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Solar Over-Irradiance Events: Preliminary Results from a Global Study

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Abstract— **This paper presents a methodology and preliminary results from a global study of solar over-irradiance events, which happen more often than previously believed and can harm utility-scale PV operations by interfering with a site's power electronics. Data from five test sites in Florianópolis and Brotas de Macaúbas in Brazil, Bernburg in Germany, Albuquerque, in the USA and Loughborough, in the United Kingdom are presented and analyzed.**

Keywords— Over-irradiance; Irradiance enhancement; Solar irradiation; PV system performance.

I. Introduction

Over-irradiance, defined as a magnification of irradiance reaching the earth's surface, occurs all over the world and has been reported in the literature for many decades ([1] and references therein), but more as a scientific curiosity than as an issue of economic or technical importance for photovoltaic (PV) systems. A recent study, however, [1] showed that over-irradiance events impact the performance of utility-scale PV power plants, especially when the events last longer than 1 min and occur when ambient temperatures exceed 30°C. Under those conditions, a sudden burst of over-irradiance can blow string fuses and overload inverters, leading to energy losses. In other words, it is the extended high magnitude events that are most concerning to plant operations.

Yet the occurrence of over-irradiance events and their effects on PV power plants are not well quantified, largely because over-irradiance is so brief in duration (generally less than 5 seconds per episode) and therefore requires high-frequency (~1 s) sampling of irradiance to be detected. In addition, the impact of over-irradiance on a PV system's power electronics depends on location and climate, which in turn determine the fuse operating temperature, and on the overall design of the PV system.

Worldwide measurements to further PV research in multiple areas, including over-irradiance, that affect the performance of power plants, are badly needed. To address that need and to ensure that data generated globally is similar in quality, multiple research organizations decided to form PV CAMPER ("PhotoVoltaic Collaborative to Advance Multiclimate Energy Research") [2]. PV CAMPER represents a global research platform with common infrastructure and protocols to address persistent PV performance challenges (uncertainty drivers, degradation rates, soiling losses, component failures), increase the accuracy of performance models, and to generate a set of best practices for data monitoring and collection.

This over-irradiance study, which is one of several PV CAMPER collaborative research projects, aims to identify solar over-irradiance events, their prevalence and duration at PV CAMPER member sites and evaluate their impact on utility-scale PV performance across different sites/climates. The purpose of this paper is to present the methodology implemented in the study and its preliminary results for five different locations: Florianópolis and Brotas de Macaúbas in Brazil, Bernburg in Germany, Albuquerque in the USA, and Loughborough in the United Kingdom.

II. Background

The research presented here reflects a joint effort by members of PV CAMPER, a cross-climate, worldwide network of research institutions committed to sharing data and advancing collaborative work related to PV performance and variability, and uncertainty in the measurement of the solar resource [2], [3]. To that end, PV CAMPER membership requires participating institutions to have well-maintained field sites with comparable meteorological and irradiance instrumentation and to commit to a common set of data-quality standards. PV CAMPER's 11 founding members collectively represent a total of 17 field sites spread across the world's main climatic zones (see Fig. 1 and [2]). To support the work being undertaken and benefit the PV industry, PV CAMPER has established a global data repository for

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meteorological and performance data that is accessible to its members [4].

