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Online application of the periodic linear regression method for daily monitoring of photovoltaic systems performance

Aplicação online do método de regressão linear periódica para monitoramento diário do desempenho de sistemas fotovoltaicos

Aplicación online del método de regresión lineal periódica para el seguimiento diario del rendimiento de los sistemas fotovoltaicos

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Abstract

This paper presents an analysis of the performance of photovoltaic (PV) systems using daily applications of the periodic linear regression method to the performance indicators Final Yield (Y_F) and Reference Yield (Y_R). The research was conducted on PV systems installed on rooftops and ground at the Federal Institute of Education, Science, and Technology of Goiás (IFG), Itumbiara Campus, from July 2022 to August 2023. The Energy Monitoring and Management Software (SMGE) was developed to calculate the performance indicators and

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perform linear regression to analyze the performance of the systems. The results demonstrate that the efficiency of the systems can be monitored by analyzing variations in the slopes of the linear regression lines. An increase in energy conversion efficiency was observed following the cleaning of the PV panels, as reflected in significant changes in the regression slopes. Additionally, natural events, such as rainfall, positively impacted system efficiency. These findings highlight the importance of proper maintenance of PV panels, whether through scheduled cleaning or natural events like rain.

Keywords: Photovoltaic Generation. Monitoring System. Electric Energy Management. Performance Indicator. Energy Performance.

Resumo

Este trabalho apresenta a análise do desempenho de sistemas fotovoltaicos (FV) utilizando a aplicação diária do método de regressão linear periódica aos índices de mérito: Produtividade Final (Y_F) e Produtividade de Referência (Y_R). O estudo foi realizado entre julho de 2022 e agosto de 2023 com base em sistemas FV instalados nos telhados e no solo do Instituto Federal de Educação, Ciência e Tecnologia de Goiás (IFG), Câmpus Itumbiara. Para realizar de forma online os cálculos dos índices de mérito e aplicar a regressão linear aos sistemas, foi desenvolvido o software de monitoramento e gestão de energia elétrica (SMGE). Os resultados obtidos indicam que a eficiência dos sistemas pode ser monitorada por meio das variações nas inclinações das linhas de regressão linear. Um aumento na eficiência da conversão de energia após a limpeza dos painéis solares foi identificado através de alterações nas inclinações das linhas regressões. Adicionalmente, eventos naturais, como chuvas, demonstraram ter um efeito positivo sobre a eficiência dos sistemas. Os resultados ressaltam a importância da manutenção adequada dos painéis solares, seja por meio de limpeza programada ou devido a eventos naturais como as chuvas.

Palavras-chave: Geração Fotovoltaica. Sistema de Monitoramento. Gestão da Energia Elétrica. Índice de Mérito. Desempenho Energético.

Resumen

Este artículo presenta un análisis del desempeño de los sistemas fotovoltaicos (PV) mediante aplicaciones diarias del método de regresión lineal periódica a los indicadores de desempeño Rendimiento Final (YF) y Rendimiento de Referencia (YR). La investigación se realizó en sistemas fotovoltaicos instalados en tejados y suelos del Instituto Federal de Educación, Ciencia y Tecnología de Goiás (IFG), Campus Itumbiara, de julio de 2022 a agosto de 2023. El Software de Monitoreo y Gestión de Energía (SMGE) se desarrolló para calcular los indicadores de desempeño y realizar una regresión lineal para analizar el desempeño de los sistemas. Los resultados demuestran que la eficiencia de los sistemas se puede monitorear analizando las variaciones en las pendientes de las líneas de regresión lineal. Se observó un aumento en la eficiencia de conversión de energía después de la limpieza de los paneles fotovoltaicos, como se reflejó en cambios significativos en las pendientes de regresión. Además, los eventos naturales, como las lluvias, impactaron positivamente en la eficiencia del sistema. Estos hallazgos resaltan la importancia del mantenimiento adecuado de los paneles fotovoltaicos, ya sea mediante una limpieza programada o eventos naturales como la lluvia.

Palabras clave: Generación Fotovoltaica. Sistema de Monitoreo. Gestión de Energía Eléctrica,Indicador de Desempeño. Desempeño Energético.

Introduction

The incessant search for sustainable energy alternatives has intensified in the face of the imminent risk of depletion of non-renewable energy sources and the growing recognition of climate change. In this context, photovoltaic (PV) generation emerges as a viable and promising solution, evidenced by the recent decade's exponential growth.

