Performance Study of A Photovoltaic System Operating on the Southeastern Coast of Brazil

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***Abstract*—The photovoltaic sector is expanding fast and reached 23.9 GW of installed power in Brazil in the first months of 2023 (occupying the 2^{nd} place in installed capacity in the Brazilian electricity mix). Such a scenario makes PV power generation a resource for regional development and socioeconomic opportunities for metropolitan regions with a high national economy share and population density. The present work investigated the PV system's performance in a coastal area subject to high atmospheric turbidity due to cargo transportation emissions and port operational procedures. The PV system operates in Santos/SP at the rooftop of the Federal University of São Paulo building, close to Latin America's largest port in trade operations. Santos is a medium-sized city with dry winters and hot, humid summers. The performance assessment evaluated the typical consolidated metrics in the worldwide PV market, including performance ratio, capacity factor, final yields and system losses, obtained based on environmental and operational data acquired between October/2020 and September/2021. The results showed that the PV performance presented a high performance ratio (around 85%) and low system losses despite the expected influence of local atmospheric conditions related to the nearby polluting economic activities. The PV system performed better than the predicted numerical simulation tool based on the solar energy resource estimated for its location. Two factors have affected the research: the reduced economic activity linked to the COVID-19 pandemic and the extended dry season in 2020-2021.**

Link to graphical and video abstracts, and to code: https://latamt.ieeer9.org/index.php/transactions/article/view/8256

***Index Terms*—Photovoltaic power system, Performance parameters, Coastal region, Distributed power generation.**

I. Introduction

Brazil is in tropical South America, receiving a high downward surface solar irradiance all year long [1]. Taking advantage of the huge solar resource and price reduction of PV technologies, the share of photovoltaic (PV) power generation in the electricity mix has increased rapidly in recent years, reaching 23,900 MW of installed capacity in January 2023 [2]. Regulatory agencies and energy entrepreneurs expected to reach such a high share of PV power generation a few years later. Brazil's Decennial Energy Plan (PDE) indicates that PV solar power would reach around 26 GW) on distributed generation (DGPV) in 2031, taking into consideration the reference scenario established by the EPE [3]. Such a planned target will probably be exceeded a few years ahead of schedule.

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Marion *et al.* [4] highlight the influence of weather conditions and the importance of accurate and consistent solar PV system performance assessments to support the continued technological development of the PV industry, system integrators and customers. Adamarola e Vagnes [5] argue that monitoring the performance of PV systems in operational conditions is the best way to evaluate the prospect of PV power production. Lima *et al.* [6] mention that many studies evaluate the performance of PV systems installed in Europe and worldwide [5], [7]–[12]. However, Brazil and Latin America are underrepresented in such studies, although they have immense potential for use in diverse climate conditions, particularly the tropical climate little investigated abroad. [13]–[16]. The Table I briefly describes an overview of some relevant worldwide studies investigating the operational and environmental influence on the PV systems performance.

Most DGPV systems operate in urban areas of large and medium-sized Brazilian cities exposed to environmental conditions very different from the standard condition assumed by the PV modules certification. Bet [17] showed that atmospheric aerosols and water vapor in urban areas affect the spectral response of PV modules. Polo *et al.* [18] showed that the spectral factor of PV modules is highly correlated with aerosol optical depth and water vapor in the atmosphere, especially for thin-film technologies.

Pinto *et al.* [15] evaluated the performance of small-scale PV systems in the Brazilian Northeast under different weather conditions based on generated energy measurements and merit indices such as final yield (Y_f) and capacity factor (CF). The authors obtained monthly yields (Y_f) above 120 kWh/kWp, and CF of around 17%. Morais *et al.* [14] evaluated the performance of the first year of operation of a PV system running in Teresina. The authors obtained capacity factor indexes of 17%, annual yield around 1500 kWh/kWp, and performance rate (PR) around 74%. The authors pointed out the low economic viability due to the specific aspects regarding the local conditions.

This work evaluated the performance of a PV system running in Santos under a typical coastal environment and climate of the Southeastern Brazilian region. The PV system operates near Latin America's largest port and regional chemical industry complex. The key research contribution concerns knowledge advancing on the PV system performance operating under conditions of a tropical medium-sized coastal city with economic activities that deliver high aerosols emissions into the atmosphere [19], [20] with a possible impact on PV system performance in the urban area due to losses related to spectral response and soiling linked to the aerosol optical depth influence.

II. Methodology

A. Experimental Setup

Santos is a coastal city with around 400 thousand inhabitants. Its climate regime is humid tropical with high mean temperatures (above 27°C in austral summer), and warm winters [22]. According to the Brazilian Solar Energy Atlas [1], the annual mean of global horizontal solar irradiation (GHI) is around 4,200 $Wh/m^2 \cdot day$, with a maximum value of up to 5,400 $Wh/m^2 \cdot day$ in February; and a minimum in June about 2,900 $Wh/m^2 \cdot day$. The region's main economic activities include trade sectors related to the largest port in Latin America, cargo transport, tourism, and the service sector. In addition, Santos is close to São Paulo's primary petrochemical industrial zone. These intense economic activities induce significant emissions of particulate matter into the atmosphere.

The photovoltaic system is at the rooftop of the Mariângela Duarte Building of the Federal University of São Paulo (see Fig. 1). The photovoltaic system comprises four polycrystalline silicon modules (p-Si) of 330 W_p, model AS-6P, produced by Amerisolar. The photovoltaic modules are installed facing geographic north and tilted at 22.8°. The power system is connected to the grid and comprises a 1.5 kW inverter, model 1500-SS, manufactured by PHB. The PHB Logger Pro stores the PV system data, and a class A pyranometer, model CMP11 from Kipp & Zonen, acquires downward surface solar irradiance data on the tilted plane of the PV system.