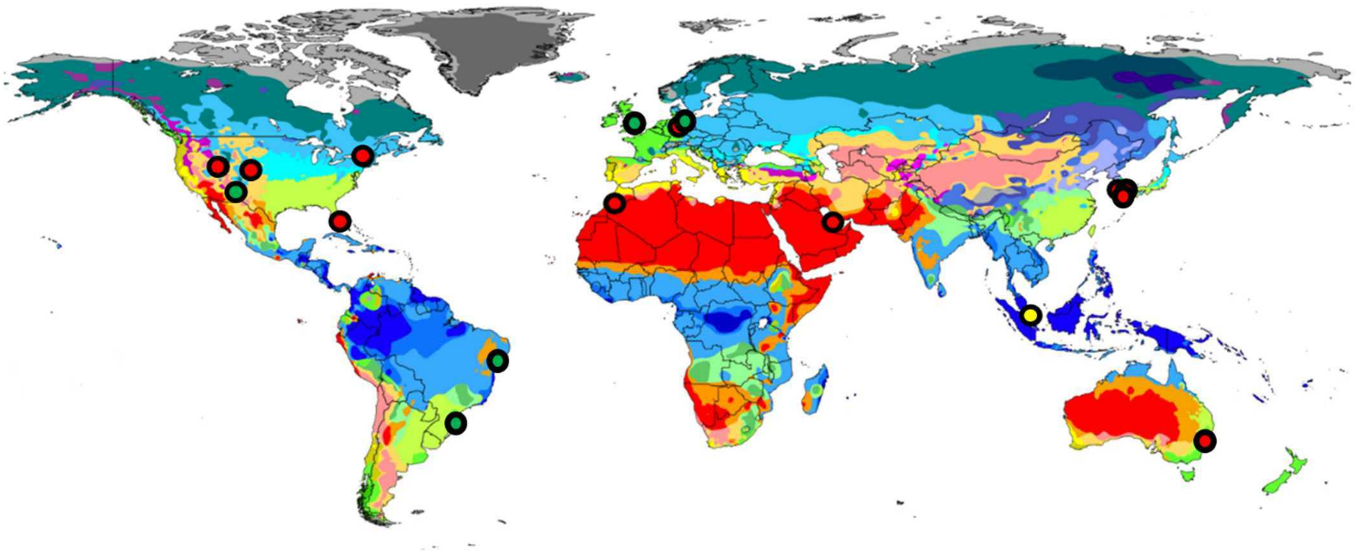

Fig. 1. PV CAMPER research sites are represented by circles superimposed on this Köppen-Geiger climate map. Sites participating in the over-irradiance study are represented by yellow and green circles. Sites contributing data to this paper are the green circles. Additional PV CAMPER test sites are shown as red circles. Map adapted from [5].

Although PV CAMPER has several research initiatives underway, this study is focused on over-irradiance, with an aim to better understand the frequency and severity of the phenomenon globally and to identify patterns that support the development of predictive models or robust PV system designs for high-risk areas.

III. Over-irradiance Effects

Over-irradiance events occur when a visible cloud-brightening event (cloud enhancement- or cloud-edge effect) causes a magnification of solar irradiance. Under these situations, values of global horizontal irradiance (GHI) or global tilted irradiance (GTI) exceed typical clear-sky levels and even the extraterrestrial irradiance (ETH) [6].

More specifically, horizontal over-irradiance events can be defined as events in which the clearness index, K_T=GHI/ETH, is greater than one [6]. Extreme over-irradiance events are also possible: in this study, the term is used to identify detected over-irradiance events in GTI measurements. Because the tilted-plane equivalent of K_T is numerically unstable for specific periods, or rather the sun angles to the tilted plane are unstable [7], the detection of such events is performed here by identifying GTI values higher than the solar constant, G_0, that although not necessarily a constant, is taken here as 1366.1 W/m^2 [8].

The analysis of over-irradiance events entails many challenges. Temporal resolution is crucial as it influences the magnitude, time of occurrence, and the number of events detected. Therefore, fast-response irradiance sensors, capable of collecting data at 1-second intervals, are recommended for measuring peaks in GHI [6]. Handling these fast measurements, however, also requires rigorous experimental procedures such as calibration, maintenance, cleaning, and precise data quality control.

IV. Research Locations

The locations from which data for this study was collected are listed in Table I and also shown as green circles on the map in Fig. 1. As can be seen, these sites coincide with regions of interest for PV systems and collectively represent hot-humid, temperate and hot-arid climates. Previous work at the test site BRA-BTS has already already indicated that over-irradiance effects are common in the region and of sufficient magnitude to impact power-plant operations [1][9]. This paper is a partial extension of that research.

TABLE I. Test Sites

Member	Test Site	Location	Latitude	Longitude	Altitude	Climate[a]
UFSC	BRA FLN	Florianópolis, Brazil	27.43°S	48.44°W	5 m	Cfa
UFSC	BRA BTS	Brotas de Macaúbas, Brazil	12.31°S	42.34°W	1112 m	Aw
Anhalt University	GER BBG	Bernburg, Germany	51.77°N	11.766°E	80 m	Cfb
Sandia National Labs	USA ABQ	Albuquerque, United States	35.05°N	106.54°W	1660 m	BSk
CREST	UK LBO	Loughborough, United Kingdom	52.76°N	1.24°W	65m	Cfb

a. According to the Köppen-Geiger climate classification.