Recent reports, such as the "Renewable Capacity Statistics 2023" of the International Renewable Energy Agency (IRENA, 2023), reveal a substantial increase in installed PV generation capacity in the global panorama and Brazil. Worldwide installed PV generation capacity grew by approximately 22%, from 855 gigawatts in 2021 to around 1,047 gigawatts in 2022. In Brazil, this growth was even more remarkable, with a 70% increase in installed capacity, jumping from 14 gigawatts to 24 gigawatts between 2021 and 2022. These shifts illustrate the growing importance of PV generation as a fundamental source in the renewable energy matrix, both globally and nationally, dominating more than half of the expansion of renewable energy in 2022, surpassing wind and hydroelectric sources. The adoption of this form of electricity generation not only offers substantial environmental benefits due to its low impact but also contributes significantly to the economy and, importantly, to the creation of new jobs, inspiring and motivating the workforce.

According to the National Energy Balance (EPE, 2023), renewable sources hold a share of approximately 88% of Brazil's domestic electricity supply, indicating the robustness of national production in addition to imports, which are predominantly of renewable origin. The Brazilian electricity matrix, with a strong presence of renewable sources, is led by hydropower, which supplies 53.4% of the domestic supply. Considering imports, mainly from the Itaipu plant, this percentage rises to almost 57%. Despite representing only 2.47% of the energy generated in the country, PV generation demonstrates an accelerated growth trajectory, which signals an increase in its participation in the energy matrix in the coming years.

Zilles *et al*. (2012) emphasize that photovoltaic cells and other electricity generation technologies cannot fully convert incident energy into electricity. These limitations are due to current technological challenges and the losses occurring during the conversion process. Therefore, it is crucial for professionals in the energy industry to understand and apply specific performance indicators to analyze the energy balance associated with photovoltaic conversion systems, underscoring the necessity of their role in the industry.

Each photovoltaic installation has specific attributes that change according to the installed power, energy generated, and the technologies used in its construction. These characteristics act as parameters to check the system's performance.

Performance indicators, which represent metrics to characterize equipment, systems, or technologies according to their efficiency in energy conversion, can assess PV systems' performance. Using these indexes, it becomes possible to continuously evaluate the operation and potential for converting solar energy into electricity.

Regardless, the analysis through these indexes can detect deficiencies in the system, making it possible to prevent economic losses resulting from malfunction and consequent low performance. Efficient monitoring can detect such issues promptly, contributing to monitored systems achieving higher productive performance than those without such monitoring (Woyte *et al*., 2014).

In this scenario, online monitoring using evaluation methods for PV systems, such as performance indicators, becomes a necessary tool to evaluate the efficiency of installed systems. This paper aims to contribute to this field of study, proposing an analysis of the application of the periodic linear regression method to the following performance indicators: Final Yield (Y_F) and Reference Yield (Y_R). As a case study, PV systems installed at the Federal Institute of Goiás (IFG), Itumbiara Campus, were used. The analysis is conducted through real-time monitoring of weather conditions and power generation, enabling the evaluation of the operation of the systems online. When meteorological data were not immediately available, the analysis was conducted based on historical information collected and stored by the Brazilian National Institute of Meteorology (INMET) weather station.

Methodology

The International Electrotechnical Commission (IEC) standardizes the performance indicators related to the performance of grid-connected PV systems (IEC, 2017). The Energy Monitoring and Management Software, or SMGE, was developed to calculate the performance indicators and apply the periodic linear regression method. The PV systems under study are installed at the IFG Itumbiara Campus, with one system on the rooftop and one on the ground. The characteristics of PV systems are presented in Tables 1 and Table 2.

Table 1

Characteristics of the PV System

Location	Number of Modules	Module Power [Wp]	Inverter Nominal Power [kW]	Array orientation[º]	Array inclination [º]
Rooftop	80	270	20	50 West	07
Ground	144	325	40	0 North	18

Table 2

Model of Inverters and PV Panels

Location	Inverter Model	Panel Model
Rooftop	ABB TRIO-20.0-TL-OUTD	Trina Solar - TSM-270-PD05.08 270Wp
Ground	WEG SIW500H - ST040	GCL P6/72 325W

The meteorological data used were obtained from the weather station installed on campus. It is equipped with a first-class digital pyranometer SR15-D2A2 and a HOBO RX3000 data logger manufactured by Onset, which provides access to sensor data via the internet.

2.1 Performance Indicators

The system's implemented indicators include yield reference, final yield, and performance ratio. The calculated performance indicators are described in the IEA-PVPS report (Woyte *et al*., 2014).

