iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 6 **Issue:** I **Month of publication:** January 2018

DOI: http://doi.org/10.22214/ijraset.2018.1030

PV Tracker System Net Gain Associated to the Local Climatic Conditions

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Abstract: The optimization procedure on a photovoltaic system design implies the best compromise between energetic production (EP) and overall associated costs (OAC), which include economic and environmental. Both variables depend on the available solar radiation; strongly the EP and, in a lesser extent, the OAC. In this paper, the required conditions so that a PV tracking system produces a net gain with respect to a PV fixed system will be evaluated. This analysis is performed as function of the location's climatic conditions in terms of production and associated multidimensional costs, including EPBT and IRR. To avoid theoretical model dependences, the whole study has been carried out under real sun conditions on a medium irradiation region. For it, an 8-month historical monitoring data of a grid-connected PV field have been analyzed. The installation has two same-manufacturer polycrystalline arrays installed the same year, one of them with a 2-axis tracker and the other in fixed tilt position. As general result, a simple algorithm for tracker net gain evaluation as function of global and diffuse radiation is provided. Also, the net benefit limit value for a tracker system as function of the diffuse fraction is calculated.
Keywords: ***PV design, Solar tracker, Multidimensional cost, Solar radiation, Diffuse fraction***

I. INTRODUCTION

In the actual renewable energies paradigm, the selection of the most appropriate design for a given location relies on the best compromise between energy production and associated overall costs. Considering the solar photo voltaics, the energy production strongly depends on the climate and the PV system design (fixed tilt or solar tracker system). The associated overall costs consider not only economic but also the environment associated costs.

The solar tracker installation optimizes a PV system in terms of energetic production. According to several authors [1][2][3][4], a 2-axis solar tracker provides between 12% and a 35% more gain in terms of production than a fixed tilt array. The wide spectrum of responses can be adjudicated to the high dependence on meteorological models, the limited historical databases and, of course, to the different climatic characteristics of the experimental setups location used for the analyses.

Several studies regarding the energy production increase when installing 2-axis solar trackers have been developed. Most of them focus on specific locations [3][4] and, often, get results after simulations [1][5] which only sometimes take into account the latitude [6]. Other studies consider extremely short evaluation periods [2][7][8]. These studies tend to lead to the conclusion of the high profitability of installing a 2-axis solar tracking system. Nevertheless, other studies consider the solar tracking suitability in overcast conditions [9][10], concluding that overcast conditions lead to less production when considering tracking systems than fixed horizontal arrays. This dependence can be evaluated through the Clearness Index (KT). As this paper focus on directly measurable parameters [11], this variable will not be considered as it is obtained with mathematical models. Thus, the production as a function of directly measurable parameters should be assessed.

To improve previous results, the full analysis in this paper is based on experimental production values of two polycrystalline slicon PV arrays. Both arrays are same brand, same manufacturer and were installed in the same location at the same time. One of the arrays is placed with a fixed tilt and the other has a 2-axis solar tracker. Moreover, diffuse and global radiation components are independently measured, ensuring no dependence on meteorological models.

To avoid the climate dependence, the PV array production gain will be evaluated as function of the diffuse fraction. As the used database covers a wide range of weather situations, this variable allowsto study the experimental setup response under different limatic conditions using a single physical location.

In terms of associated overall costs, it is well known that selecting a fixed tilt system ensures the minimum initial economic investment and simple maintenance needs. This characteristic should be measured by the balance between profits and costs (Internal Rate of Return, IRR, [12][13]). According to NREL [14], in a rough approximation, IRR increases in a 50-60% when solar tracking is considered [5][15]. These systems also rise the maintenance costs, as they present a 45% of the unexpected failures on PV systems (but only lead to a 10% associated production losses) [16].

The environmental effects should be evaluated using the PV the Energy Payback Time (EPBT), defined as the required time for a renewable energy-based system to generate the same amount of energy used on its production. The EPBT depends on irradiation levels, ranging from 1.2 to 2.5 years [17][18]. For a 2-axis solar tracking system, EPBT increases up to 6.5 years [15].

In this paper, a brief overview about the influence of the global costs on the decision of the utilization of a tracker PV array will be provided. By using experimental the values, the conditions under which a solar tracker increases the production compared with a fixed tilt array will be evaluated.