B. Database

The database used to evaluate the performance of the power generation system includes the following quantities:

- the rated voltage (V_{mp}) and rated current of the PV array (I_{mp});
- AC voltage (V_{AC}), AC current (I_{AC}), and AC power at the inverter output (P_{AC});
- generated energy (E_{AC});
- solar irradiance data on the tilted plane of the PV array;
- local primary meteorological data acquired by an automated weather station next to the PV system;
- meteorological data acquired nearby the PV system in QUALAR (Air Quality) network sites in Santos [23];
- aerosol concentration data (MP_{10} and $MP_{2.5}$) also acquired nearby the PV system in QUALAR (Air Quality) network sites in Santos [23]. Coarse atmospheric particulates (MP_{10}) have an average aerodynamic diameter range of 2.5 to 10 μm, and fine particulates ($MP_{2.5}$) are smaller than 2.5 μm.

The meteorological database comprises air temperature, relative humidity, downward surface global horizontal irradiance, and wind speed, stored at a time resolution of 10 minutes [23]. The database reliability was evaluated based on a quality control procedure similar to that used in the SONDA (National Data Acquisition applied to the energy sector) network operated by the National Institute for Space Research (INPE) [24].

C. Metrics for Performance Evaluation

Table II lists the parameters used for the performance evaluation as defined by the International Energy Agency [25]. The same performance metrics were used by [26]–[29] to compare the PV power systems with different configurations, designs, and conversion technologies operating worldwide. The array yield (Y_A) is defined as the ratio between the DC energy output (E_{DC}) and the nominal power of the PV system (P_0) [30]. Thus, Y_A represents the equivalent time in which the PV arrays would have operated at nominal power to generate the produced energy [31]. The system or final yield (Y_f) evaluates the ratio between the AC energy output (E_{AC}) and P_0 of the PV system. It can be understood as the number of hours the system has operated at full power. The reference yield (Y_r) compares the solar irradiation reaching the module's surface (H_I) with the reference global solar irradiance (G_{STC}) as defined at IEC 61538 [32].

The performance ratio (PR) is frequently used to compare the PV system's performance based on the ratio of Y_f and Y_r. It is independent of solar irradiance on the PV module and considers optical and radiative losses (pre-conversion), inverter losses, and thermal and electrical losses. Therefore, PR is a helpful performance metric throughout the system's operation. For example, it can help identify the causes of yield losses in the event of deterioration. Finally, the capacity factor (CF) parameter measures the ratio between the actual and maximum possible electricity output [33].

D. Performance Comparison with other PV Systems

In this study, we compared the 1-year performance metrics from the UNIFESP's PV system with outcomes achieved by other studies prepared using PV systems based on p-Si technology:

- 1-year operational data from two PV systems operating in the - Aratiba – RS and Itiquira – MT [34];
- 2-year data from a PV system operating in Northeastern Brazilian coast (Natal - RN) based on data acquired in 2014-2015 [16];
- and 1-year operational data from two coastal locations abroad - Delft/Nederlands and Stellenbosch/South Africa [35]–[37].

According to the published studies, all the systems were attended to by the qualified technical team to run the operational procedures for high performance.

The Itiquira PV system is located at the coordinates 17°S, 54°W, in the Center-West region of Brazil. Itiquira, according to the Köppen climate classification, is characterized by an Aw - tropical climate, with a dry winter and a rainy season from November to April. The Aratiba's PV system is located at coordinates 27°S, 52°W, in the southern region of Brazil, characterized by a Cfa - subtropical climate with hot summers. The Cfa climate has dry summer with temperatures above 22°C. The Natal's PV system is located at 6°S, 35°W. According to the Köppen climate classification, the Natal's climate is Aw, with an average temperature around 26°C, presenting low variability throughout the year. Summer season is hot, but the breeze from the Atlantic Ocean makes the thermal

TABLE I
RECENT STUDIES ON THE PERFORMANCE EVALUATION OF PV SYSTEMS IN DISTRIBUTED GENERATION

Authors	Performance parameters [1]	Study region	Data timeframe	Key comments
Marion et al. [4]	Y_f, Y_r, PR and PVUSA ratings	NREL PV Systems in USA territory	12 months	Y_f shows the most significant variability related to the climate conditions, and PR exhibits influence from temperature with smaller intensity in summer than winter
Adaramola e Vagnes [5]	Y_f, CF and L_s	Grid-connected PV system at the Norwegian University of Life Science	12 months	The performance parameters were affected by soiling due to snow and frost during the winter. The authors concluded that the PV system performed similarly to other plants in northern Europe despite the more extreme weather conditions in winter
Micheli *et al.* [7]	Y_f and PR	Two PV facilities operating over buildings at Science Park in Trieste, Italy	12 months	The authors analyzed the actual performances of PV plants, separating the effects of the environmental conditions from those due to the variability of operational and electrical parameters
Mediavilla *et al.* [8]	Y_f and PR	PV system in Palencia, at the centre of the autonomous region of Castilla y León in Spain	12 months	The authors highlighted the performance of PV plants concerning improvements in critical components
Ayompe *et al.* [9]	Y_f, CF, PR and L_s	PV system installed over a 12 m high building in Dublin, Ireland	12 months	The authors compared results with other systems in Germany, Poland and Northern Ireland. Their PV system showed the highest performance ratio (81.5%) and daily final yield (2.4 $kWh/kWp \cdot day$)
Mpholo *et al.* [10]	Y_f, CF, PR and L_s	281 kWp grid-connected PV plant in Lesotho	8 months	The authors presented a performance comparison with other PV plants across the globe to assess the relative performance concerning environmental and operational conditions
Kumar *et al.* [11]	Y_f, CF, and PR	20 kWp grid-connected PV power systemin India	12 months	The authors evaluated PR for every month and the annual mean PR reached 82%, and the average annual CF was 17.2%, against the expected (19%)
Lima *et al.* [6]	Y_f, CF, PR and L_s	2.2 kWp PV system installed at the State University building in Fortaleza, Northeast of Brazil	12 months	The annual final yield was 4.6 $kWh/kWp \cdot day$. The average PR was greater than 82.9%
Morais *et al.* [14]	Y_f, CF and PR	171.6 kWp PV system installed at the Federal Institute of Piauí, Northeast of Brazil	12 months	The authors concluded that PV system had excellent performance (CF above 17% and PR around 74%). The authors highlight the need for more in-depth studies where environmental factors' influence on PV system performance can be assessed
Bet *et al.* [21]	Spectral factor and PV power generated	150 kWp PV system at the rooftop of the library building in the Institute of Energy and Environment/USP	36 months	The authors identified a reduction in spectral performance of around 5% for different scenarios of water vapor and atmospheric aerosol concentrations in urban areas

