Insights into the Frequency and Intensity of Overirradiance Events in Diverse Brazilian Climates

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Abstract

This study investigated the occurrence, duration, and intensity of extreme overirradiance events (EOIE) at five solarimetric stations located in different climatic regions of Brazil, using irradiance data with one-second resolution, between November 2021 and March 2023. Only events with irradiance greater than 1000 W/m² were considered, classified into two bands: between 1000 and 1367 W/m² (OIE) and above 1367 W/m² (EOIE). The results showed that stations SE01 (Sousa-PB) and SE02 (São João do Piauí-PI) presented the highest numbers of occurrences, with 5446 and 4025 events, respectively, while SE05 (Bom Jesus da Lapa-BA) recorded the lowest number (1291). SE03 (Ilha Solteira-SP) stood out for its seasonality and the occurrence of the most intense and long-lasting events, including one lasting 535 seconds and with a maximum irradiance of 1549 W/m². Most events in all stations lasted less than 30 seconds, revealing the transient nature of overirradiance and reinforcing the need for monitoring at high temporal resolution.

Keywords: EOIE, Extreme irradiance, Cloud enhancement

1. Introduction

Photovoltaic modules exhibit an almost linear response to solar irradiance, so the efficiency of a photovoltaic system is directly related to the solar radiation incident on the plane of the modules (do Nascimento, de Souza Viana, Campos, and Rüther, 2019). Thus, photovoltaic systems are susceptible to variations in irradiance caused by cloud cover and climatic conditions in the region. The modules are also influenced by temperature, shifting the maximum power point as the temperature increases. In order to evaluate the efficiency of modules under standardized conditions, international organizations such as the International Electrotechnical Commission (IEC) specify the requirements for characterizing modules under standard test conditions (STC, 25 °C cell temperature, 1000 W/m² irradiance, and AM = 1.5 spectral distribution of incident sunlight). However, in operation, the modules experience adverse environmental conditions and, in particular, receive irradiance values much higher than 1000 W/m². On some occasions, the positive correlation of different environmental factors can produce irradiance values of the order of or even greater than the Solar Constant (Isc) for short periods of time (Piacentini, Salum, Fraidenraich, and Tiba, 2011).

The Solar Constant is the value of extraterrestrial solar radiation incident on a surface perpendicular to the average distance between the Sun and Earth (Andrade and Tiba, 2016). According to Rabl (1985), the solar constant has an average flux density of approximately 1367 W/m², which corresponds to the irradiance limit value at the top of the atmosphere and can vary by ± 3% during the year. However, several studies have shown that under specific conditions, the irradiance values measured on Earth's surface can exceed this limit, as observed in the work of (Piacentini, Salum, Fraidenraich, and Tiba, 2011), in the region of Recife (8.05°S, 34.90°W, 4 m asl) located on the coast of Brazil, several values higher than the Solar Constant were obtained, with an extreme maximum of 1477 W/m², recorded at 11:34 local time. In the literature, this event has several names, being best known as the cloud edge effect, lens effect, extreme irradiance, superirradiance, and overirradiance, the latter terminology being adopted in this study.

Despite the technical and economic relevance of these impacts, systematic monitoring of overirradiance is still limited. This is partly due to the fact that many sensors in solar plants have slow response times or operate with long temporal integrations, which smooths and even hides irradiance peaks in aggregated temporal analyses (Martins *et*

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al., 2022). In addition, most records focus on point observations, without detailing the spatial extent of the events.

This study monitored the occurrence of EOIE in five solarimetric stations installed in five different climatic regions in Brazil, with the purpose of investigating the characteristics of frequency of occurrence, duration and intensity of the events. Mapping and spatially characterizing overirradiance in Brazil is essential to improve system sizing, reduce operational losses and avoid undersizing of inverters, especially in large-scale plants installed in the Northeast, where the phenomenon has been shown to be recurrent and potentially harmful.

2. Materials and Methods

The study was conducted using global horizontal irradiance (GHI) data measured at solarimetric stations located in five different climatic regions. GHI data were measured using Kipp & Zonen CMP11 pyranometers, classified as class A according to ISO 9060, with valid calibration. Measurements were taken every second and recorded by a Campbell Scientific CR1000X datalogger. The list of meteorological data measured by the station can be seen in Table 1. Data from the period November 2021 to January 2023 was used for this analysis. The geographic coordinates of each station can be seen in Table 2.