II. EXPERIMENTAL SET-UP

The experimental set-up is compounded by two identical PV arrays, part of a grid-connected electric power plant owned by Norvento Enerxía [19] and located in Vilalba (Spain) (coordinates 43.3146; -7.6650) (Figure 1). One of the arrays is installed at fixed tilt (horizontally oriented), while the other has a 2-axis solar tracker (clock type, pan & tilt system). Selected arrays characteristics (hereafter, Fixed and Track) are shown in Table 1. Both arrays are same brand, same manufacturer and were installed in the same location at the same time.


Figure 1. Considered PV arrays (left, Fixed; right, Track)

TABLE 1.Considered PV arrays characteristics

PV Panel technology	Brand and model (ID)	Unit power P_{rated} (W)	Array power P_{total}(W)	Inverter	Solar tracking
p-Si (Fixed)	Suntech STP260	260	14040	Ingeteam Ingecon Sun 12,5	No (Horizontal)
p-Si (Track)	Suntech STP270	270	10530	Sunways NT10000	2-axis (Pan & Tilt)

Even both arrays have different brand inverters, the losses difference is less than 3% [20]. The production values are measured at the inverter output with a 10-minute frequency. Inverter associated losses are neglected.

Simultaneously to the production data-taking, the global radiation values are collected using a local pyranometer (LI-COR model LI-200SZ, 80μA per 1000 W/m2 sensitivity). A greater precision pyranometer located 13 km far from the photovoltaic field (Meteogalicia's Guitiriz-Mirador meteorological station [21]) has been used as cross-check. The acceptable correspondence between meteorological station values (G_{Guit}) and the PV field (G_{Norv}) has been verified over 80 days along a 5-month period and compared in terms of daily total global radiation.

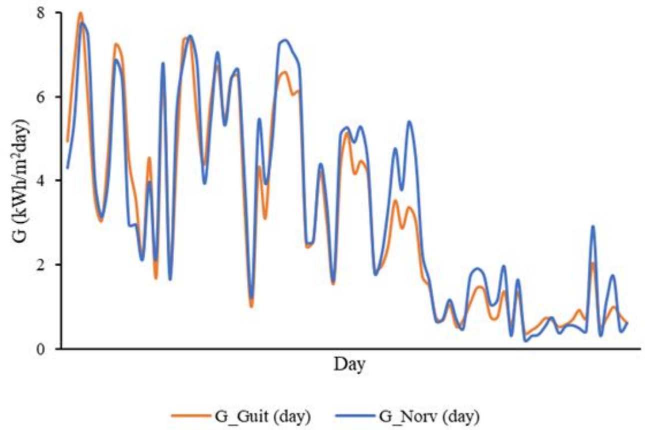

Figure 2. Meteorological station (G_{Guit}) and on-location (G_{Norv}) daily solar radiation values for a 5-month consecutive period (year 2014)

Figure 2 shows the daily global irradiation from each data source ($G_{Guit,day}$) and ($G_{Norv,day}$). A 6.3% difference between them is measured on the total sum of the global radiation over the considered period, with an average -7.3% difference for the daily deviation (considering G_{Guit} as reference).
In order to avoid model dependence, diffuse radiation component experimental values are acquired using a meteorological station. The nearest station with diffuse radiation measurements is located 84 km far from the experimental setup (Meteogalicia-EOAS [21]). This station is equipped with global horizontal and diffuse horizontal pyranometers and provides 10-minute frequency values for each data (hereafter, GEOAS for the station global horizontal radiation values and DEOAS for the diffuse horizontal values). To ensure a correct match between data samples, a simple similarity criterion (see next section for details) has been applied.

III.METHODOLOGY

The production difference of the arrays along a cumulative sample of over 80 no consecutives days is measured. The obtained gain is studied according to the climatic conditions, characterized by the percentage of diffuse radiation component compared to the global. A simple calculation of costs will be carried out. This will allow to make a study of both technological design and economic costs. In what follows, the variables of merit to be used will be defined.

A. Production variables

The most commonly used variable [25] to evaluate a PV array production is the performance ratio [1][2]. The PR is an unbiased measure of the production with respect to the incoming radiation, providing dimensionless and absolute values of the installation performance regardless the location or time of the year.
To study the behaviour´s differences between two PV identical arrays, the gain in terms of performance ratio,ΔPR, will be considered for the analysis (Eq. 1).

$$\Delta PR = PR_{Track} - PR_{Fixed} \qquad \text{Eq. 1}$$

To define the net benefit limits of a tracker with respect to a fixed tilt system, the variables Performance Ratio variation, σ(PR), Internal Rate of Return variation, σ(IRR), and Energy Payback Time variation, σ(EPBT), are defined as in Eq. 2.

$$\sigma(X) = 100 \cdot \frac{X_{Track} - X_{Fixed}}{X_{Fixed}} \ (\%) \qquad \text{Eq. 2}$$

where X = PR, IRR or EPBT.