V. Experimental Methodology

Each PV CAMPER research site contributed one year of high-resolution irradiance data to this study . Fig. 2 presents an example of a solar measurement station at the Fotovoltaica-UFSC field laboratory (www.fotovoltaica.ufsc.br), at the

Universidade Federal de Santa Catarina (UFSC), in the city of Florianópolis-SC, southern Brazil.

For all sites shown in this paper, data are sampled and stored at 1 s time intervals, a resolution needed to detect short (< 5 sec) bursts of irradiance, with the exception of the GER-BBG test site, where data is sampled on a 1 s basis but stored as 10 s averages. All irradiance sensors across the five sites are of similar high quality and are regularly cleaned and calibrated. Table II provides the specifications for each sensor type used for this research. At both Brazilian sites, SRF-02 all-sky cameras are also employed and provided data for this study.

TABLE II. INSTRUMENTATION

Test Site	Sampling / Averaging Intervals	Global Tilted Irradiance	Global Horizontal Irradiance	Diffuse Horizontal Irradiance
BRA-FLN	1s / -	SMP11-V Pyranometer (LT)	SMP22-V Pyranometer	SMP22 Pyranometer on tracker with shading ball
BRA-BTS	1s / -	CMP11 Pyranometer (LT)	SMP11-V Pyranometer	SPN1 Pyranometer
GER-BBG	1s / 10s	SMP10-V Pyranometer (35°)	SMP10-V* Pyranometer	SMP10-V* Pyranometer on tracker with shading ball
USA-ABQ	1s / -	CMP11-V Pyranometer (LT)	CMP22-V Pyranometer	Eppley 848 Pyranometer on tracker with shading ball
UK-LBO	1s / -	CMP11 Pyranometer (34°)	CMP11-V Pyranometer	CMP11-V Pyranometer on tracker with shading ball

* not considered in this paper

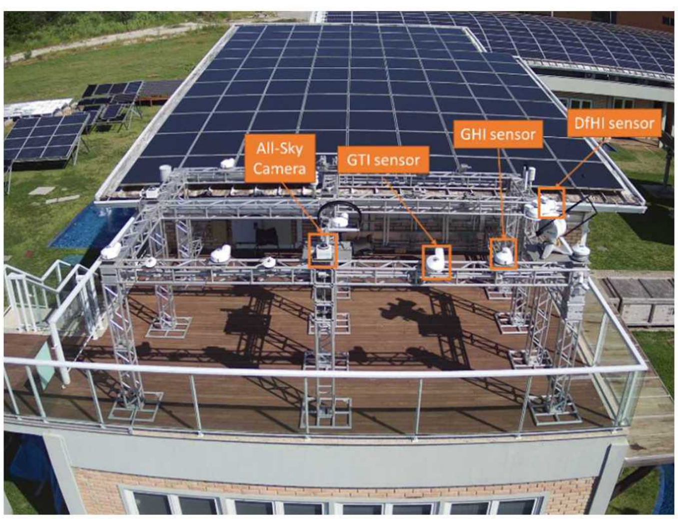

Fig. 2. BRA-FLN test site solar measurement station located at the Fotovoltaica-UFSC research laboratory in Florianópolis, Brazil (27°S, 48°W), 5m altitude.

VI. DATA ANALYSIS

One year of data was acquired from each of the field sites identified in Table I and for all the sensors listed in Table II. All GHI data for that year were processed, flagged, and filtered according to the quality-check algorithm proposed by the Baseline Surface Radiation Network (BSRN) [10]. No such standard quality-check procedure currently exists for tilted irradiance measurements [6], so simple quality checks and a visual inspection for erroneous GTI data were conducted.

In this study, over-irradiance events are defined as events in which the clearness index, K_T=GHI/ETH, is greater than 1.0 [6]. The calculation of the ETH follows the equations described in [11]. Extreme over-irradiance events are identified as having GTI values higher than the solar constant, G_0.

Fig. 3 presents a flowchart for the data analysis process used in this study, culminating in the detection of over-irradiance and extreme over-irradiance events within the datasets.

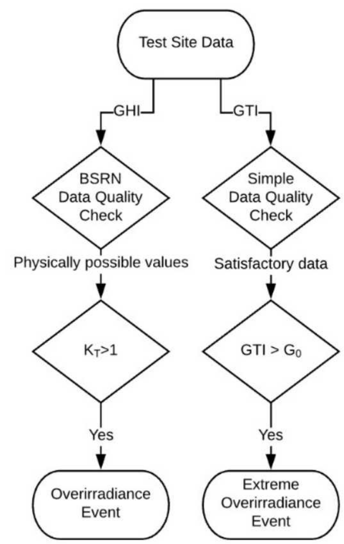

Fig. 3. Data quality check and analysis flowchart.