The Reference Yield (Y_R) represents the theoretical energy of a specific location over a certain period, calculated as the ratio between the solar irradiation on the inclined plane of the PV panel (Wh/m^2) (G_I) and reference irradiation (H_R) of the PV system (1,000 W/m²). Thus, Y_R refers to the number of hours of solar irradiation, expressed in units of kWh/m^2, and calculated using Equation (1).

$$Y_R = \frac{G_I}{H_R} \qquad (1)$$

where:

Y_R = reference yield (Wh/W)

G_I = solar irradiation on the inclined plane of the photovoltaic panel (Wh/m²)

H_R = reference irradiance (1,000 W/m²)

The Final Yield (Y_F) indicates the number of hours per day the PV system must operate at its nominal power to produce the same amount of energy injected into the grid. This metric also reflects the energy produced over a specific period, expressed in kilowatt-hours (kWh) per installed kilowatt-peak (kWp). Y_F allows the standardization of energy production relative to the system's size or installed capacity, enabling the comparison of PV system of different sizes or capacities. The calculation of the Y_F is performed using Equation (2).

$$Y_F = \frac{E_{CA}}{P_{PVnom}} \qquad (2)$$

where:

Y_F = Final Yield (Wh/W)

E_{CA} = Power at the inverter output (kWh)

P_{PVnom} = Nominal installed power (kWp)

The Performance Ratio (PR) indicates the system's capacity to convert available solar energy into electricity. It is calculated by dividing the Final Yield (Y_F) by the Reference Yield (Y_R) (Ortega *et al.*, 2017; Haibaoui *et al.*, 2017). Moreover, it allows for comparing systems installed in different locations and conditions. It is calculated using Equation (3).

$$PR = \frac{Y_F}{Y_R}.100 \qquad (3)$$

where:

PR = Performance Ratio (%)
Y_F = Final Yield (Wh/W)
Y_R = Reference Yield (Wh/W)

2.2 Periodic Linear Regression Method

The "System Performance" is based on the application of the periodic linear regression method to the performance indicators Final Yield (Y_F) and Reference Yield (Y_R). This method was first published by Woyte *et al*. (2013) and was developed as part of the IEA-PVPS report (Woyte *et al*., 2014). According to Woyte *et al*. (2013), the method is based on simplified physical relationships between two variables, and these physical relationships can be approximated as a straight line using linear regression. In practical implementation, this connection can be observed periodically by comparing recent regression lines with historical data or by identifying trends or sudden changes.

The system Performance method plays a key role in evaluating the performance of grid-connected PV systems. It does so by comparing the Final Yield (Y_F) and the Reference Yield (Y_R), which represent the overall energy conversion efficiency of the system. This comparison is established by monitoring two variables: the power delivered to the grid and the solar irradiation in the plane of the panels (Woyte *et al*., 2014).

PV systems can be considered linear, meaning Y_F is proportional to Y_R. When plotted on a scatter plot, this relationship can be represented by a straight line through the origin. This line is determined by linear regression of the sample data.

The slope of the resulting line serves as an estimate of the average performance of the PV system. Specifically, it indicates how the actual yield of the system compares with the reference yield of solar irradiation. The System Performance can be described analytically as Equation (4), where $\overline{pr}$ is the slope of the linear regression line and reflects the average performance ratio of all samples used to calculate the line. Here, y_f and y_r are represented with lowercase letters as they refer to averages calculated over a short recording period or instantaneous values.

$$y_f = \overline{pr}.y_r \quad (4)$$

where:

y_f = Instantaneous Final Yield (Wh/W)

$\overline{pr}$ =Average performance ratio (%)

y_r = Instantaneous Reference Yield (Wh/W)

The periodic linear regression method provides several indicators that depend on the variables used and the different stages of energy conversion. According to Woyte *et al*. (2014):

> "regression lines not changing significantly over time indicate that the system properties remained constant; changing regression lines over time indicate a trend-wise change of system parameters; samples suddenly significantly deviating from the regression lines hint towards exceptional operating points; samples regularly deviating from the regression lines hint towards a design flaw".

Plotting the scatter plot with a new regression line for each week allows the identification of the slope and, consequently, the mean of the Performance Ratio per week. Therefore, sudden changes from one week to the next, as well as significant trends, are indicated by the change in slope (Woyte *et al*., 2014). In this study, the periodic linear regression method will be used to calculate daily regression lines, integrating the measurements performed at hourly intervals, thus allowing the identification of variations between days instead of weeks.

2.3 Electrical Energy Monitoring and Management System Software - SMGE

The software was implemented as a web application with an architecture comprising three main components:

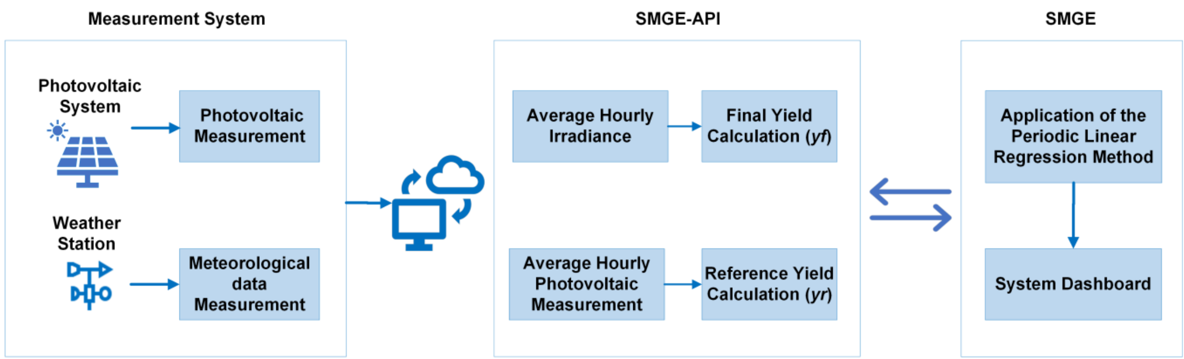
a) the SMGE user interface;
b) an Application Programming Interface (API) named SMGE-API;
c) a measurement system.

The first two components were developed using the Django framework and integrated with a PostgreSQL database. This database, designed to operate in a cloud computing environment, brings significant benefits such as greater efficiency, scalability, and robustness to the application. The cloud environment also facilitates the deployment and continuous updating of the system, ensuring greater agility in the development life cycle.

The measurement system was implemented at the IFG Itumbiara Campus to perform real-time measurements of photovoltaic generation. These measurements, transmitted via the SMGE-API, allow the system to persist the information collected in its database. User interaction with the system occurs through the SMGE web interface, which sends requests to the SMGE-API to process and fulfill user requests. Subsequently, the processed data are displayed, offering graphical visualization and analysis of energy management. Figure 1 illustrates the software architecture for the application of the periodic linear regression method.

Figure 1

Software architecture for applying the periodic linear regression method



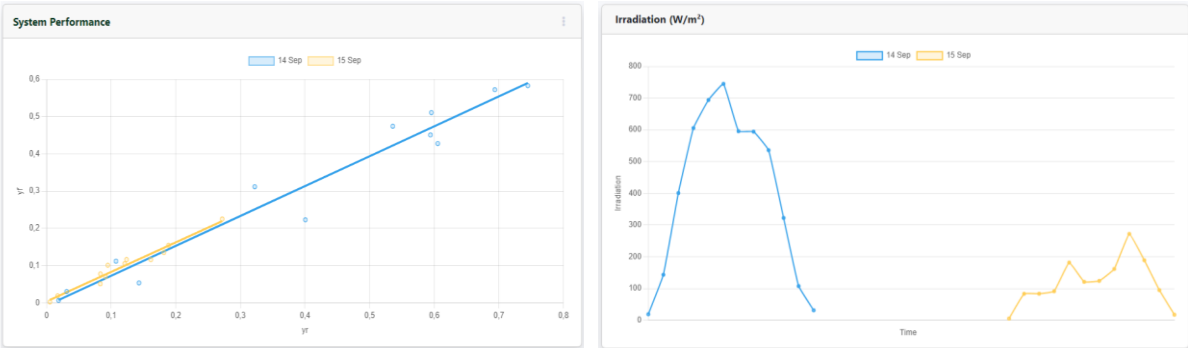
The monitoring system stores photovoltaic generation data at 5-minute intervals and weather station data at 1-minute intervals. Synchronization between the meteorological data measurements and the generation values is necessary for the practical application of the proposed methodology. The system was developed to integrate this data hourly, facilitating the generation of a dashboard for daily analysis.

The SMGE software applies the periodic linear regression method to determine the system's performance, with each regression line representing a measurement day. Figure 2 shows the scatter plot of y_f versus y_r from the ground-mounted installation on September 14th and 15th, 2022.

Using scatter plots combined with daily regression lines facilitates the perception of inclination trends, enabling continuous monitoring of fluctuations in the Performance Ratio. Even under different solar irradiation levels, if the system's capacity to convert irradiation into electrical energy remains constant, the slopes of the regression lines are expected to show similar values. Thus, sudden changes from one day to another, as well as significant trends, are indicated by the regression line's slope variation. Graphical analysis is used to highlight differences between weekdays.

Figure 2

Screenshot of the SMGE software - Measurements using hourly averages, September 14th and 15th, 2022. (a) System performance (b) Hourly irradiation.



(a) (b)

The variations in the slopes reflect the variations in the Performance Ratio (*PR*). Thus, a higher slope of the regression line, or a value of $\overline{pr}$ approaching 1, indicates that the system operates at high efficiency, converting a significant proportion of the received solar irradiation into electricity. Conversely, a slope farther from 1 may indicate inefficiencies or issues within the system. These inefficiencies may result from shading, inverter conversion losses, or other technical issues compromising the overall system.