[1] Y_f stands for final yield, Y_f, Y_r is the reference yield, PR is the performance ratio, CF is the capacity factor, L_S is the system losses.

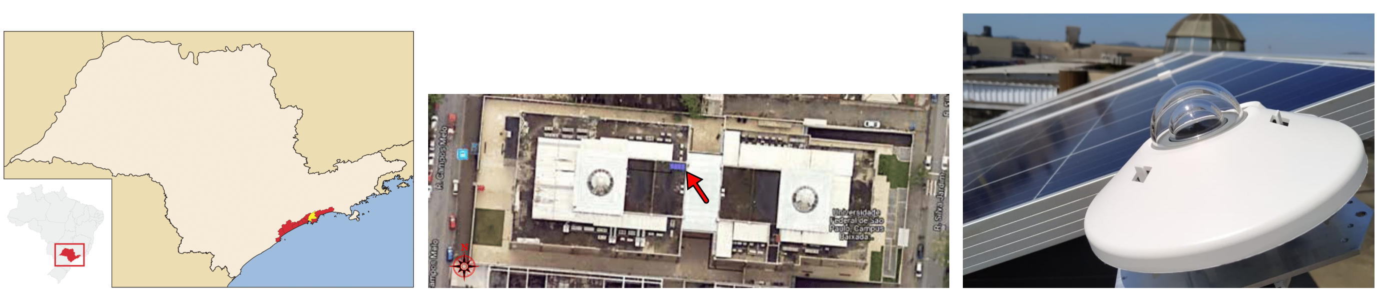


Fig. 1. Location of the installed PV system, in Santos, coastal city in the Brazilian Southeastern region. The central image shows the Unifesp's rooftop where the PV and data acquisiton systems (right) are operating.

sensation more pleasant. The rainfall season starts in February and finishes in August.

The two near-coast sites used to compare PV system performance have quite diverse climates due to geographical locations on different continents:

- Santos - South America, 23°S, 46°W;
- Delft - Europe, 51°N, 4°E;
- Stellenbosch - Africa, 33°S, 18°E.

TABLE II
METRICS USED TO EVALUATE THE PV POWER SYSTEM PERFORMANCE

Measure	Equation	Unit
Array yield	$Y_A = \frac{E_{DC}}{P_0}$	kWh/kW_p
Capacity factor	$CF = \frac{100 \times E_{AC}}{P_0 \times 365 \times 24}$	%
Performance Ratio	$PR = \frac{100 \times Y_f}{Y_r}$	%
PV System Efficiency	$\eta_{SYS} = \frac{100 \times E_{AC}}{H_I \times A_m}$	%
Reference yield	$Y_r = \frac{H_I}{G_{STC}}$	kWh/kW_p
System yield	$Y_f = \frac{E_{AC}}{P_0}$	kWh/kW_p
System losses	$L_S = Y_A - Y_f$	kWh/kW_p

Santos and Stellenbosch are in the Southern Hemisphere, while Delft is in Northern Europe. In Stellenbosch, summers are dry and warm to hot, with some February and March days rising to over 40°C. The climate in Delft is temperate, cold, and rainy. The average winter temperature is 4°C, and the summer temperature averages at 18°C. Rain is very common in Delft throughout the year (around 60mm per month).

E. Software Simulation

The SOLergo software is a computational package that uses solar irradiation data from the Brazilian Solar Energy Atlas to estimate the PV power generation in any location of the Brazilian territory [1]. For this work, we compared data from the PV system at the Unifesp building rooftop with the output from the SOLergo simulation for the first year of operation. The setup used in the Solergo simulation assumed an expected PV system lifetime equal to 30 years and module degradation of 0.8% per year (according to the manufacturer datasheet).

III. RESULTS AND DISCUSSIONS

A. Performance Parameters

Fig. 2 shows the monthly average values of the performance parameters achieved by the PV system operating on the roof of the Unifesp building. Observational data acquisition failed for a few days in October/2020 and July/2021. Despite the acquisition failure in both months, the performance parameters were evaluated using only good-quality data. Except for those months, the final yield (Y_f) ranged around 3 $kWh/kWp \cdot day$ (see the plot in Fig. 2a), with a similar yield achieved by the PV system operating in Natal [16].