B. Solar radiation variables

The total incoming solar radiation over a surface is defined as the sum of two components, direct and diffuse radiation [3][4]**.** The third component, the reflected radiation, is small enough to be neglected on this analysis. To evaluate the effect of climatic conditions on a PV array production, the diffuse fraction (per-unit) over a surface is defined as the ratio between the diffuse (G_d) and the solar global horizontal radiation (G) values for a specific time interval (Eq. 3). In the present work, the diffuse fraction (DF) value is defined in daily frequency.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor:6.887
Volume 6 Issue I, January 2018- Available at www.ijraset.com

$$DF = \frac{G_d}{G} \quad \text{Eq. 3}$$

C. Similarity criteria

As previously explained, the reference meteorological station used for diffuse radiation component experimental measurement, $D_{EOAS,}$ is located 84 km far from the PV array under study. To avoid distance-associated data sources mismatches, a **similarity** criterion between both stations, based on three conditions is defined (see Table 2). For the present analysis, only data verifying similarity criteria are considered. Figure 2 shows the radiation plot for a day fulfilling the 3 conditions.

TABLE 2. Similarity criterion conditions

Condition 1:	Absolute difference between average global radiation values along the same day between both locations is less than or equal to 50 W/m^2 (Eq. 4). $\Delta < G > = < G_{EOAS} > - < G_{Norv} > \leq \pm 50\ W/m^2$ Eq. 4
Condition 2:	The difference between daily sum of global radiation between locations for the same day is less than or equal to 15% (Eq. 5). $\Delta\left(\sum_n G\right) = 100 \cdot \frac{\sum_n G_{Norv} - \sum_n G_{EOAS}}{\sum_n G_{Norv}} \leq 15\%$ Eq. 5
Condition 3:	The global radiation spectra along the same day is similar for both locations.

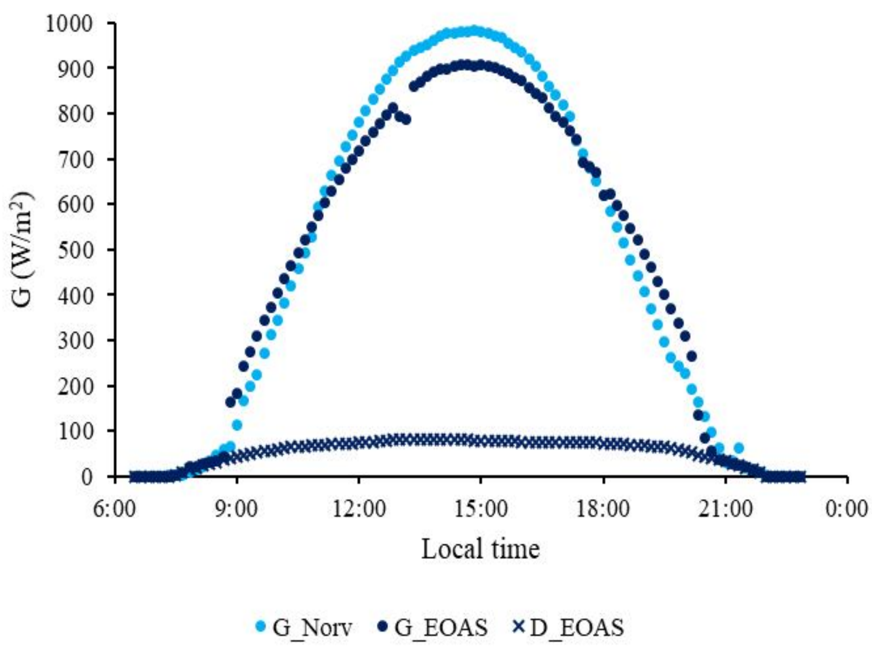

Figure 2. Example of day fulfilling Condition 1 (Δ<G>=10 W/m^2), Condition 2 ($\Delta(\Sigma G)$=2%) and Condition 3

IV. RESULTS

The initial assumption of this paper is how the production associated gain to a PV track system depends on the climate conditions. Because the tracker system is optimized for direct radiation component, its performance can be visualized when considering a fully sunny and an overcast day. For an overcast day, direct radiation is negligible being the diffuse the main component. Contrary, during a sunny day, the direct component is dominant [5][6].

