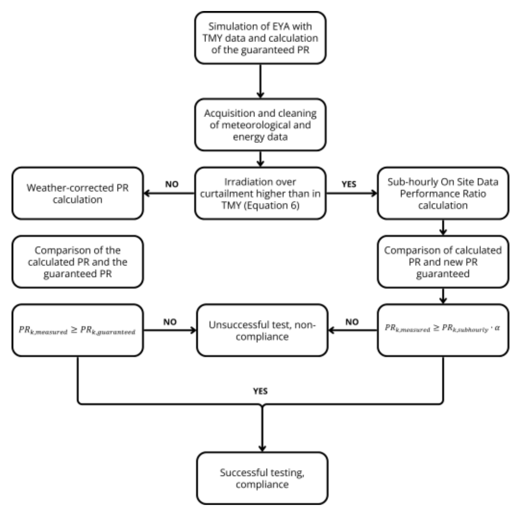

Figure 9. Performance evaluation methodology proposal.

The proposed methodology was evaluated for the periods where there were on-site measurements of Solar Plant B in which only for on site data of May and February of 2024 the irradiance level above curtailment was higher in the TMY simulation than in reality. It is evident in Figure 10 that for those periods where the saturation was higher than in the original simulation, the new subhourly simulated PR is closer to the plant PR. The weather-corrected PR for the periods where the POA over curtailment is not bigger than in the TMY must be done the same way it was done originally, which is using the annual average irradiance-weighted module temperature of the TMY for the correction.

While originally in Figure 5 it was evidenced that there were several periods for which there was a Non-Compliance despite having a plant without failures, using the proposed methodology no period is found as Non-Compliance allowing the plant to be properly evaluated under real operating conditions.

Figure 10. Performance evaluation methodology validation.

V. CONCLUSION

The present study addresses the problem of low performance in solar PV plants in the context of EPC contracts in Colombia. The objective was to identify the causes of this problem and propose solutions to mitigate its consequences. Previous studies had already evaluated conditions in which performance indices, such as PR, do not work properly, and the reasons behind this were explored.

Through simulations of two types of plants in operational and pre-operational contexts, it was possible to observe how performance expectations are built at each stage. It was shown that these expectations depend significantly on the databases used, since differences were observed between the data measured on site and those obtained by satellite databases. An evaluation of the PR and weather-corrected PR performance index was carried out for both plants. The results showed that, although expectations were adequate when working with satellite databases, when simulating with data measured on site, the performance of the plant decreased, and variables such as module temperature and irradiance increased significantly. Even using an ideal simulation model, discrepancies of up to 2% with the guaranteed PR were observed. These discrepancies increased to a range of between 3% and 10% when evaluating with on-site data, falling outside the maximum limits established in the contracts and qualifying the plant as unsatisfactory.

The main cause of these discrepancies was the higher frequency of nonlinear events, such as Curtailment and Clipping, compared to TMY-based simulations. This led to increased plant saturation and a PR that did not adequately represent these phenomena. The standard on which this performance index is based clarifies that these non-linear data must be considered in the original model, so a greater saturation implies that the model does not faithfully reflect the performance of the plant for that period.

A sub-hourly simulation was then evaluated to account for the effects of intra-hour saturation, the EPI was calculated and was within acceptable ranges. A performance evaluation methodology was then proposed where the guaranteed PR should be obtained from a sub-hourly simulation for those periods where saturation exceeds what was expected in the original TMY simulation since in such a case the original guaranteed PR does not represent the reality of the plant for that period.

The main criterion to define the use of a new subhourly PR simulated is the comparison between the amount of irradiation above the saturation level in an evaluated period and what was expected in the original simulation.

This methodology seeks to fairly evaluate solar plants in Colombia, ensuring transparency for all parties involved in EPC contracts. Thus, it is ensured that the methods used comply with the established assumptions, maintaining trust between the parties without favoring or disadvantage any of them.

ACKNOWLEDGMENTS

This research was developed under the supervision and guidance of all members of the research group of the company Ingeniería Creativa S.A.S. (ICREA). The authors would like to extend their gratitude to the entire research team as well as the commercial area that has made it possible for this project to have an impact on the Colombian solar generation industry to allow for a fair advancement of all parties involved.

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