Fig. 2a also indicates that the system losses (L_S) were low throughout the study period, indicating a high system performance. It is worth mentioning that the system losses presented a slight increase in May and September, as indicated by Fig. 2a. The most conceivable reason for such an increase is related to higher atmospheric aerosol load (MP_{10}) in May (see Fig. 4a), which contributes to the reduction of atmospheric transmittance and increase in soiling losses due to particulate deposition on the surface of the PV modules. The aerosol composition includes marine particulates (typical in coastal areas) and particulates emitted by cargo transportation and routine port activities. The cargo movement increases in May due to the soybean harvest season in the Cerrado and Central Brazilian region, moving to the international market through Port of Santos. Furthermore, historically, the dry season starts in May resulting in less natural aerosol remotion from the atmosphere and cleaning of the surface of PV modules. The aerosol composition changes seasonally, and its influence on the atmospheric condition and PV system performance will be investigated in future research in order to understand the losses behavior in September.

Fig. 2b shows the capacity factor (CF) ranging between 14-18% all year round, except in September/2021. The CF values are slightly lower than those obtained in the study in Natal (around 18%) [16], and consistent with results achieved by Morais *et al.* [14] for PV systems operating in the continental area of Brazil.

The system efficiency η_{SYS} showed a reasonably constant behavior with values around 15% throughout the year. The performance ratio PR ranged from 80% to 90%, similar to the mean value achieved by Buiatti *et al.* [16] for Natal (see Table III). The PV system was new during the study moment (the first year since its installation) and received monthly cleaning to avoid dust deposition over the PV modules. In addition, the precipitation was lower than the local climate average for nine of the twelve months, indicating higher solar irradiance than the typical values for the region. Both particular conditions help explain such high PR values.

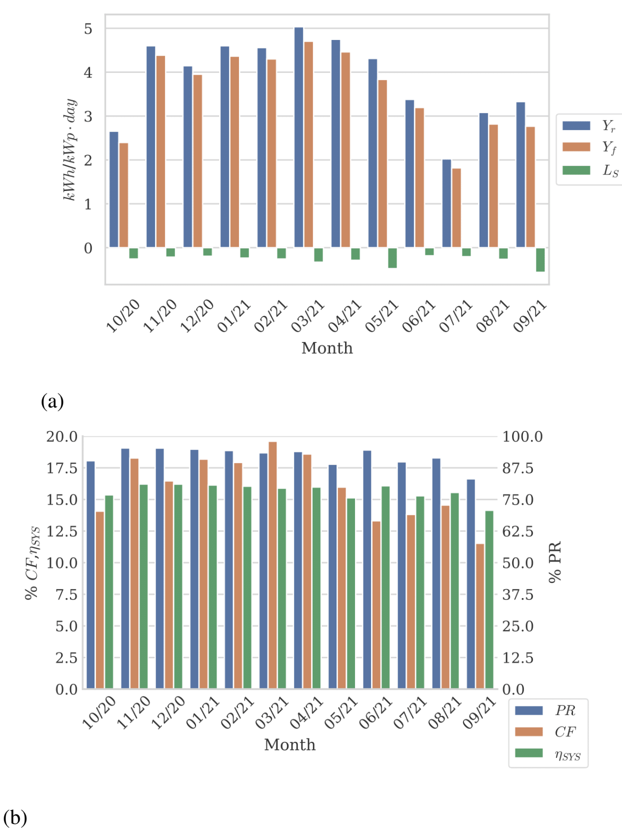


Fig. 2. Performance parameters achieved by PV system at Unifesp/Santos: final and reference yields (Y_f, Y_r) and system losses; and (b) performance ratio (PR), capacity factor (CF) and system Efficiency.

B. Local PV System Data Versus SOLergo Estimates

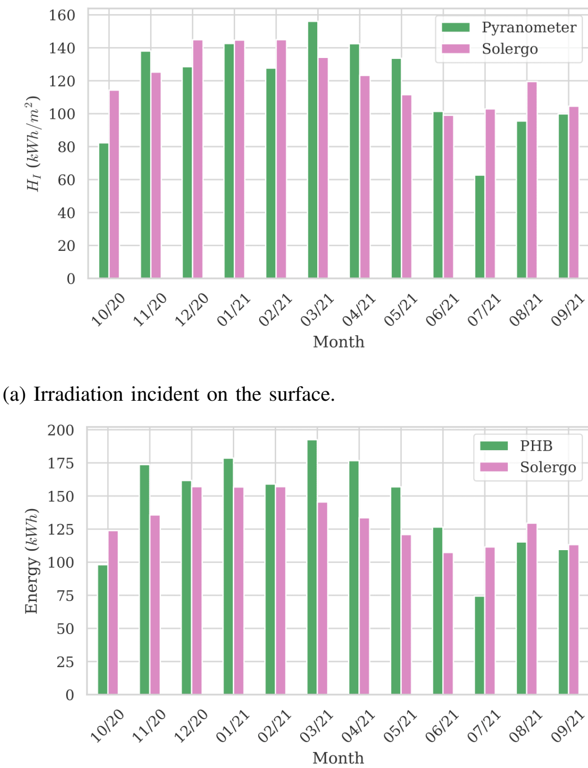
Fig. 3 presents two plots comparing data acquired at the Unifesp rooftop and SOLergo output for solar irradiation reaching the PV modules and the produced electricity. A data acquisition failure occurred in October 2020 and July 2021, so it is not possible to state that the discrepancies observed in these two months are factual and related to weather or climate variability, high concentration of atmospheric aerosols reducing the solar radiation transmittance or uncertainties associated with the numerical approach.

Fig. 3a shows the monthly average values of the downward solar irradiance reaching the photovoltaic modules are higher than the data provided by SOLergo computational tool in November 2020 and between March and May 2021. The opposite happened in December 2020, February and August 2021. The observed and simulated mean values were very close in the remaining three months: January, June, and September 2021. Two fundamental issues can help to understand the discrepancies between observed and SOLergo-simulated data:

- the uncertainties associated with the numerical modeling approach and with the downward surface solar irradiance database used by SOLergo simulation tool;
- the reduced concentration of atmospheric particulates (MP_{10} and $MP_{2.5}$) from March to May 2021 compared to data records acquired in the previous years.