Figure 3 shows production comparison (in terms of yield factor) for both tracker and fixed PV arrays. The behaviour during a fully sunny (Figure 3a) and an overcast day (Figure 3b) are shown separately. In the first case, with a direct radiation component higher than 90%, the solar tracker system shows a 60% higher production than the fixed array. Meanwhile, for the overcast day, where the direct component is smaller than 10%, the tracker system production is even lower than the fixed array (-1.3% less production).

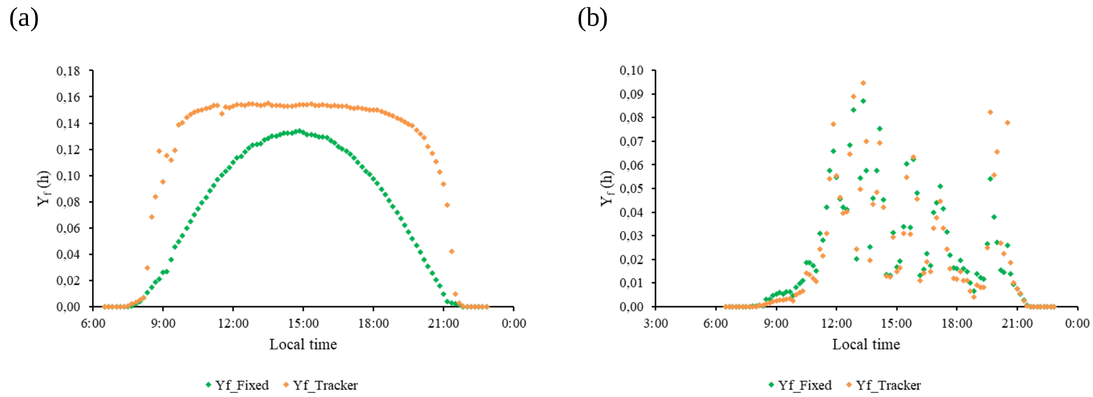

Figure 3. Yield factor for a fully sunny day (a) and an overcast one (b)

In conclusion, the solar tracker production gain decreases in comparison with the fixed tilt array as the diffuse fraction increases. In the following sections, the dependence shape will be carefully analysed.

A. Track system performance dependence

The performance ratio of each considered PV array (Fixed and Tracker) has been analysed on an experimental data sample covering the complete diffuse fraction range. Aiming to assess the PR gain with the daily average diffuse fraction, only days fulfilling the similarity criteria will be used.

To provide an absolute and dimensionless value of a solar installation performance despite the climate conditions, the PR gain is calculated following Eq. 1. Figure 4a shows the linear tendency of DF with the PR gain (including σ and 2σ standard deviation intervals). This means that, as the weather conditions tend to be cloudy, the associated gain to the solar tracker installation decreases. The resulting linear correlation is shown in Eq. 6.

$$\Delta PR = -0.597\ DF + 0.625 \qquad \text{Eq. 6}$$

The result after Eq. 6 offers a powerful tool to primarily evaluate the suitability of installing a tracker system. Just by knowing the annual average diffuse fraction for a location, the tracker installation profitability in terms of gain can be obtained.

Besides, this experimental result makes clear the inaccuracy of previously referenced studies which stated that installing a tracker always improve the system performance. The fact of focus studies over theoretical values, simulations or not considering the climate variabilities (for example, with limited experimental data intervals) lead to overrated performance increase values not replicable under experimental usage conditions.