Table 1: Sensors at solarimetric stations

Instruments	Variable	Acronym	Unit
Datalogger CR1000X - Campbell Scientific	Data acquisition	-	-
Piranômetro CPM 11 - Kipp & Zonen	Global Horizontal Irradiance	GHI	W/m²
Piranômetro CPM 11 - Kipp & Zonen	Global Horizontal Irradiance	GHI	W/m²
Célula de referência RC18 series - PVE	Global Horizontal Irradiance	GHI	W/m²
Piranômetro CPM 11 - Kipp & Zonen	Global Irradiance Reflected by the Ground	GRI	W/m²
Termohigrômetro Hygro VUE10-Campbell Scitenfic	Air Temperature	Temp	°C
	Relative Air Humidity	UR	%
Anemômetro Wind SPD Sensor-Met One Instruments	Wind Speed	Vel	m/s
Painel Fotovoltaico 20M-VElectrical Raiting	Energy Generation	-	W

Table 2: Geographical location of solarametric stations

Station	City	Latitude	Longitude
ESA01	Sousa-PB	-6.77	-38.20
ESA02	São João do Piauí-PI	-8.36	-42.25
ESA03	Ilha Solteira-SP	-20.43	-51,34
ESA04	Mossoró-RN	-5.18	-37-34
ESA05	Bom Jesus da Lapa-BA	-13.14	-43.24

Figure 1 shows the geographical distribution of the five solar radiation stations analyzed, located in different climatic contexts in Brazil. Four of them are located in the Northeast region: Sousa (PB) – ESA01, São João do Piauí (PI) – ESA02, Mossoró (RN) – ESA04, and Bom Jesus da Lapa (BA) – ESA05, while the fifth is located in the Southeast region, in the municipality of Ilha Solteira (SP) – ESA03. The study therefore covers five different states, allowing for comparisons between different locations.

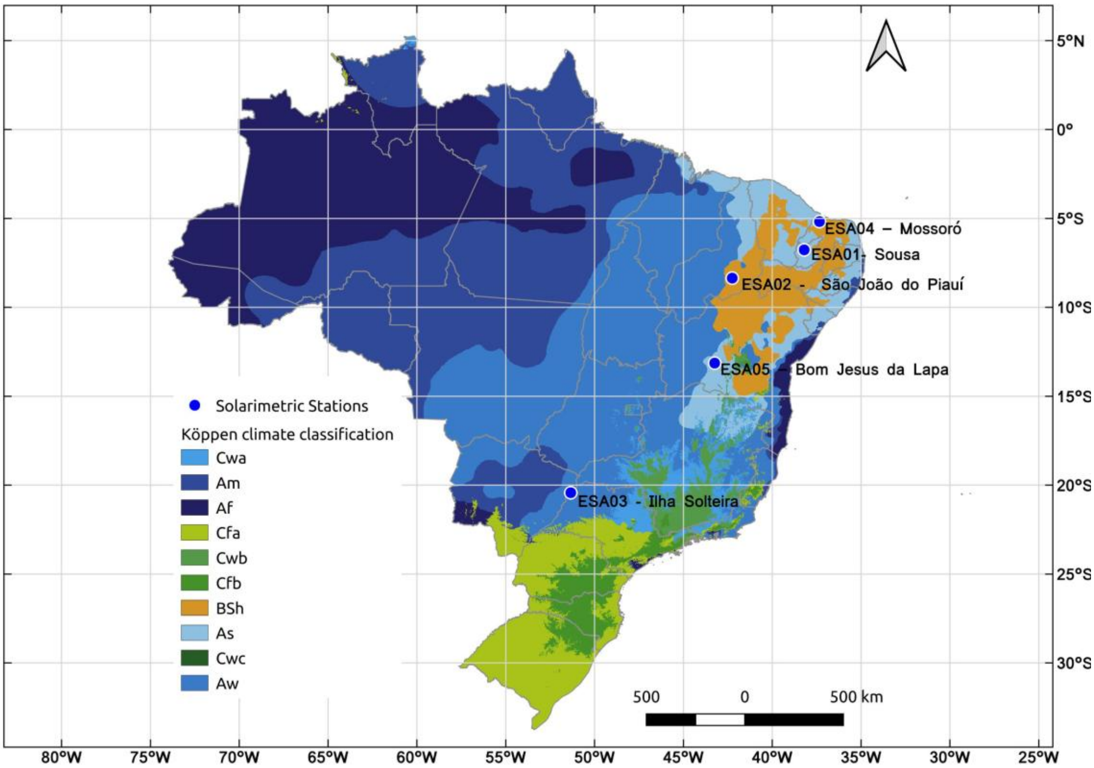


Figure 1: The Köppen climate classification map shows the locations of the solarimetric stations involved in this study: ESA01 – Sousa/PB, ESA02 – São João do Piauí/PI, ESA03 – Ilha Solteira/SP, ESA04 – Mossoró/RN and ESA05 – Bom Jesus da Lapa/BA. Source: Adapted from Álvarez et al., 2013.