The SOLergo software is a consolidated PV power plant design and sizing simulation tool [38]. Nevertheless, numerical approaches are always associated with uncertainties. To minimize uncertainties for SOLergo applications in Brazilian territory, it uses the downward surface solar irradiation database provided by the Brazilian Atlas of Solar Energy. According to Pereira *et al.* [1], the average deviation in downward solar irradiance ranges between 4% and 8% for the Southeastern Brazilian region. These deviations are associated with the inter-annual variability of surface solar irradiance and the spatial resolution of the Atlas (16 km^2). The Southeast of Brazil presents the largest interannual variability of the Brazilian territory [1].

Fig. 3b shows that the PV power generation at the Unifesp rooftop was higher than estimated by the SOLergo computational package from November 2020 until June 2021. In contrast, more investigation is required to understand the discrepancy in August 2021 when the measured energy at the inverter output was around 10% lower than SOLergo output data. The transition from the dry to the rainy season in the coastal region may not be well represented by numerical approaches used in the Brazilian Atlas and SOLergo tool. Due to failures in recording the produced electricity data in a few days of October 2020 and July 2021, the actual E_{AC} is higher than the stored values presented in Fig. 3b. Such failure does not affect the following analysis.



(a) Irradiation incident on the surface.

(b) Generated energy.

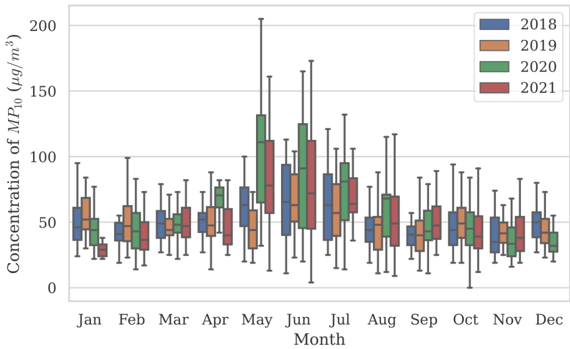
Fig. 3. Plots comparing data acquired at the Unifesp rooftop and provided by SOLergo simulation tool: (a) monthly average of the downward solar irradiation at the PV and (b) monthly total generated energy.

C. Performance Comparison between PV Systems

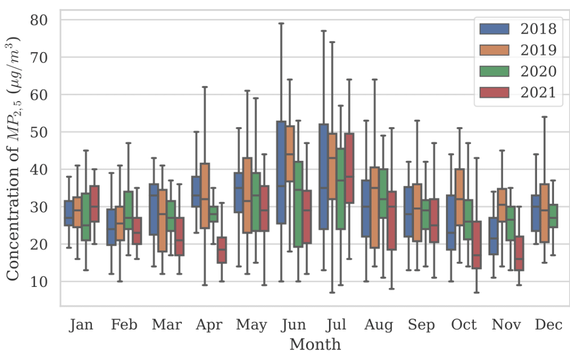
Table III allows inferring the excellent performance of Unifesp's PV system in Santos compared to the ones in Arat-iba, Itiquira, and Natal. Unifesp's PV system presented intermediate values for the final yield Y_f; and the highest PR value. We highlight that both PV systems operating in the coastal cities obtained top PR values. They were recently installed at the University buildings and receive careful maintenance from the institution's staff once used to reduce energy costs and as educational equipment in the undergraduate courses.

Table III also lists all the performance parameters achieved by the PV systems in Santos and abroad coastal cities: Delft (Europe) and Stellenbosch (Africa). Two environmental quantities are also listed: air temperature (T_{air}) and direct normal solar irradiance (DNI). The DNI data for Santos was extracted from the database made available by the Brazilian Atlas of Solar Energy [1]. The air temperature is the climate average published by the Brazilian Institute for Meteorology [22].

Santos is the coastal city presenting the highest annual mean air temperature (T_{air}) and the second highest annual average of direct solar irradiation at the surface (DNI) compared to the other two abroad cities (see Table III). The highest annual average of DNI occurs in Stellenbosch (Africa). Even the minimum DNI in Stellenbosch is higher than the mean DNI in Santos. The annual average DNI is primarily associated with the local cloudiness variability and, secondly, with atmospheric aerosols emitted locally or transported from surroundings areas like large metropolitan regions or biomass burning events. Such a difference in the surface solar irradiation regime explains the largest CF of the African PV system, demonstrating



(a) MP_{10} (coarse particles from 2.5 to $10\mu m$).



(b) $MP_{2.5}$ (fine particles up to $2.5\mu m$).

Fig. 4. Monthly distribution of maximum daily concentrations of Particulate Material for the CETESB station "Santos - Ponta da Praia" (2018–2021).

Source: Adapted from 23.

that it should be exposed during more time to solar incidence than the plants located in Santos and Delft. The Unifesp's PV system got the intermediate CF parameter of the three locations.

Although the air temperature is 3.5°C higher than Stellenbosch and 10.5°C than Delft, the PV system installed in Santos presented the highest annual average of PR parameter among all three locations. The Delft's PV system also got a high annual mean for the PR, higher than 80%.

IV. Conclusions

Former studies highlighted the importance of accurately evaluating the PV system's performance to understand the impact of the weather and atmospheric conditions on PV power generation. However, few studies were focused on a medium-size coastal city with an economy strongly based on activities that emit high amounts of particulates and pollutant gases into the atmosphere.

This work used meteorological and operational PV system databases to verify and evaluate the performance of photovoltaic solar power systems in an urban area on the Southeastern Brazilian coast. The results show that the PV system operating at the Unifesp Building rooftop presented as good performance as other systems working in coastal regions or in the continental areas despite issues related to the local weather conditions (high cloud coverage variability and high aerosol load all around the year), climate features (hot and humid summers and dry winters), and economic activities emitting a high rate of pollutants into the atmosphere.