VII. RESULTS AND DISCUSSION

Fig. 4 presents the distribution of over-irradiance events throughout the year for the BRA-FLN field sites, showing the monthly average diffuse fraction. The total number of events for 2019 and the percentage of days in which over-irradiance events were detected are also provided. As the figure shows, over-irradiance events are evenly distributed throughout the year, with a smaller number of events happening between April and September, which are slightly drier months compared to rainier spring and summer months. The fact that humid subtropical climates (Cfa) typically have little difference in precipitation between seasons might be the reason for the uniformity of over-irradiance events throughout the year.

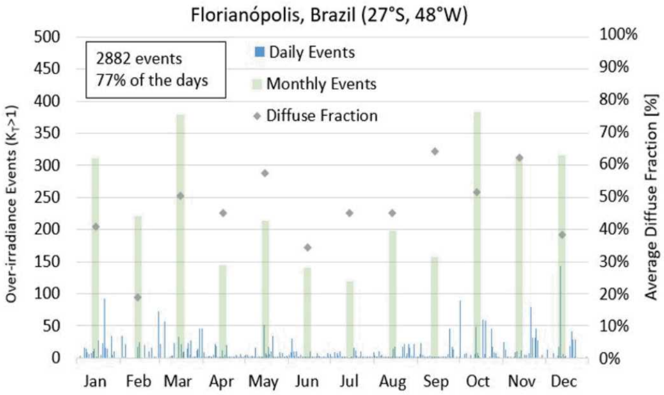

Fig. 4. Daily (blue narrow bars) and monthly (light green bars) distribution of horizontal over-irradiance events (K_T>1) identified throughout 2019 for the BRA-FLN site in southern Brazil. Monthly average diffuse fraction is also presented (gray diamonds).

The field sites at lower latitudes (BRA-FLN and BRA-BTS) are exposed to smaller ranges of solar elevation angle over the year, but also these sites use latitude-tilt test planes, which gives rise to two annual minima in the solar angle of incidence to the GTI sensors, at the equinoxes. In Fig. 5, corresponding maxima in the frequency of extreme over-irradiance events can be seen at these times. Overlaid are effects of climate seasonality. At the BRA-FLN site, most events occur during the summer (January through March), accounting for nearly 60% of that site's events in 2019. Spring is also an active time for over-irradiance, and contributes to another 35% of the events. Besides having intrinsically lower irradiance values, winter is also a low-precipitation period in the region, usually associated with clear blue skies, reducing the frequency of cloud-edge effects and thus the occurrence over-irradiance events.

The BRA-BTS site shows frequent extreme over-irradiance events in March, April and September, months with high irradiation [9], [12], in addition to the near-normal solar incidence to the test plane. BRA-BTS is located within a tropical savanna climate region with dry winter (Aw), which hinders the formation of clouds in winter months, explaining the low frequency of extreme irradiance events between May and July.

The USA-ABQ site presents a similar distribution profile, however much more accentuated: 76% of all registered extreme irradiance events happened between February and March, and another 21% between August and October. The preponderance of events in winter may be attributable to an increase in diffuse irradiation but could also be a function of a low incident angle on a latitude-tilt pyrometer near the equinox. Another possibility is that events occurring primarily in the morning are exacerbated by solar reflectivity from adjacent PV systems or other reflective surfaces. Further investigation is warranted and will be included in a future analysis.

The increase of extreme irradiance events between August and October might be related to slightly higher precipitation since cold semi-arid climates (BSk) at higher latitudes tend to have dry winters and wet summers; sky images would help make that determination and will also be included in a future study

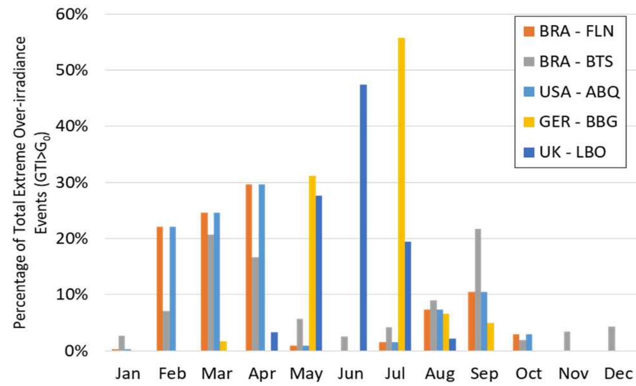

Fig. 5. Monthly distribution of tilted extreme over-irradiance events (GTI>G_0) detected throughout a full year of data for all five test sites: BRA-FLN (orange bars), BRA-BTS (gray bars), USA-ABQ (light-blue bars), GER-BBG (yellow bars) and UK-LBO (dark-blue bars).