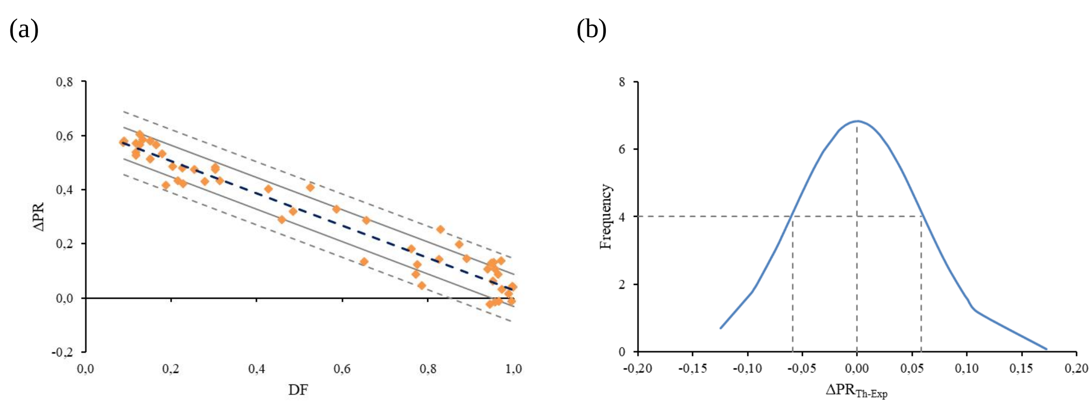

Figure 4. (a) Gain versus Diffuse Fraction for days verifying the similarity criterion
(b) Frequency distribution of theoretical and experimental gain values difference

To estimate the accuracy of the considered experimental data for the analysis its uncertainty will be analysed. For this, the experimental ΔPR data difference with respect to the linear fit theoretical values will be calculated and its difference frequency, plotted (Figure 4b).

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor:6.887
Volume 6 Issue I, January 2018- Available at www.ijraset.com

Mathematically analysing the data, a mean value of μ=-0.0001 is calculated; the most probable result is that there is no difference between experimental and theoretical value. The standard deviation leads to a result of σ=0.0585 (68.52% of values less than one standard deviation away from the mean value and 96.30% less than two standard deviation).

When analysing the Figure 4b frequency plot, a slight asymmetry appears on the right end of the distribution. This asymmetry comes after the combination of data variations due to minor diffuse fraction differences between locations (Norvento and EOAS) and the measurement errors. The sum of both effects lead to an experimental result lightly worse than theoretically expected. Anyhow, 96% are less than two standard deviation from the mean value. Thus, the considered data associated error is admissible.

The performance ratio variation, σ(PR) (after Eq. 2), ensures the quantification of the production dependence with weather conditions. Figure 5a shows the PR deviation decrease as function of the increasing diffuse fraction (including the σ and 2σ intervals). The theoretical benefit of installing a solar tracking, when the direct component leads the global irradiation, arrives to 80%. The σ(PR) becomes even negative as diffuse fraction tends to 1, i.e., the solar tracker system performs worse than the fixed tilt array when considering overcast scenarios.

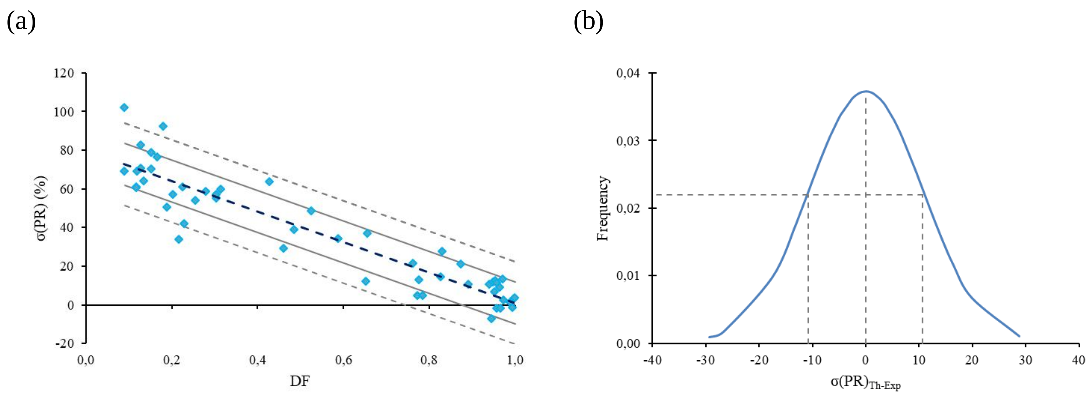

Figure 5. (a) Performance Ratio variation versus Diffuse Fraction for days verifying the similarity criterion
(b) Frequency distribution of theoretical and experimental PR variation values difference

For the uncertainty analysis, the difference of the experimental σ(PR) and the linear fit theoretical values frequency is analysed. Figure 5b shows the frequency distribution of theoretical minus experimental σ(PR) values (with σ and 2σ intervals). With a mean value of μ=-0.0002 and a standard deviation of σ=10.7034, the 72.22% of values are less than one standard deviation away from the mean, 94.44% are 2σ away and all the values lie inside the 3σ interval. It can be stated that considered values are statistically reliable.