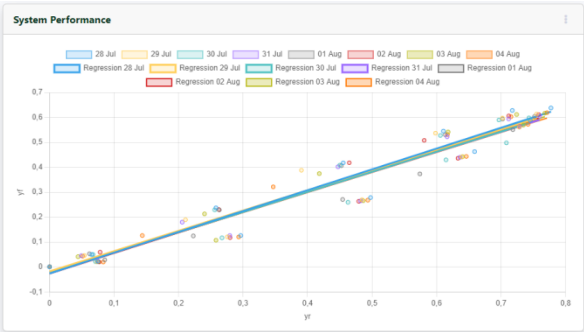
Results and Discussions

This section presents the results of the application of System Performance over the period of time between July 2022 and August 2023. The measurements are hourly averages, and each regression line represents a measurement day. The graphs illustrate the indicator variation, which includes eight plotted regression lines.

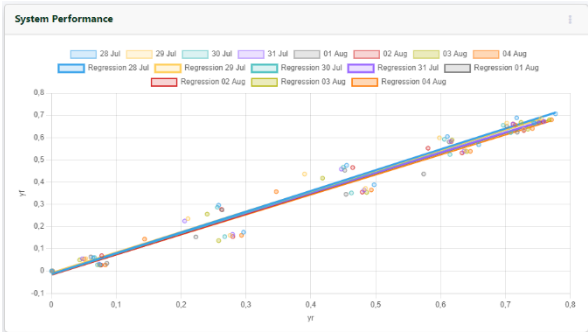
Figure 3 illustrates the behavior of the graph representing the System Performance for the rooftop and ground-mounted systems. The regression lines exhibit identical slopes, indicating regular system operation and demonstrating that the system's properties and efficiency remained constant over eight days. The observed standard deviation among the slopes of the lines was 0.03.

Figure 3

Screenshot of the SMGE software - System Performance using hourly averages, July 28th to August 04th, 2022. (a) Normal operation - rooftop system. (b) Normal operation – ground system.



(a)

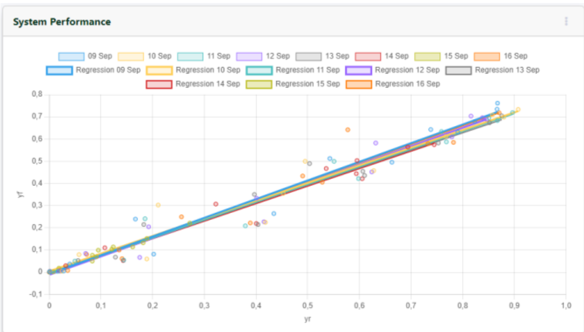


(b)

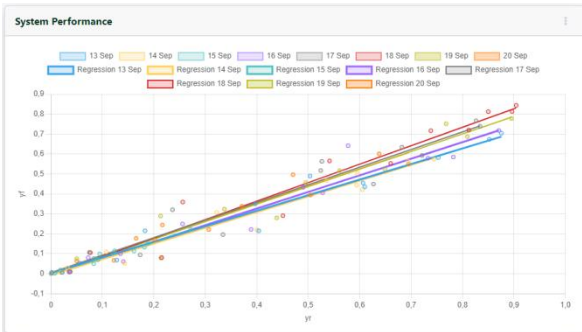
The PV system operated normally until September 17th, 2022, when the slope of one of the regression lines for the ground-mounted system increased by 12%. After this date, the new regression lines plotted showed a higher slope value. The rooftop PV system did not experience changes in the regression lines during the same period. Figure 4 illustrates this change.

Figure 4

Screenshot of the SMGE software - Ground system - System Performance. (a) Normal operation, September 9th to 16th, 2022. (b) Change in the slope of the regression lines, September 13th to 20th, 2022. (c) New slope of regression lines, September 18th to 25th, 2022.



(a)



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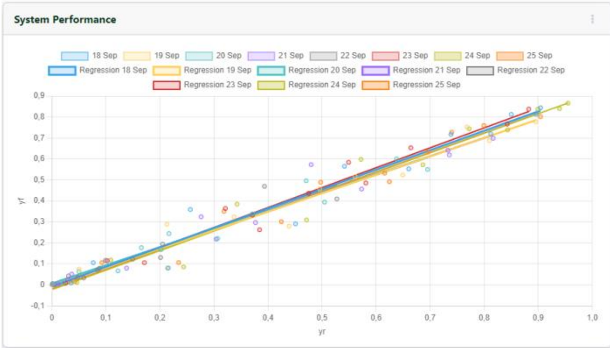


(c)

The change in the slope of the regression line occurred due to the manual cleaning of the ground-mounted PV panels on September 17th, 2022. The increase in the slope indicates an improvement in the effectiveness of the PV panels, suggesting that adverse elements, such as dust accumulation on the panels, were reducing the efficiency of electricity generation.