The Unifesp PV system produced more electricity than expected based on the SOLergo software simulation. The SOLergo tool uses the Brazilian Solar Energy Atlas database, prepared using satellite data from 2000-2017. This database provides monthly average data of surface solar irradiation that reflects regional cloud cover patterns [39], [40] and atmospheric properties, such as aerosol optical depth from biomass burning events [41], [42]. However, the extended dry season and lower atmospheric aerosol levels in Santos during 2020-2021 were unusual conditions, contributing to higher solar irradiation and the difference between the actual and estimated electricity output.

The mean CF and η_{SYS} were around 16%, and the mean PR was 89.8%, presenting a minimum value of 83.1% (in September 2021) and a maximum of 95.3% (in November 2020). Studies developed in other Brazilian coastal areas and abroad obtained similar values for those performance parameters. PR values around or above 80% were obtained for the PV systems installed in Natal (a coastal city in the Brazilian Northeast) in Itiquira (a city located in the interior of the country), and in Delft (a city located in the North of Europe). The PV systems working in Santos, Itiquira, and Natal were recently installed before data acquisition and performance evaluation. Besides that, operational and maintenance activities were done to avoid losses due to soiling and operational interferences during the research timeframe.

The PV system in Natal got the highest CF in Brazil, around 19%. Still, the solar energy resource is higher in Natal (annual mean around 5674 $Wh/m^2 \cdot day$ [1] than Santos (around 4142 $Wh/m^2 \cdot day$ [1]).

To summarize, the findings indicate that Unifesp's PV system performed well despite unfavorable weather conditions, high humidity, and atmospheric aerosols. During the research data collection period, economic activities were lower than usual due to COVID-19 safety measures, resulting in decreased international trade of agribusiness commodities through the port of Santos and lower atmospheric aerosol levels. Moreover, the climate in 2020-2021 was drier than the usual average, which contributed to higher PV performance. However, future research will provide more comprehensive data based on long-term performance monitoring of 5-10 years.

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TABLE III
COMPARISON OF THE PERFORMANCE PARAMETERS OF THE STUDIED SYSTEM (SANTOS) WITH OTHER COASTAL CITIES

City	Location	Parameters	Annual average	Maximum		Minimum		Unity
				Value	Month	Value	Month	
Santos	Tropical and Coastal	Y_r	3.9	5.0	Mar	2.0	Jul	$kWh/kWp \cdot day$
		Y_f	3.6	4.7	Mar	1.8	Jul	$kWh/kWp \cdot day$
		L_S	0.6	0.8	Mar	0.3	Jul	$kWh/kWp \cdot day$
		PR	89.8	95.3	Nov	83.1	Sep	$\%$
		CF	16.0	19.6	Mar	11.5	Sep	$\%$
		η_{SYS}	15.6	16.2	Nov	14.1	Sep	$\%$
		T_{air}	21.0	24	Jan	18	Jun	$^\circ C$
		DNI	2.9	101.5	Jul	66	Sep	$kWh/m^2 \cdot day$
Delft	Non-tropical and Coastal	Y_r	3.4	5.4	May	0.9	Dec	$kWh/kWp \cdot day$
		Y_f	2.7	4.3	May	0.8	Dec	$kWh/kWp \cdot day$
		L_S	0.7	1.1	Jul	0.2	Dec	$kWh/kWp \cdot day$
		PR	81	84	Jan	78	Jul	$\%$
		CF	11.06	17.9	May	3.2	Dec	$\%$
		η_{SYS}	12.62	13.1	Fev	12.2	Jul	$\%$
		T_{air}	10.5	18	Jul	4	Jan	$^\circ C$
		DNI	2.7	4.3	May	0.9	Dec	$kWh/m^2 \cdot day$
Stellenbosch	Non-tropical and Coastal	Y_r	5.9	8.1	Feb	3.3	Jun	$kWh/kWp \cdot day$
		Y_f	4.4	5.9	Feb	2.7	Jun	$kWh/kWp \cdot day$
		L_S	1.5	2.3	Feb	0.7	Jun	$kWh/kWp \cdot day$
		PR	76	80	Jun	72	Jan	$\%$
		CF	18.42	24.2	Dec	11.1	Jun	$\%$
		η_{SYS}	11.67	12.3	Jun	11.1	Jan	$\%$
		T_{air}	17.5	22	Jan	13	Jun	$^\circ C$
		DNI	6.2	9.1	Jan	3.6	Jun	$kWh/m^2 \cdot day$
Aratiba	Tropical and Non-coastal	Y_r	3.9	5.4	Jan	2.7	Jul	$kWh/kWp \cdot day$
		Y_f	3.3	4.1	Jan	2.4	Jul	$kWh/kWp \cdot day$
		PR	85.3	96.8	Feb	75.6	Jan	$\%$
		CF	13.9	17.2	Jan	9.8	Jul	$\%$
		η_{SYS}	11.4	12.4	May	10.5	Jan	$\%$
		T_{air}	20.2	25.3	Jan	14.5	Jun	$^\circ C$
		DNI	4.4	6.0	Dec	2.6	Jun	$kWh/m^2 \cdot day$
Itiquira	Tropical and Non-coastal	Y_r	5.1	6.3	Aug	4.6	Feb	$kWh/kWp \cdot day$
		Y_f	4.2	4.9	Aug	3.8	Jan	$kWh/kWp \cdot day$
		PR	81.2	93.5	Feb	75.4	Mar	$\%$
		CF	17.3	20.6	Aug	16.0	Jan	$\%$
		η_{SYS}	10.8	11.8	Jun	10.2	Apr	$\%$
		T_{air}	26.4	28.4	Sep	24.1	May	$^\circ C$
		DNI	4.8	6.5	Aug	4.0	Oct	$kWh/m^2 \cdot day$
Natal	Tropical and Coastal	Y_r	5.7	6.1	Mar	4.9	Jun	$kWh/kWp \cdot day$
		Y_f	4.5	5.0	Oct	3.6	Jun	$kWh/kWp \cdot day$
		PR	79.4	83.3	Dec	73.4	Jun	$\%$
		CF	18.8	20.8	Oct	14.9	Jun	$\%$
		η_{SYS}	10.6	11.5	Dec	9.2	Feb	$\%$
		T_{air}	26.8	27.8	Jan	25.5	Jul	$^\circ C$
		DNI	5.2	5.7	Nov	4.6	Jun	$kWh/m^2 \cdot day$