The obtained result is independent of the climatic area as each point corresponds to the difference of production between both arrays for a given diffuse fraction. Thus, the obtained fit facilitates the profit calculation for any location or day type. The daily production radiation integral corresponds to the gain integral weighted using the diffuse fraction.

B. Tracker associated costs

After Figure 5 it can be seen that the increasing diffuse fraction values decrease the advantage of installing a solar tracker. But climate conditions are not the only parameters affecting to the solar tracker profitability. An adequate study of a tracker installation needs to take into consideration the energy consumption (both as EPBT and tracker rotor system) and the economic expenses (for the installation and maintenance costs). Following Eq. 2, Internal Rate of Return variation, σ(IRR), and Energy Payback Time variation, σ(EPBT), can be calculated as:

$$\sigma(\mathrm{IRR}) = 100 \cdot \left[\left(\frac{C_{Track}}{C_{Fixed}}\frac{E_{Fixed}^{Out}}{E_{Track}^{Out}} - 1\right)\right] (\%) \quad \text{Eq. 7}$$

$$\sigma(\mathrm{EPBT}) = 100 \cdot \left[\left(\frac{E_{Track}^{M}}{E_{Fixed}^{M}}\frac{E_{Fixed}^{Out}}{E_{Track}^{Out}} - 1\right)\right] (\%) \quad \text{Eq. 8}$$

where, with i as the sub-index for track or fixed PV system, C_i is the installation cost, E^M the required energy for manufacturing and E^{Out} the energy production for each array.

Table2 contains some hypothesis obtained from the bibliography and assumed during the analysis. Results are considered for polycrystalline silicon solar panels, assuming a 25 years lifespan for the installations. Figure 6 shows the linear dependence of the Internal Rate of Return and the Energy Payback Time variations separately (both with σ and 2σ intervals).

TABLE2: Hypothesis assumed for σ(IRR) and σ(EPBT) calculations

Solar tracker	Hypothesis
Energy consumption	Around 50 Wh (for a 1 kW solar array) [7]
Installation and maintenance associated costs	50% is generally assumed [8][9][10]
Energy Payback Time	Twice the EPBT for the fixed tilt system [9][11]

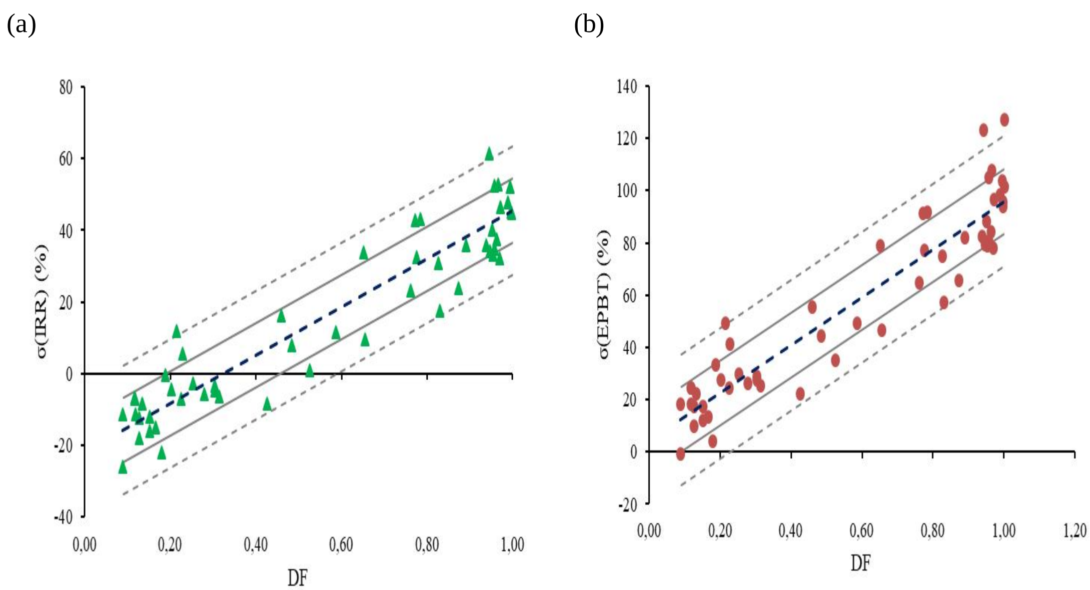

Figure 6. Linear fit (with σ and 2σ intervals) for Internal Rate of Return (a) and Energy Payback Time (b) variation

Finally, the overall costs are evaluated in terms of the total cost (hereafter**, Cost variation**), as the direct convolution of the terms obtained for IRR and EPBT, σ(CV) (Eq. 9).

$$\sigma(CV) = \sigma(IRR) \otimes \sigma(EPBT) \quad \text{Eq. 9}$$

The linearfit for the σ(CV) is plotted in Figure 7 (with positive slope). The 68.52% of the values belong to the ±σ interval. For the ±2σ, the value is 94.44% and all the values are inside the 3σ band. This ensures the results validity.