According to the Köppen climate classification (Alvares et al., 2013), illustrated in Fig. 1, the locations cover three main climate types. Sousa (PB) and Bom Jesus da Lapa (BA) have a tropical climate with dry summers (As), while São João do Piauí (PI) and Mossoró (RN) have a semi-arid climate (BSh). In general, these four locations are characterized by high temperatures and high solar radiation during most of the year, conditions favorable to solar energy generation. Ilha Solteira (SP), on the other hand, has a tropical climate with dry winters (Aw), typical of the tropical portion of the state of São Paulo, which is influenced by the subtropical climate. This climate regime is distinguished by its wide annual temperature range, with hot summers and cold winters. During winter, the incursion of cold air masses often reduces minimum temperatures to below 18 °C and, at the same time, favors clear skies.

Thus, the spatial distribution of solar radiation stations covers a wide range of Brazilian climatic conditions, from the semi-arid northeast to the interior of São Paulo state, enabling a comprehensive analysis of solar irradiance variability in different atmospheric and geographical contexts.

Overirradiance events can occur at various times of the day, but some events present values much lower than 1000 W/m², the intensity for which the modules are certified, and do not present any relevance or problems for the operation of photovoltaic systems (do Nascimento et al, 2019). Therefore, in this study, only overirradiance events greater than 1000 W/m² were counted. As a way of classifying in terms of intensity, the analysis also separated events with irradiance between 1000 and 1367 W/m² (OIE) and events greater than 1367 W/m² (EOIE).

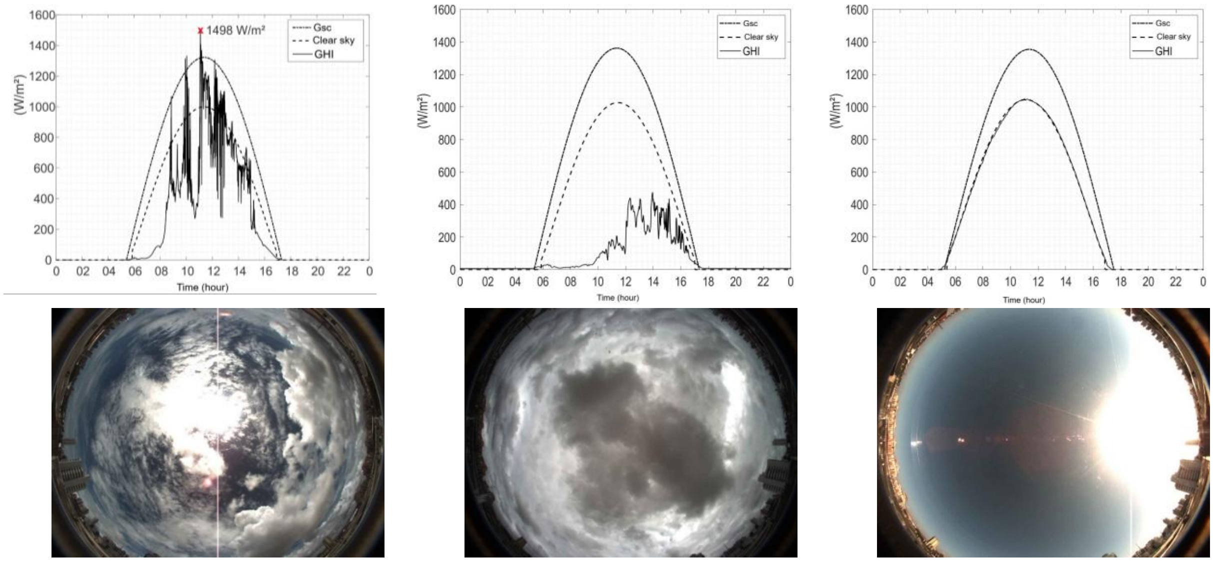
To identify EOIE, the measured GHI values that exceeded the extraterrestrial horizontal irradiance values (G_0) were analysed. The G_0 values were estimated using the following expression:

$$G_0 = G_{sc} \,.\, \varepsilon_0 \,.\, \cos(\Theta_z) \qquad \text{(eq. 1)}$$

where Gsc is the solar constant, equal to 1367 W/m², ε_0 é is the eccentricity of the Earth's orbit and $\cos(\Theta_z)$ is the cosine of the zenith angle. GHI above 1000 W/m² were considered for the analyses of overirradiance events, as values much lower than the Standard Test Conditions (STC) irradiance (1000 W/m^2) do not present relevant or potential problems that affect the operational performance of photovoltaic plants. To ensure data reliability, a robust data quality assurance procedure was applied as per (da Silva et al., 2024). The flowchart shown in Figure 2 illustrates the sequence of steps adopted for the characterization of the overirradiance event.

Figure 2: Flowchart illustrating the sequence of methods used to identify over-irradiance events.

According to Emiliavaca and Sousa (2025), the type and fraction of cloud cover are considered modulators of the occurrence of over-irradiance events. Andrade and Tiba (2016) showed that the presence of cumulus clouds increases the possibility of extreme irradiance values due to reflections at the edges of the clouds and also to the various scatterings that occur on the surface of the clouds (Costa et al., 2021). In Figure 3, it can be observed that the over-irradiance event is conditioned to days with cloud cover (Figure 3a), but not when this cloud cover is total (Fig. 3b) or on clear sky days (Fig. 3c).



(a) **(b)** **(c)**

Figure 3: Irradiance profiles and images from the allsky camera (a) for an overirradiance event (b) for a cloudy day and (c) for a clear sky day. Source: Adapted from Emiliavaca and Sousa, 2025.

The overirradiance data were classified based on irradiance ranges and event duration. Events were considered distinct when values exceeded 1000 W/m² for at least 1 second. Durations were categorized according to Table 3.

Table 3: Classification of event duration in seconds and minutes.

Duration		Color
≤ 30 s	-	Green
> 30 ≤ 60 s	1 min	Yellow
> 60 ≤ 120 s	2 min	Orange
> 120 ≤ 180 s	3 min	Red
> 180 s	> 3 min	Purple

3. Results and Discussion

Table 4 shows the monthly distribution of the number of events recorded with irradiance greater than 1000 W/m² over the period analyzed. The analysis shows that, depending on the temporal resolution of the data, the totals recorded are much higher when events are observed on a scale of seconds. the variations between the totals recorded for ESA01 – Sousa-PB varied in November 2021 from 9 events recorded on a minute scale to 48 events recorded on a second scale, representing a total of 19% more events on the second scale. Also, in ESA01, August 2022 had the highest number of events on both time scales. On the minute scale, January 2023 had the lowest number of events, while on the second time scale, November 2021 had the lowest number of records.

ESA02-São João do Piauí-PI had the highest number of records in July 2022 in both time resolutions. Meanwhile, September 2022 had the lowest occurrence of data in minutes, and October 2022 had the lowest occurrence of data in seconds. At ESA ESA03-Ilha Solteira-SP, there is initially a marked seasonality, with a much lower occurrence of events in the winter period, resulting from the high incidence of clear skies during this period. In terms of seconds, February 2023 is the month with the most occurrences, while in terms of minutes, January 2022 has the highest value. The months of November 2021 and July 2022 have gaps in the data series.

In ESA04-Mossoró-RN, there is a gap in the measurements in seconds in November 2021 and January 2023. The highest occurrences took place in November 2022 in both time resolutions. The data series in minutes showed January 2023 as the month with the lowest occurrence, while the series in seconds showed December 2021 as the month with the lowest occurrence. ESA05-Bom Jesus da Lapa-BA had the lowest number of occurrences among the stations. The highest record occurred in November 2022 and the lowest in August 2022 in both temporal resolutions. In summary, ESA01 is the station that presented the highest number of occurrences, followed by ESA02 and then ESA03. ESA05 presented the lowest number of occurrences. ESA03 was the station with the highest seasonality in occurrences, with one period marked by many occurrences and another by very few.