Source: Prepared by the authors based on data provided by [35]–[37].

REFERENCES

[1] E. B. Pereira, F. R. Martins, A. R. Gonçalves, R. S. Costa, F. J. L. de Lima, R. Rüther, S. L. de Abreu, G. M. Tiepolo, S. V. Pereira, and J. G. de Souza, *Atlas Brasileiro de Energia Solar*. São José dos Campos: INPE, 2 ed., 2017.

[2] ABSOLAR, "Panorama da solar fotovoltaica no Brasil e no mundo." Available at https://www.absolar.org.br/mercado/infografico/ (2023/02/20).

[3] EPE, "Estudos do Plano Decenal de Expansão de Energia 2031: Micro e Minigeração Distribuída e Baterias," 2021.

[4] B. Marion, J. Adelstein, K. e. Boyle, H. Hayden, B. Hammond, T. Fletcher, B. Canada, D. Narang, A. Kimber, L. Mitchell, *et al.*, "Performance parameters for grid-connected PV systems," in *Conference Record of the Thirty-first IEEE Photovoltaic Specialists Conference, 2005.*, pp. 1601–1606, IEEE, 2005.

[5] M. S. Adaramola and E. E. Vågnes, "Preliminary assessment of a small-scale rooftop PV-grid tied in Norwegian climatic conditions," *Energy Conversion and Management*, vol. 90, pp. 458–465, 2015.

[6] L. C. de Lima, L. de Araújo Ferreira, and F. H. B. de Lima Morais, "Performance analysis of a grid connected photovoltaic system in northeastern Brazil," *Energy for Sustainable Development*, vol. 37, pp. 79–85, 2017.

[7] D. Micheli, S. Alessandrini, R. Radu, and I. Casula, "Analysis of the outdoor performance and efficiency of two grid-connected photovoltaic systems in northern Italy," *Energy conversion and management*, vol. 80, pp. 436–445, 2014.

[8] M. Díez-Mediavilla, C. Alonso-Tristán, M. d. C. Rodríguez-Amigo, T. García-Calderón, and M. Dieste-Velasco, "Performance analysis of PV plants: Optimization for improving profitability," *Energy conversion and management*, vol. 54, no. 1, pp. 17–23, 2012.

[9] L. Ayompe, A. Duffy, S. McCormack, and M. Conlon, "Measured performance of a 1.72 kW rooftop grid connected photovoltaic system in Ireland," *Energy conversion and management*, vol. 52, no. 2, pp. 816–825, 2011.

[10] M. Mpholo, T. Nchaba, and M. Monese, "Yield and performance analysis of the first grid-connected solar farm at Moshoeshoe I International Airport, Lesotho," *Renewable energy*, vol. 81, pp. 845–852, 2015.

[11] K. A. Kumar, K. Sundareswaran, and P. Venkateswaran, "Performance study on a grid connected 20 kWp solar photovoltaic installation in an industry in Tiruchirappalli (India)," *Energy for Sustainable Development*, vol. 23, pp. 294–304, 2014.

[12] K. Padmavathi and S. A. Daniel, "Performance analysis of a 3 MWp grid connected solar photovoltaic power plant in India," *Energy for Sustainable Development*, vol. 17, no. 6, pp. 615–625, 2013.

[13] G. A. Dávi, E. Caamaño-Martín, R. Rüther, and J. Solano, "Energy performance evaluation of a net plus-energy residential building with grid-connected photovoltaic system in Brazil," *Energy and Buildings*, vol. 120, pp. 19–29, 2016.

[14] F. H. M. d. Morais, A. M. d. Moraes, and F. R. Barbosa, "Technical-economic analysis of the first mini-generation photovoltaic system of piauí, Brazil," *IEEE Latin America Transactions*, vol. 17, p. 1706–1714, Dec. 2019.

[15] A. C. Pinto, T. G. d. Silva Filho, and E. P. Machado, "Evaluation of photovoltaic microgeneration systems connected to utility: Cases studies in petrolina," *IEEE Latin America Transactions*, vol. 18, p. 1538–1546, Mar. 2021.

[16] G. M. Buiatti, F. R. S. Junior, A. C. F. Wanderley, and S. B. Maciel, "Desempenho de micro e mini usinas fotovoltaicas no Instituto Federal do Rio Grade do Norte," in *Proc. of the VI Brazilian Congress of Solar Energy, Belo Horizonte, Brazil*, 2016.

[17] L. G. Bet, "Impacto dos aerossóis atmosféricos no fator espectral de módulos fotovoltaicos em São Paulo.," mestrado em ciências, Programa Análise Ambiental Integrada, UNIFESP, Diadema, 2021.

[18] J. Polo, M. Alonso-Abella, J. A. Ruiz-Arias, and J. L. Balenzategui, "Worldwide analysis of spectral factors for seven photovoltaic technologies," *Solar Energy*, vol. 142, pp. 194–203, 2017.