The diurnal distribution of tilted extreme over-irradiance for the five sites is presented in Fig. 6. As expected, these events are most likely to happen during peak irradiance hours. Over-irradiance events (K_T>1) are also registered in lower irradiance periods of the day, typically at times corresponding to very low solar elevation angles. However, these events, despite exceeding the ETH at that moment, are unlikely to register significant irradiance levels (due to being an artifact of low in-plane beam component and the lack of diffuse component to the ETH). Therefore, they do not pose risks to PV plant performance in the way that over-irradiance events at higher irradiance levels do.

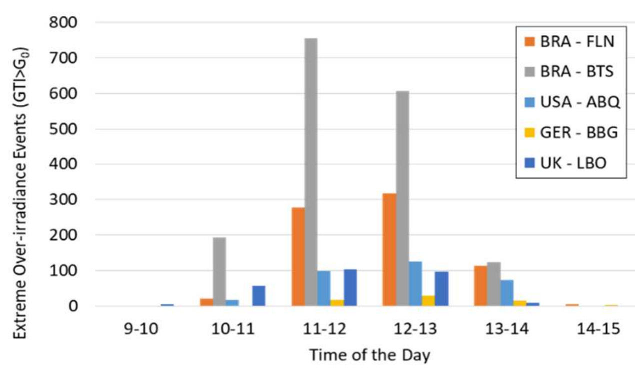

Fig. 6. Distribution of registered tilted extreme over-irradiance events (GTI>G_0) according to their time of occurrence throughout the day for the five test sites: BRA-FLN (orange bars), BRA-BTS (gray bars), USA-ABQ (light-blue bars), GER-BBG (yellow bars) and UK-LBO (dark-blue bars).

Fig. 7, Fig. 8 and Fig. 9 show irradiance measurements corresponding to the highest GHI values at the respective test sites. In BRA-BTS, peak GHI coincides with the GTI peak, whereas in USA-ABQ, GTI and GHI peak a few seconds apart. The three graphs also indicate, as evidenced by diffuse horizontal irradiance (DfHI) measurements, the strong correlation between over-irradiance events and cloud-covered skies. This correlation is also visible in Fig. 10 that shows an all-sky camera image of sky conditions during the maximum over-irradiance event registered for the BRA-FLN site.

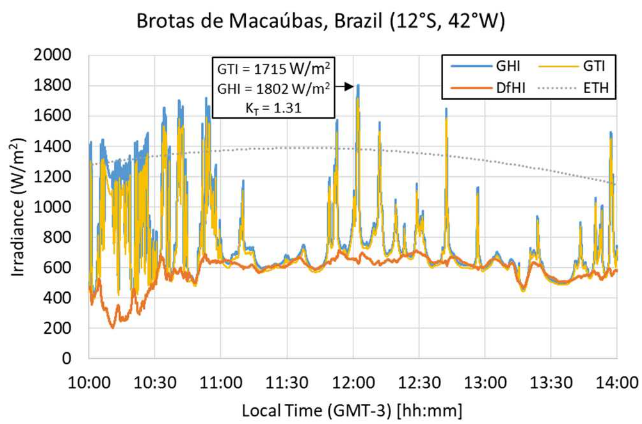

Fig. 7. Highest overall GHI and GTI values of 1802 W/m² (K_T=1.31) and 1715 W/m², respectively, occurred at the BRA-BTS test site on November 27th, 2019.