The presence of clouds is the main factor causing high variability in irradiance during the day and, according to (Andrade and Tiba, 2016), the appearance of cumulus clouds increases the probability of high irradiance values as a result of the reflectivity phenomenon of cloud edges. Thus, to evaluate over-irradiance events, high temporal variability must be considered. Figure 4 illustrates the comparison between the daily irradiance profile when recorded every minute compared to when recorded every second on a day with high irradiance variability. When comparing the profiles, there is a certain variation in the percentages of maximum and minimum values recorded, with the minute data showing a smoothing in its profile. However, in the second profile, it is possible to see greater variability, with more prominent extremes, due to the short recording time. When analyzing the maximum irradiance value in minute resolution, illustrated in Figure 4b, it can be observed that the values do not exceed the solar constant value (1367 W/m²), while when analyzing the values measured in second resolution, shown in Figure 4a, the values exceed it, representing a difference of approximately 10% in the intensity of the overirradiance event.

Table 4: Number of occurrences of overirradiance events at second and minute resolution for stations ESA01, ESA2, ESA03, ESA04, and ESA05.

Month/Year	ESA01		ESA02		ESA03		ESA04		ESA05	
	Seconds	Minutes	Seconds	Minutes	Seconds	Minutes	Seconds	Minutes	Seconds	Minutes
nov/21	48	9	229	23	-	9	-	32	-	-
dec/21	263	17	250	16	134	14	40	10	-	8
jan/22	287	28	335	38	346	41	135	8	-	14
fev/22	166	21	139	11	146	13	45	2	71	14
mar/22	466	32	370	14	131	15	260	19	40	6
apr/22	611	31	243	17	80	4	356	18	78	7
may/22	466	25	194	12	78	8	462	25	82	4
jun/22	517	29	103	16	2	0	247	32	38	6
jul/22	468	27	646	45	0	0	317	14	69	3
aug/22	768	41	340	22	0	0	105	6	32	1
sep/22	493	31	26	1	26	0	307	14	67	6
oct/22	182	9	11	2	157	8	351	23	59	2
nov/22	337	37	331	27	217	9	532	38	323	27
dec/22	288	26	486	24	250	15	157	6	278	26
jan/23	86	4	322	18	177	14	-	1	154	13

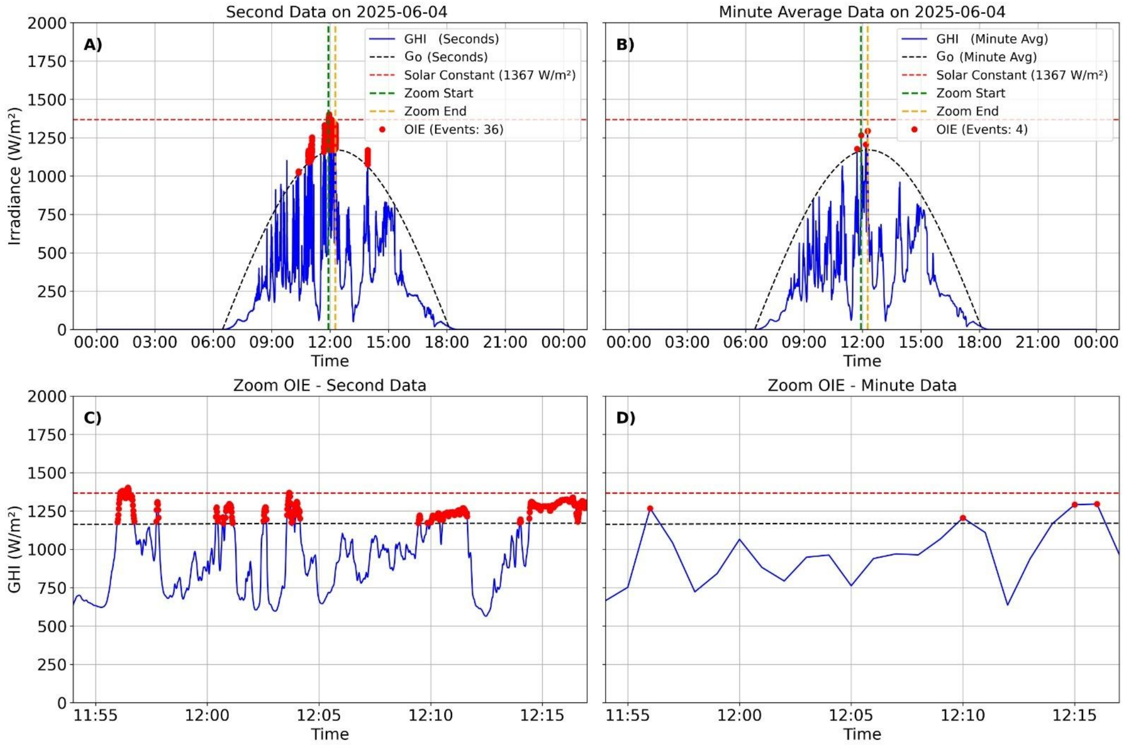


Figure 4: Comparison of the solar radiation profile recorded (a) in minutes and (b) in seconds by the ISI-ER solar radiation station installed in Sousa, Paraíba.