[19] M. Viana, F. Amato, A. Alastuey, X. Querol, T. Moreno, S. Garcia Dos Santos, M. D. Herce, and R. Fernandez-Patier, "Chemical tracers of particulate emissions from commercial shipping," *Environmental Science & Technology*, vol. 43, no. 19, pp. 7472–7477, 2009. PMID: 19848163.

[20] M. Viana, P. Hammingh, A. Colette, X. Querol, B. Degraeuwe, I. de Vlieger, and J. van Aardenne, "Impact of maritime transport emissions on coastal air quality in Europe," *Atmospheric Environment*, vol. 90, pp. 96–105, 2014.

[21] L. G. Bet, F. R. Martins, N. M. Évora do Rosario, and R. Zilles, "Worldwide analysis of spectral factors for seven photovoltaic technologies," *Revista Brasileira de Energia Solar*, vol. 13, pp. 146–156, 2022.

[22] INMET, "Normais climatológicas do Brasil," 2021. Brasília: Instituto Nacional de Meteorologia.

[23] CETESB, "Qualar: Sistema de informações da qualidade do ar," 2021.

[24] P. E. Dias da Silva, F. R. Martins, and E. B. Pereira, "Quality Control of Solar Radiation Data within SONDA Network in Brazil: Preliminary results," in *Conference Proc. of the EUROSUN 2014, Aix-les-Bains, France*, 2014.

[25] IEA-PVPS, "Analytical Monitoring of Grid-connected Photovoltaic Systems ," *Report IEA-PVPS T13-03:2014*, 2014.

[26] S. Thotakura, S. Chandan Kondamudi, J. F. Xavier, M. Quanjin, G. R. Reddy, P. Gangwar, and S. L. Davuluri, "Operational performance of megawatt-scale grid integrated rooftop solar pv system in tropical wet and dry climates of india," *Case Studies in Thermal Engineering*, vol. 18, p. 100602, 2020.

[27] L. R. do Nascimento, M. Braga, R. A. Campos, H. F. Naspolini, and R. RÃ¼ther, "Performance assessment of solar photovoltaic technologies under different climatic conditions in Brazil," *Renewable Energy*, vol. 146, pp. 1070–1082, 2020.

[28] A. Woyte, M. Richter, D. Moser, N. Reich, M. Green, S. Mau, and H. Beyer, "Analytical monitoring of grid-connected photovoltaic systems: good practices for monitoring and performance analysis," *Report IEA PVPS T13-03*, pp. 14–15, 2014.

[29] R. H. Fusano, "Análise dos índices de mérito do sistema fotovoltaico conectado à rede do escritório verde da UTFPR," B.S. thesis, Universidade Tecnológica Federal do Paraná, 2013.

[30] M. S. Adaramola, "Techno-economic analysis of a 2.1 kW rooftop photovoltaic-grid-tied system based on actual performance," *Energy Conversion and Management*, vol. 101, pp. 85–93, 2015.

[31] C. E. B. E. Sidi, M. L. Ndiaye, M. El Bah, A. Mbodji, A. Ndiaye, and P. A. Ndiaye, "Performance analysis of the first large-scale (15 MWp) grid-connected photovoltaic plant in Mauritania," *Energy conversion and management*, vol. 119, pp. 411–421, 2016.

[32] S. D. Guide, "STC and NOCT: Solar Panel Test Conditions Explained," 2023.

[33] J. d. O. Gonzalez and F. R. Martins, "Performance evaluation of a pv system operating in a coastal city of the southeastern Brazilian region," in *2021 IEEE 48th Photovoltaic Specialists Conference (PVSC)*, pp. 2446–2452, IEEE, 2021.

[34] R. Dolla, H. F. Naspolini, and R. Rüther, "Desempenho das tecnologias de módulos em diferentes climas: desempenho de diferentes módulos em climas distintos no Brasil," *FotoVolt*, vol. 30, pp. 1–76, 2020.

[35] Solargis, "Solar resource maps and GIS data," 2016.

[36] Solargis, ESMAP, and World Bank Group, "Global solar atlas.," 2019.

[37] CustomWeather, "Syndicated content for complete global weather coverage," 2021.

[38] Hyper Energy do Brasil LTDA., "Relatório descritivo-econômico do Software SOLergo," 2020.

[39] F. R. Martins, S. A. B. Silva, E. B. Pereira, and S. L. Abreu, "The influence of cloud cover index on the accuracy of solar irradiance model estimates," *METEOROLOGY AND ATMOSPHERIC PHYSICS*, vol. 99, pp. 169–180, APR 2008.

[40] E. W. Luiz, F. R. Martins, R. S. Costa, and E. B. Pereira, "Comparison of methodologies for cloud cover estimation in brazil - a case study," *ENERGY FOR SUSTAINABLE DEVELOPMENT*, vol. 43, pp. 15–22, APR 2018.

[41] F. Martins and E. Pereira, "Parameterization of aerosols from burning biomass in the brazil-sr radiative transfer model," *SOLAR ENERGY*, vol. 80, no. 3, pp. 231–239, 2006.

[42] M. S. G. Casagrande, F. R. Martins, N. E. Rosario, F. J. L. Lima, A. R. Goncalves, R. S. Costa, M. Zarzur, M. P. Pes, and E. B. Pereira, "Numerical assessment of downward incoming solar irradiance in smoke influenced regions-a case study in brazilian amazon and cerrado," *REMOTE SENSING*, vol. 13, NOV 2021.

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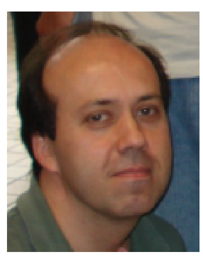

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