Table 3 presents the solar irradiation values for the analyzed period, regression line slope, and performance ratio. The average slope of the regression lines was 0.819 before the panel cleaning. After the cleaning, this slope increased to 0.924, representing a 12.8% increase in the slope of the linear regression line and the system efficiency. It is important to note that there was a 1.2% reduction in irradiation during the period.

Table 3

Average Values for Irradiation, Regression Lines, and Performance Ratio – Ground – 2022

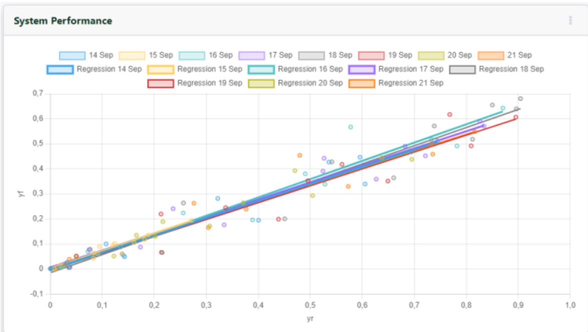
Period	Irradiation (kWh/m^2)	Slope	Performance Ratio (%)
September 09th to 16th	40.78	0.819	78%
September 18th to 25th	40.29	0.924	88%
Percentage Change	**-1.22%**	**12.82%**	**12.82%**

The *PR* values tend to approximate the slopes of the linear regression lines, although they are not identical. This difference arises from the periodic linear regression method, where each line represents a day of measurements. The daily lines identify variations between days. However, the slopes differ from the *PR* values. This difference occurs because hourly measurements capture short-term fluctuations, which may be smoothed out in daily averages of weekly charts. Thus, by utilizing hourly averages, the linear regression adjusts the line to the points that exhibit the most significant intraday variation.

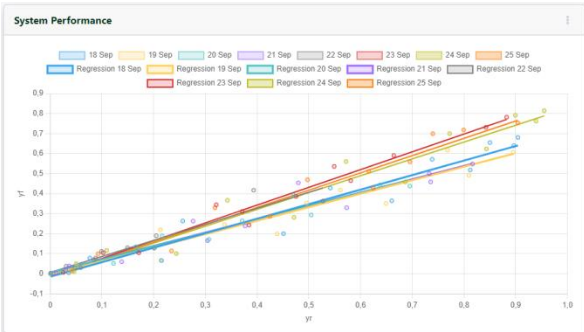
After these dates, the PV system maintained its regular operation until September 22nd, 2022. On this date, the regression lines in the rooftop system changed. In contrast, the ground system continued its regular operation. Figure 5 illustrates this transition.

Figure 5

Screenshot of the SMGE software - System Performance. (a) Rooftop - Normal operation, September 14th to 21st, 2022. (b) Rooftop - Change in slope of regression lines, September 18th to 25th, 2022. (c) Rooftop - New slope of the regression lines, September 23rd to 30th, 2022. (d) Ground - Normal operation, September 18th to 25th, 2022.



(a)



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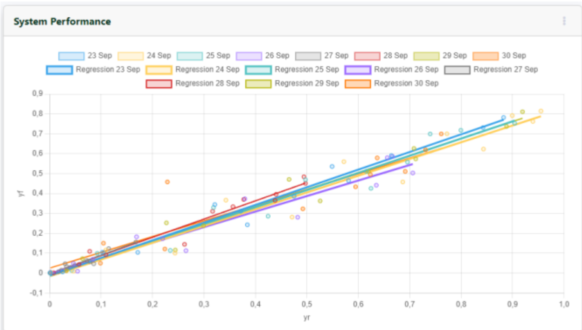
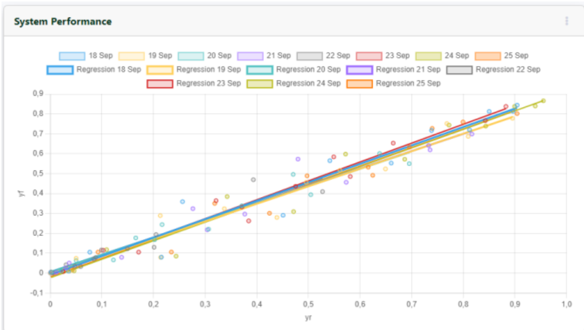


(c)



(d)

During this period, the rainy season began in the Itumbiara region. According to data from the Brazilian National Institute of Meteorology (INMET), rainfall events were recorded in the area, as illustrated in Fig. 6. On September 21st, a light rain occurred with an intensity of 0.2 mm/h at 22:00 hours. The following day, September 22nd, the rainfall was more substantial, totaling 18.6 mm, thereby ending a 106-day dry spell. This rainfall helped clean the PV panels, contributing to the observed increase in the system's efficiency after approximately three months without rain. The regression lines of the ground-mounted system showed no changes because the panels had already been cleaned on September 17th.