Figures 5 and 6 show the frequency distribution of the events according to their duration, with Figure 6 presented on a minute scale and Figure 7 on a second scale. It can be seen that most events lasted less than 30 seconds, highlighting the transient and short-term nature of these overirradiance occurrences. The duration of overirradiance events is one of the most important factors to be monitored. Depending on their intensity, the longer the events last, the greater the likelihood of some impact on the plants. It can be seen that in ESA01 (Fig. 5a and Fig. 6a), the longest events tend to occur throughout all months, with a slight predominance between January, February, and March. Very similar behavior is also observed in ESA02 (Fig. 5b and Fig. 6b) and ESA04 (Fig. 5d and Fig. 6d). In ESA02, the longest event was recorded on December 29, 2021, at 11:20 a.m. and lasted 368 seconds, reaching a maximum value of 1440 W/m² and an average value of 1428. 4 W/m². In ESA04, the longest event was recorded on November 13, 2022, at 11:13 a.m. and lasted 159 seconds, reaching a maximum value of 1420 W/m² and an average value of 1391.0 W/m².

ESA03 is the station that presented the most long-lasting events, and Figure 6c clearly shows that the longest events occur from December to March. The longest event at ESA03 was recorded on January 18, 2022, at 12:28 p.m. and lasted 535 seconds, reaching a maximum value of 1549 W/m² and an average value of 1501.2 W/m².

ESA04, in turn, despite being the station with the lowest number of events, has the highest percentage of long-lasting events, i.e., of the total number of events recorded, the percentage of longer-lasting occurrences is higher than the percentage of the other stations. The longest event at ESA05 was recorded on December 6, 2022, at 12:19 p.m. and lasted 186 seconds, reaching a maximum value of 1574 W/m² and an average value of 1498.3 W/m².

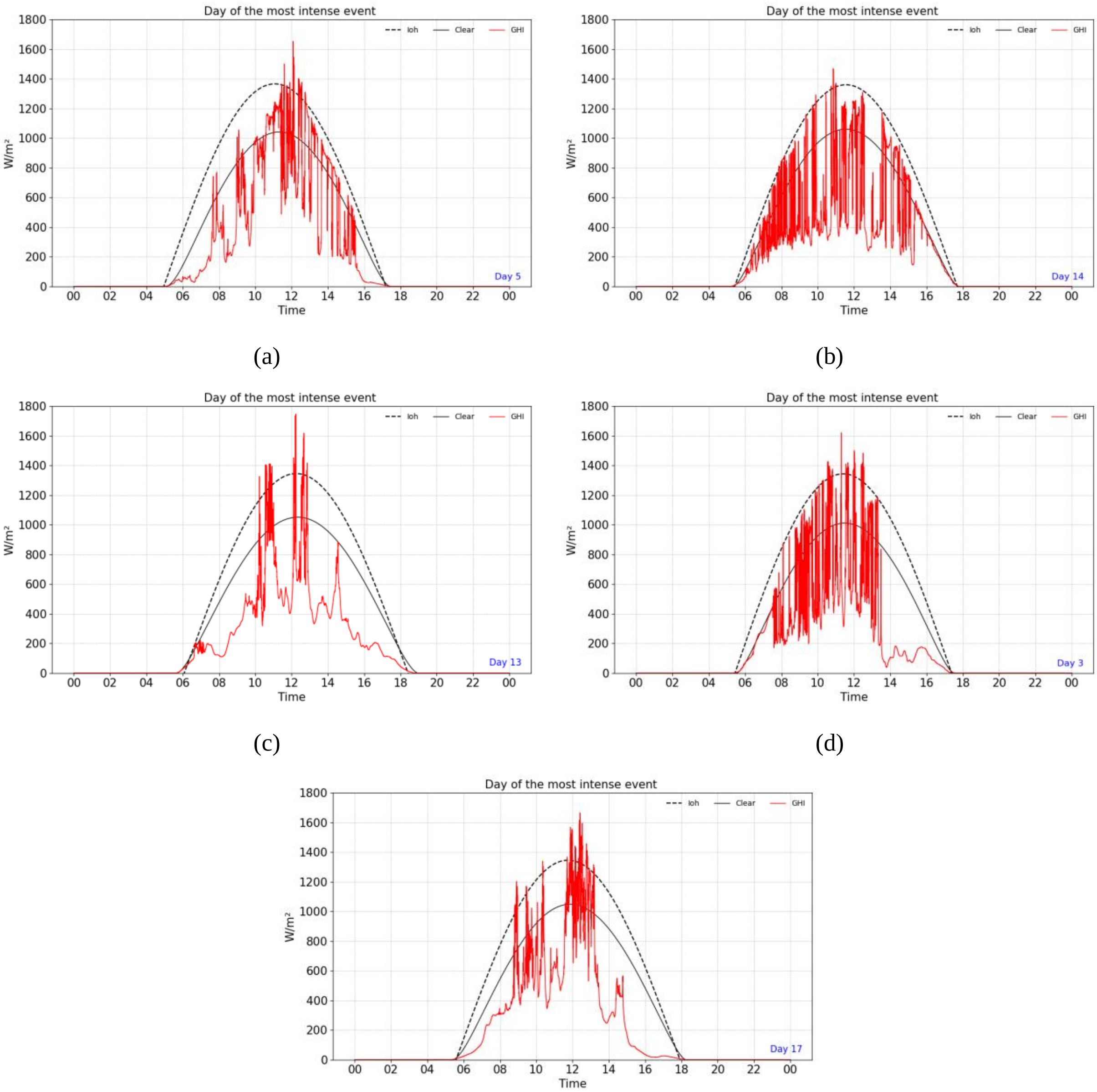
The most intense events recorded each month are illustrated in Figure 6. It should be noted that in ESA03, in January 2023, the most intense event of the entire period analyzed occurred, with a maximum irradiance of 1765 W/m², on January 6, 2023, at 12:11 p.m. This value is significantly higher than the standard test conditions (STC) under which photovoltaic modules are tested, which have a limit of 1000 W/m². ESA03 also stands out as the station with the most intense events recorded.