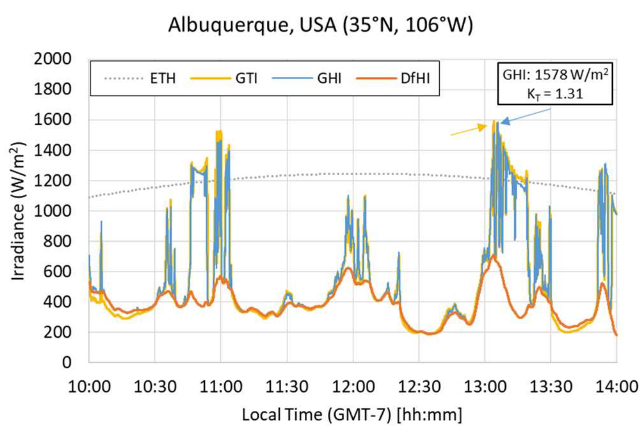

Fig. 8. Highest GHI and GTI values at the USA-ABQ site reached 1578 W/m² (K_T=1.31) and 1592 W/m², respectively. on April 23rd, 2019..

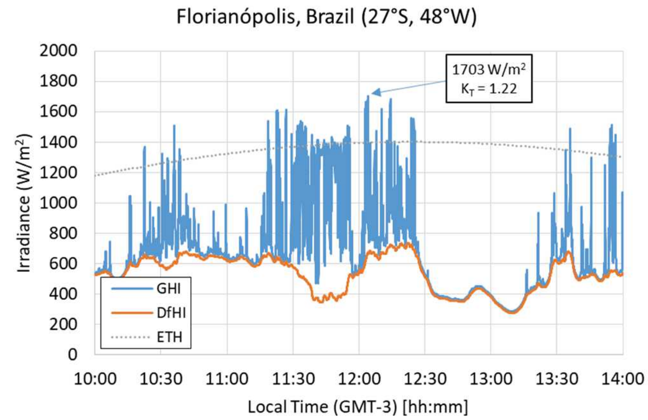

Fig. 9. Highest GHI measurement for the BRA-FLN test site was 1703 W/m² (K_T=1.22).on January 20th, 2019.

From Fig. 7, Fig. 8 and Fig. 9 it can also be observed that GHI may or may not fall back to DfHI values, after an irradiance peak. Sometimes the GHI values decrease, but they also may stay well above DfHI values. These different patterns are attributable to different cloud geometries and thicknesses, which can vary greatly according to local climate. More investigation is necessary to correlate these findings to sky images.

Fig. 10. All-sky camera image illustrating the sky conditions at the moment in which the highest GHI value was registered for the BRA-FLN site on January 20th, 2019, 1703 W/m² (K_T=1.22).

The duration of the detected over-irradiance events is shown in Table III. While most of the occurrences have a duration of less than 5 sec, 7% of horizontal over-irradiance events are sustained for over 1 min, long enough to impact the power electronics of a PV system. In the case of tilted extreme over-irradiance events, only 3.5% are in the minute-range and only one event, measured at the BRA-BTS site, lasts longer than 5 min. In a PV power plant, irradiance bursts in the one-minute range occurring concurrently with high equipment operating temperatures can cause even slow-blow fuses to fail [1].

TABLE III. DURATION OF OVER-IRRADIANCE EVENTS

Duration	Horizontal Over-irradiance Events (K_T>1)				Tilted Extreme Over-irradiance Events (GTI>G_0)				
	BRA FLN	*BRA BTS*	*USA ABQ*	*UK LBO*	*BRA FLN*	*BRA BTS*	*GER BBG*	*USA ABQ*	*UK LBO*
Shorter than 5s	1077	4857	812	1381	380	772	54	124	163
Between 5s and 10s	511	2021	479	605	152	335	7	67	53
Between 10s and 30s	682	2633	623	762	144	369	0	87	42
Between 30s and 1 min	263	1089	237	267	37	126	0	27	9
Between 1 and 5 min	344	630	195	157	21	75	0	8	1
Longer than 5 min	5	21	15	2	0	1	0	0	0
Total	2882	11251	2361	3174	734	1678	61	313	268

In addition to quantifying the frequency of long duration over-irradiance events, this study also demonstrates that multiple over-irradiance events can occur within a short time interval, resulting in a clustering pattern. This pattern is visible in Table IV, which shows the time interval between tilted extreme over-irradiance events for four test sites.. The sites present very similar patterns for the occurrence of subsequent events, even though they are located in significantly different climate zones and latitudes.

At least 49% of the tilted extreme over-irradiance events at the four sites happened less than a minute after the previous event. This finding is of serious concern for PV plants because high-current generating events occurring in quick succession can have an additive effect, increasing the temperature of cables, fuses and PV module. Such events can also affect inverter MPPT tracker efficiency, also reducing power output.