Figure 6

Amount Daily rainfall amount, September 18th to 25th, 2022

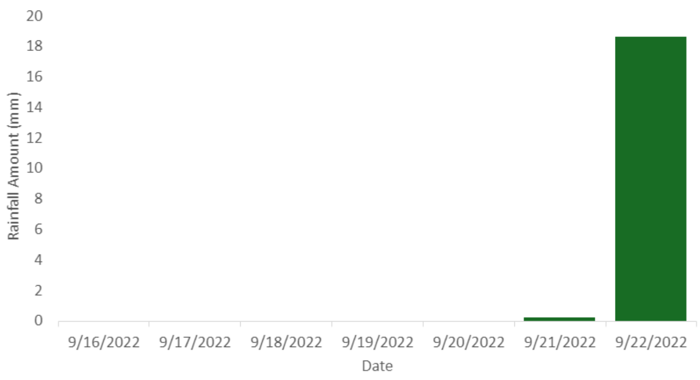


Table 4 presents data on the variation in solar irradiation, the slope of the regression line, and the Performance Ratio (*PR*) of the roof-mounted PV system. An increase of 24.31% in the slope was recorded. The calculations considered data collected over two distinct periods:

a) before the rain, from September 14th to 21st;
b) after the rain, from September 23rd to 30th, 2022.

Table 4

Average Values for Irradiation, Regression Lines, and Performance Ratio – Rooftop – 2022

Period	Irradiation (kWh/m^2)	Slope	Performance Ratio (%)
September 14th to 21st	37.17	0.691	66%
September 23rd to 30th	38.00	0.859	82%
Percentage Change	**2.23%**	**24.31%**	**24.24%**

Measurements indicate that the *PR* value of the ground-mounted PV panels increased from 78% to approximately 88% after washing. The high values can be attributed to the array orientation of the panels, positioned at 0º north direction, with a tilt angle of 18º. In the rooftop PV system, the *PR* increased from 66% to 82% after the rain-induced cleaning, indicating an improvement in efficiency.

Comparing the results obtained from cleaning the ground-mounted PV system with the results obtained after rain on the roof-mounted system, it is observed that the roof-mounted system achieved a more significant increase in efficiency. Abdeen *et al*. (2017) and Xu *et al*. (2017) emphasize that variations in the tilt angle can significantly influence the amount of dust accumulated on the panels, with smaller tilt angles leading to more dust accumulation. The rooftop PV system has an array tilt angle of 7°, which tends to accumulate more dust compared to the ground-mounted system, which has an array tilt angle of 18°, as shown in Table 1.

In 2023, the irradiation values were obtained from the INMET automatic weather station located in Itumbiara, approximately 3.5 km from the campus. This INMET station provides hourly irradiation data in kJ/m². These data are converted to kWh/m² and incorporated into the SMGE software, replacing the information from the local weather station.

On July 14th, 2023, a new change in the regression lines of both PV systems was observed, which resulted in a 9.07% increase in the slope of the lines for the ground-mounted system and a 10.73% increase for the rooftop system. According to INMET data, on July 14th, there was 8.6 millimeters of rainfall, ending a 77-day dry period. Table 5 shows these values.

Table 5

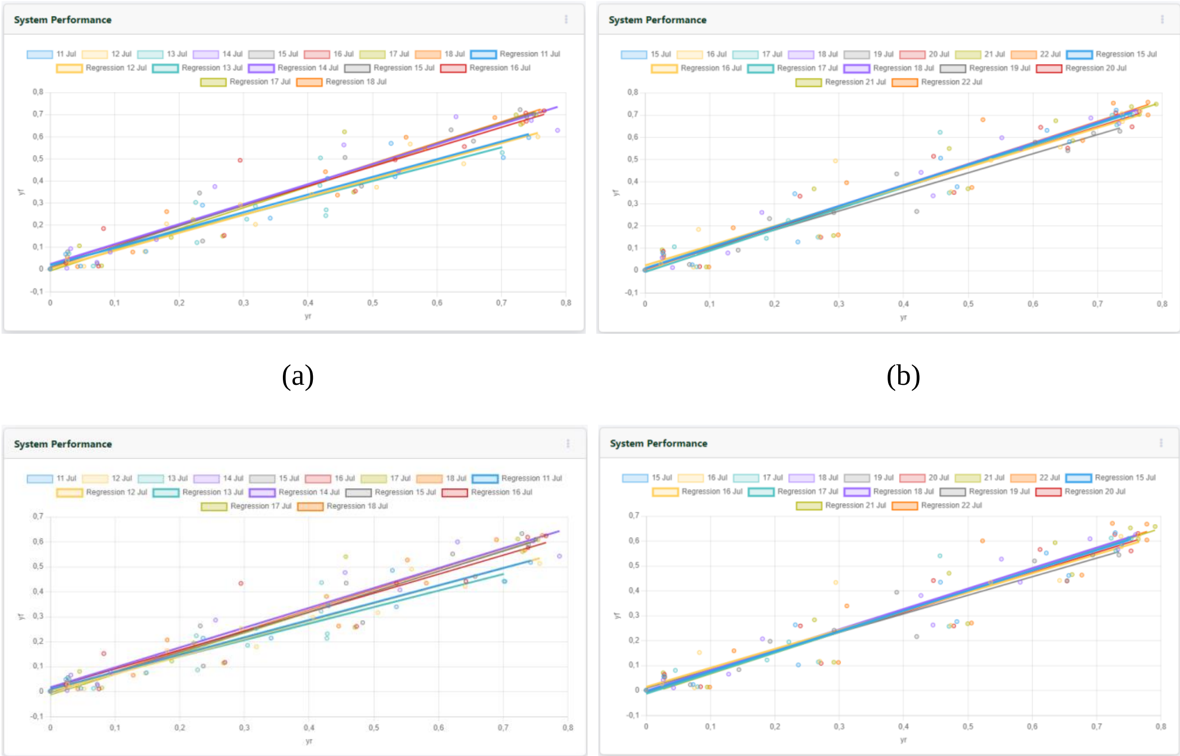
Average Values for Irradiation, Regression Lines, and Performance Ratio – July 2023