The intersection region between the σ(PR) and σ(CV) curves provides the minimum diffuse fraction limits to ensure the solar tracker installation. Figure 7 shows the intersection region of Performance Ratio and Total Costs variations for 3 different working reliability ranges.

After Figure 7the profitability maximum diffuse fraction value can be visualized, including the σ and 2σ interval cuts. Table3 shows the maximum DF value to ensure a net gain when installing a solar tracker.

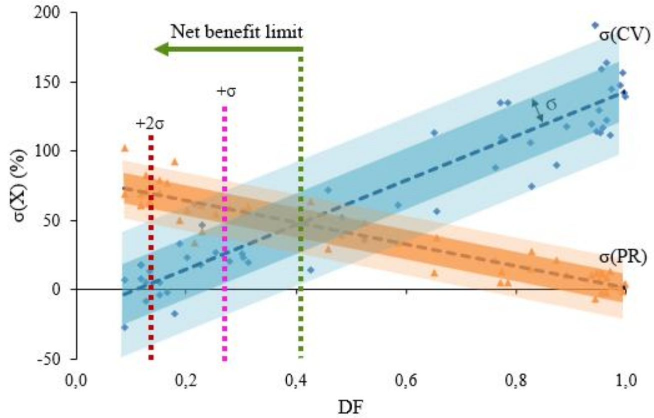

Figure 7: Performance Ratio and Cost variation versus diffuse fraction

TABLE3. Diffuse fraction limits for solar tracker net gain

	Limit DF value for net gain	Reliability level
Interaction point	0.41	
σ criteria	0.27	49.48%
2σ criteria	0.14	89.18%

With a theoretical maximum performance ratio gain of a 60%, the real value is almost a 20% minor than when these diminishments are not considered. It must be noticed that this gain is calculated for a solar tracker system versus horizontally-fixed tilt array positioning. The zero-tilt is way far than the optimal tilt for the location. Thus, the PR gain will decrease to lower values if considering tracker versus optimal tilt production. In the high diffuse limit, both scenarios tend to be equal, while the relevance of the associated costs is more relevant as the diffuse fraction decreases.

Thus, it can be stated that the installation of a solar tracker system must be carefully assessed prior to design an installation. Its suitability depends on the diffuse fraction, which can be easily gathered from different sources or, if available, from direct measurements on location. These results contradict several previous results, mainly based on extremely short direct measurement periods or on direct use of simulation programs.

The relevance of the diffuse fraction as a key parameter for the solar tracker installation profitability is assessed also.

V. CONCLUSIONS

One of the crucial problems in the design of grid-connected PV systems is decide on fixed tilt or tracker PV design. In this paper, the performance of a PV solar tracking system in terms of power production and associated overall costs is evaluated. To avoid theoretical model dependence, the full analysis is developed using an experimental setup performed by two identical PV arrays, one in fixed position (horizontal) and other with a 2-axis solar tracker. Both PV systems are part of a grid-connected installation. Solar radiation characteristics, both global and diffuse, are experimentally measured independently. The full analysis is performed using normalized variables to ensure global validity.

After a data sample selection dedicated to ensure an unbiased dataset, the PV arrays power production is analysed in terms of Performance Ratio. A clear linear correlation between Performance Ratio gain and Diffuse Fraction is fitted (Eq. 6). This relation is useful to determine the 2-axis tracker installation suitability. Thus, intending to decide in terms of energy production for a given location, the gain can be calculated with no more than the average annual diffuse fraction using the given equation.

The overall associated cost is evaluated as a convolution of the Internal Rate of Return and the Energy Payback Time. Both bibliographic and observation data are used on the analysis. As in the previous case, a clear linear correlation with diffuse fraction was observed (Figure 7).

Finally, the limit diffuse fraction value to achieve net gain installing a tracker is computed as the intersection point between the corresponding production and the overall associated cost fitted curves. The results analysis leads to net gain for a tracker system with respect to a fix tilt only if the annual diffuse fraction is 0.41 at most. Applying sigma criteria to ensure reliability, the net gain

DF limits became even more demanding. In fact, a 2sigma criteria, which ensure a 99% reliability, fix the DF limits for net gain on a 14% of annual diffuse radiation component.