TABLE IV. TIME INTERVAL BETWEEN TILTED EXTREME OVER-IRRADIANCE EVENTS

Time Interval between Events	BRA FLN	BRA BTS	USA ABQ	UK LBO
Less than 5s	13%	15%	12%	14%
Less than 10s	23%	27%	23%	24%
Less than 15s	30%	33%	30%	28%
Less than 30s	40%	44%	44%	41%
Less than 60s	50%	54%	57%	49%
Less than 5min	74%	76%	73%	67%
More than 5min	26%	24%	27%	33%

Table V and Table VI present a summary of this study's findings for over-irradiance and extreme over-irradiance events, respectively, for the five PV CAMPER member sites. The sites' recorded GHI peak measurements (1802 W/m2 in BRA-BTS, 1703 W/m2 in BRA-FLN, 1578 W/m2 in USA-ABQ and 1426 W/m2 in UK-LBO) represent respectively the 5th, 8th,14th and 24th highest GHI events recorded worldwide [1], a remarkable result considering the modest period (one year) of data analyzed thus far.

TABLE V. SUMMARY OF HORIZONTAL OVER-IRRADIANCE EVENTS FOR THE EVALUATED SITES

	BRA FLN	BRA BTS	USA ABQ	UK LBO
Number of Over-Irradiance Events	2882	11251	2361	3174
Maximum Peak (W/m^2)	1703	1802	1578	1426
Maximum Peak Date	20/01/19	27/11/19	23/04/19	15/06/19
Maximum Peak Event Duration (s)	16	80	64	2
Maximum Peak K_T	1.22	1.31	1.31	1.24
Longest Event Duration (s)	467	1159	1291	388
Longest Event Date	24/04/19	11/04/19	17/02/19	01/07/19

TABLE V. THE FOUR PEAK VALUES HIGHLIGHTED ABOVE ARE (FROM LEFT TO RIGHT) T*HE 5TH, 8TH,14TH AND 24TH HIGHEST GHI EVENTS RECORDED WORLDWID*E, SUGGESTING THAT GLOBAL OVER-IRRADIANCE EVENTS ARE GROSSLY UNDER-ESTIMATED.

TABLE VI. SUMMARY OF TILTED EXTREME OVER-IRRADIANCE EVENTS FOR THE EVALUATED SITES

	BRA FLN	BRA BTS	GER BBG	USA ABQ	UK LBO
Number of Extreme Over-irradiance Events	734	1678	61	313	268
Maximum Peak (W/m^2)	1685	1715	1546	1592	1570
Maximum Peak Date	23/09/19	27/11/19	05/07/19	23/04/19	15/06/19
Maximum Peak Event Duration (s)	13	64	10	9	38
Longest Event Duration (s)	204	308	90	117	93
Longest Event Date	11/03/19	22/02/19	06/05/19 03/07/19	14/03/19	15/06/19

VIII. CONCLUSIONS

This paper presents preliminary results on the frequency and duration of over-irradiance events for five PV CAMPER member research sites in Brazil, Germany, the USA and the UK. The results presented so far suggest that 1) over-irradiance events are far more common at low altitudes than previously presumed; 2) a full understanding of over-irradiance as it impacts PV operations requires high frequency GHI and GTI data; and 3) over-irradiance is a serious but unrecognized concern for utility-scale power plants (for both plant design and operation), with a significant number (7.0%) of over-irradiance events lasting one minute or longer and more than half of extreme over-irradiance events occurring in quick succession. These findings are especially concerning as over-irradiance—combined with high operating temperatures—may lead to widespread fuse failures in utility-scale PV plants and inverter clipping.

We look forward to collecting and analyzing data from more sites worldwide to better understand patterns of over-irradiance occurrences, to correlate the later with PV plant failures and energy losses and to develop a technical basis for future mitigation strategies.

IX. Future Work

Future investigations will include a study of over-irradiance monitoring using different sensor types and time resolutions and also a more thorough analysis of factors, such as cloud types and diffuse ratio, that influence the occurrence of such events in different climates. Future investigations will also include collecting O&M and performance data from utility-scale PV systems and correlating the later with irradiance data. In addition, the PV CAMPER initiative aims to continue the over-irradiance study, expanding the analysis to other member sites.

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