Period	Irradiation (kWh/m^2)	Slope		Performance Ratio (%)	
		Rooftop	Ground	Rooftop	Ground
July 06th to 13th	35.16	0.755	0.871	70%	81%
July 15th to 22nd	37.55	0.836	0.950	78%	89%
Percentage Change	**6.80%**	**10.73%**	**9.07%**	**11.43%**	**9.88%**

The PV panels were cleaned by rain in 2022 and 2023. In the rooftop system, there was a 24.31% increase in the slope of the regression lines in 2022, while in 2023, the increase was 10.73%. This difference is because the dry period in 2023 was 29 days shorter than in 2022. Additionally, during this period, three days of low-intensity rain, less than 1 mm per day, contributed to reduced dust accumulation on the panels. The rainfall on July 14th, 2023, was 8.6 mm, whereas the rainfall on September 22nd, 2022, was 18.6 mm, resulting in a more effective cleaning of the PV panels. The system did not show changes in the regression lines due to rains with intensities below 1 mm. Figure 7 displays the software screenshots for the analyzed period.

Figure 7

Screenshot of the SMGE software - System Performance - 2023. (a) Ground - Change in the slope of the regression lines, July 11th to 18th. (b) Ground - New slope of the regression lines, July 15th to 22nd. (c) Rooftop - Change in the slope of the regression lines, July 11th to 18th. (d) Rooftop - New slope of regression lines, July 15th to 22nd.



(a) (b)

(c) (d)

Conclusion

The development of an online tool to identify variations in system efficiency between days is adequate. The daily application of the periodic linear regression method enabled the rapid identification of sudden changes in system performance. The software detected significant variations in the slopes of the regression lines. The first event occurred following the manual cleaning of the panels, while the second and third events resulted from natural cleaning by rainfall in the years 2022 and 2023. These variations were characterized by a positive increase in the slope of the regression lines, and no failures that could negatively impact these slopes occurred in this period.

Comparing the results obtained after cleaning the panels of the ground-mounted PV system with the effects of rain on the rooftop PV system in 2022, there was an increase in the

Performance Ratio (*PR*) of the ground system from 78% to 88%, indicating a 12.82% improvement in efficiency. The *PR* increased from 66% to 82% in the roof-mounted system, representing a 24.24% improvement. The cleaning results are more significant for the roof-mounted system due to the 7º tilt angle of the panels, which tends to accumulate more dust when compared with the ground-mounted system, which has a tilt angle of 18º.

In 2023, rainfall cleaning increased the Performance Ratio (*PR*) of the roof-mounted PV system from 70% to 78%. The *PR* increased from 81% to 89% for the ground-mounted system. The high efficiency of the ground-mounted system is due to its specific characteristics, such as the azimuth of the panels positioned at 0º towards the north with an 18° tilt angle.

The results of this paper underscore the practical implications of regular maintenance for the efficiency of PV systems. The data in Table 3 show that energy conversion efficiency increased after the panels were cleaned, even with reduced solar irradiation. Thus, scheduled cleaning and cleaning resulting from natural events, such as rain, are essential to maintain the system's operational efficiency.

Finally, it was possible to observe that daily linear regression lines allowed for the rapid identification of variations in efficiency but caused a difference between the slope values and the *PR*. This strategy is due to hourly averages for daily regression lines capturing short-term measurement fluctuations. These fluctuations can be smoothed out by performing weekly regression lines.

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