Considering these results, the solar tracker suitability is demonstrated to be location-dependent as climate (via the diffuse fraction) plays a key role on its profitability. In further analysis, this diffuse fraction values dependence with location climates will be assessed. Also, a comparison of the experimental values with theoretical models can be considered.

VI. ACKNOWLEDGMENT

Theauthors would like to thank Norvento S.A. Company for their support and data sharing.

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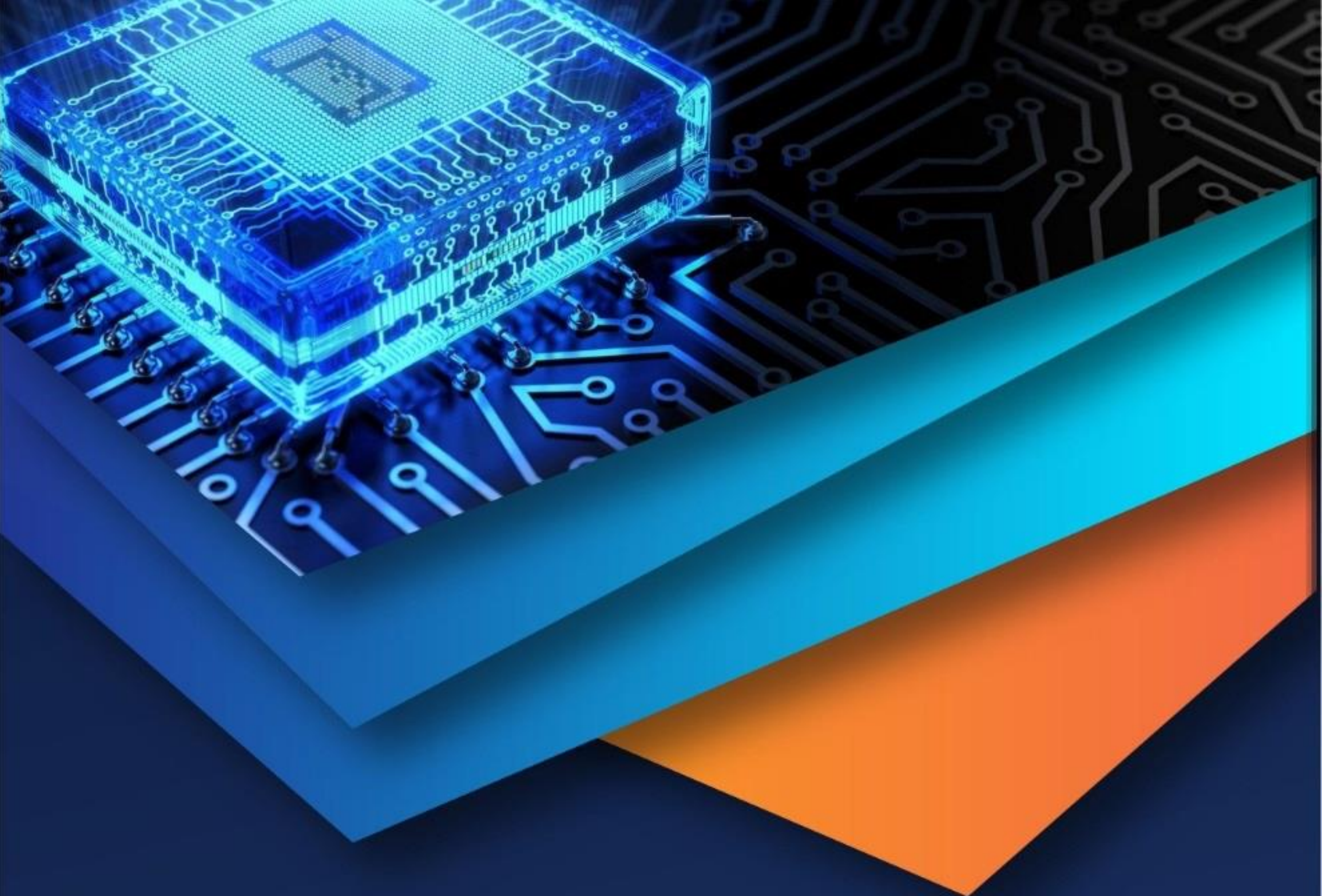

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