It was observed that ESA01 and ESA02 exhibit similar occurrence patterns, with these two stations registering the highest number of events, 5446 and 4025, respectively. ESA04, despite having a four-month data gap, recorded a total of 3314 events, with May 2022 showing the highest monthly count (462 events). ESA05 registered the lowest number of occurrences (1291) among the analyzed stations. One likely explanation is that the regions where ESA01, ESA02, and ESA03 are located tend to experience greater cloud cover compared to ESA05. ESA03 recorded a total of 1759 events and exhibited a well-defined seasonal pattern. Few events were observed during the winter, which may be associated with a higher incidence of clear-sky days. In addition to its seasonality, ESA03 also registered the most intense overirradiance events. The intensity values observed are consistent with those reported by do

Nascimento et al. (2019). The daily irradiance profile for the day with the highest intensity of the over-irradiance event at each station is shown in Figure 7, where a significant presence of clouds and, in some cases, precipitation can be observed. These findings indicate that the effect is associated with cloud cover and high atmospheric humidity, corroborating the results reported by Segal and Davis (1992), Piacentini et al. (2011), and de Andrade and Tiba (2016).

Figure 5: Distribution of the duration of overirradiance events at minute resolution at stations (a) ESA01, (b) ESA02, (c) ESA03, (d) ESA04, and (e) ESA05. The gray bar represents the absence of OIE events, while the red bar represents that no data is available.

Figure 6: Distribution of the duration of overirradiance events at second resolution at stations (a) ESA01, (b) ESA02, (c) ESA03, (d) ESA04, and (e) ESA05. The gray bar represents the absence of OIE events, while the red bar represents that no data is available.



(a) (b) (c) (d) (e)

Figure 7: Daily irradiance profiles on the days with the highest intensity of over-irradiance events at each station, highlighting the presence of clouds and, in some cases, precipitation.

4. Conclusion

This study presented the results of the analysis of overirradiance monitored by five solarimetric stations located in different regions of Brazil, between November 2021 and January 2023. All regions monitored by these stations experienced overirradiance events with high intensities and duration. The highest irradiance value was recorded at the ESA03-Ilha Solteira/SP station, reaching a value of 1765 W/m², considerably above the reference irradiance under Standard Test Conditions (STC). At the same station, the longest event was also observed, with 569 consecutive seconds above the overirradiance threshold. The station with the highest total number of events was ESA01-Sousa/PB, with 5446 recorded occurrences, where the month of August 2022 stood out for having the highest monthly volume of events, with 768 records, among all the stations analyzed.

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6. References

Alvares, C. A., Stape, J. L., Sentelhas, P. C., Gonçalves, J. L. de M., & Sparovek, G. (2013). Köppen's climate classification map for Brazil. Meteorologische Zeitschrift, 22(6), 711-728. doi:10.1127/0941-2948/2013/0507

Braga, M., Campos, R.A., do Nascimento, L.R., Santos, E.M., Rüther, R., 2018. Avaliação de desempenho de diferentes tecnologias fotovoltaicas em irecê, ba, in: VII Congresso Brasileiro de Energia Solar-CBENS 2018.

da Costa, M.E.R., Emiliavaca, S.d.A.S., de Freitas, I.T.A., de Araújo, P.A.A., Mutti, P.R., 2021. Análise da ocorrência de eventos de sobreirradiância em natal-rn, brasil, in: Congresso Brasileiro de Meteorologia.

de Andrade, R.C., Tiba, C., 2016. Extreme global solar irradiance due to cloud enhancement in northeastern brazil. Renewable energy 86, 1433– 1441.

Emiliavaca, S. A. S, & Rodrigues, S. A. (2025). Análise do Espectro da Radiação Solar na Cidade de Natal-RN. Revista Brasileira De Energia Solar, 16(1), 28–38. https://doi.org/10.59627/rbens.2025v16i1.502.

Gueymard, C.A., 2017. Cloud and albedo enhancement impacts on solar irradiance using high-frequency measurements from thermopile and photodiode radiometers. part 1: Impacts on global horizontal irradiance. Solar Energy 153, 755–765.

Jara, M.Z., Berg, H., Conde, L., Sevillano-Bendezú, M., Carhuavilca, A., Grieseler, R., Töfflinger, J., 2021. Extreme overirradiance events and their spectral distribution in lima, peru, in: Journal of Physics: Conference Series, IOP Publishing. p. 012006.

Luoma, J., Kleissl, J., Murray, K., 2012. Optimal inverter sizing considering cloud enhancement. Solar energy 86, 421–429.

Piacentini, R.D., Salum, G.M., Fraidenraich, N., Tiba, C., 2011. Extreme total solar irradiance due to cloud enhancement at sea level of the ne atlantic coast of brazil. Renewable Energy 36, 409–412.

Rabl, A., 1985. Active solar collectors and their applications. Oxford University Press on Demand.

Tapakis, R., Charalambides, A., 2014. Enhanced values of global irradiance due to the presence of clouds in eastern mediterranean. Renewable energy 62, 459–467.

Teixeira, V.A., de OP Filho, M.H., 2020. Análise da influéncia do efeito borda de nuvem sobre os parámetros elétricos da rede ca em sistemas fv conectados á rede. Avances en Energías Renovables y Medio Ambiente-AVERMA 24, 130–138.

Yordanov, G.H., Midtgård, O.M., Saetre, T.O., Nielsen, H.K., Norum, L.E., 2013. Overirradiance (cloud enhancement) events at high latitudes, in: 2012 IEEE 38th photovoltaic specialists conference (PVSC) part 2, IEEE. pp. 1–7.

Horner, N., Braga, M., Mantelli, S.L., Rüther, R., 2023. Eventos de sobreirradiância em sistemas fotovoltaicos em Florianópolis – SC. Revista Brasileira de Energia Solar 14 (1), 11–20. https://doi.org/10.59627/rbens.2023v14i1.419

da Silva, L. S., Emiliavaca, S. D. A. S., de Sousa, A. R., de Souza, V. R. S., de Oliveira, J. V., do Nascimento, B., ... & de Araujo, P. A. A., 2024. Procedimento para qualidade de dados solarimétricos em estações padrão EPE com medição de albedo. In Anais Congresso Brasileiro de Energia Solar-CBENS.

Martins, G. L., Mantelli, S. L., & Rüther, R. (2022). Evaluating the performance of radiometers for solar overirradiance events. Solar Energy, 231, 47-56.

Nascimento, L. R., de Souza Viana, T., Campos, R. A., & Rüther, R. (2019). Extreme solar overirradiance events: Occurrence and impacts on utility-scale photovoltaic power plants in Brazil. Solar Energy, 186, 370-381.Reference to a journal publication