Extreme Overirradiance events and their spectral distribution in Lima, Peru

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Abstract. We report on 'extreme overirradiance' events measured in Lima, Peru. The highest measured irradiance value was 1543 W/m² on March 23rd, 2020. The measurements were carried out by four different, independent instruments, all simultaneously recording their maximum values. The spectral distribution of the extreme overirradiance event was also recorded and compared to the spectral distributions of a clear and a cloudy sky. The extreme overirradiance phenomenon demonstrated an irradiance enhancement in the entire measured spectrum, but predominantly in the visible and the near infrared region of the spectrum (450 nm to 1100 nm). This spectral enhancement leads to a redshift of the spectrum during the extreme overirradiance event, as is observed by its lower average photon energy in comparison to the clear and cloudy sky spectra.

1. Introduction

The solar constant of 1367 W/m² is the average irradiance received at the equatorial belt by satellites outside the earth’s atmosphere with air mass 0 (AM0) [1]. This solar constant includes the entire solar spectrum range, from X-rays to microwaves. The solar constant is not a physical constant, but an average, depending on several factors such as the sun’s temperature, the distance between sun and earth, sun spots and more.

The earth’s atmosphere absorbs, reflects and disperses the solar radiation at most wavelengths [2]. X-rays and the UVC are totally absorbed by the ozone in the atmosphere. 99% of the UV radiation that reaches the surface of the earth is UVA. In the infrared (IR) range, the absorption is mainly due to water vapour, oxygen, and carbon dioxide. Therefore, the solar irradiance on the earth’s surface is reduced below 1367 W/m² with values and spectral distributions depending on location and time.

However, occasionally, the solar irradiance measured on the surface of the earth is higher than AM0. This phenomenon is described as 'extreme overirradiance' (EOI). Several singular events have been documented, as can be found for example in references [3–6].

Solar irradiance exceeding AM0 levels is observed when the unobstructed sun radiation is influenced by borders of clouds around the sun disc, for example through reflection. This is known as cloud enhancement (CE) [7–9]. Another explanation attributes the EOI to a strong forward
Mie-scattering of light inside the optically thin clouds. This forward Mie-scattering may occur not only at the edges of the thin clouds, but also within a narrow angle around the solar disk [3,6]. However, little is still known about the physical origin of these recorded events.

Recent studies concentrated on developing platforms to monitor EOI events [10]. Some recent works were motivated by possible impacts of EOI on the operational performance of photovoltaic plants [11–14]. In one of the last articles by Gueymard et al. [5], an overview of global horizontal irradiance (GHI) values measured by different types of instruments is given to study EOI events. Other studies demonstrate the impact of EOI event on the UV region and indexes [15–17]. However, an extensive search of the literature by the authors did not find any prior report on the spectral distribution of EOI events from UV to near IR, as can be obtained by a spectroradiometer. An analysis of the spectral distribution may shed more light on the physical origin of such events.

This article reports on the three highest EOI events recorded in Lima on three different days between October 2019 and April 2020. These EOI events were measured using four independent sensors: two pyranometers, one calibrated mini-module and a spectroradiometer. The latter gives information on the impact of the EOI event on the spectral distribution.

2. Methodology

Two class A, secondary standard pyranometers (EKO MS-80), one for the global horizontal irradiance (GHI) and one for the global tilted irradiance (GTI), a polycrystalline calibrated PV mini module and a spectroradiometer (EKO MS-711, spectral range 300 nm – 1100 nm), were used to measure the solar irradiance and its spectral distribution. The tilted pyranometer, the spectroradiometer and the PV mini module are on the same plane tilted at 20° degrees. The instruments (Figure 1) are located at the PV Research Laboratory of the Physics Section at Pontificia Universidad Católica del Perú, in Lima, 12°04’18” S 77°04’49” W and 54 m ASL. [18]

![Figure 1. PV Research Laboratory at PUCP equipped with pyranometers, calibrated PV mini module and spectroradiometer.](image)

The pyranometers measure the total solar irradiance in W/m², while the calibrated PV mini module provides information in volts that can be correlated with the solar irradiance of the tilted pyranometer.

To calibrate the reference PV mini module, we determined the correlation between the PV mini module with the tilted pyranometer using the least squares method (LSM) and the data from a sunny day. In this case the data from March 11th, 2020 was used.
The spectroradiometer provides the spectral distribution of the solar irradiance in W/m²/nm and thus requires a numerical integration to obtain the global solar irradiance. Furthermore, to expand the spectroradiometer range from the measuring range of 300 nm to 1100 nm to the full solar spectrum range of 300 nm to 4000 nm, we realized an extrapolation according to Martín and Ruiz [19]. Using this procedure, it was possible to compare the irradiance measurements of the spectroradiometer with the tilted pyranometer and the calibrated PV mini module.

All devices simultaneously collect data approximately every 38 seconds during daylight, collecting each day little more than 1050 different data sets. For data processing we used the computer programme RStudio.

The spectral distribution can be quantified by the Average Photon Energy (APE) which represents the average energy per photon in a defined spectral range, in our case from 350 nm to 1050 nm. The APE can indicate if the solar irradiance spectrum is either blue shifted or red shifted in respect to a reference spectrum. This can be an important information to evaluate the outdoor performance of PV modules [20–22]. The APE for standard test conditions at AM1.5 is 1.88 eV [21].

The APE is calculated by dividing the total energy of the spectral irradiance by the total number of photons, as show in Eq. (1) [22].

\[
APE [eV] = \frac{\int_{350}^{1050} E_\lambda \, d\lambda}{\int \frac{q}{hc} \, d\lambda} \tag{1}
\]

Here, q is the fundamental charge, E_\lambda is the spectral irradiance at wavelength \( \lambda \), h is the Planck constant \( h = 6.62606877 \times 10^{-34} \) Js and c is the velocity of light in the vacuum \( c = 2.99792458 \times 10^8 \) m/s.

### 3. Results and discussion

In Table 1 we show exemplarily three days with the highest values during EOI events observed between October 2019, and April 2020. The highest EOI value measured by a pyranometer (both GTI or GHI) on the corresponding day is shown. The highest overall value measured was using the tilted pyranometer with 1543 W/m² on March 23\textsuperscript{rd}, 2020 at 12:48:56 hours. This corresponds to more than 12% above the extra-terrestrial irradiance (1367 W/m²), and about 50% more than the maximum clear sky solar irradiance value expected in Lima for that day (~ 1000 W/m²). We also show the time when the highest EOI events occur, indicating that they all occurred around midday.

| Day            | Number of EOI events observed per day | Highest EOI (W/m²) | Hour of highest EOI |
|----------------|---------------------------------------|--------------------|---------------------|
| March 23\textsuperscript{rd}, 2020 | 2                                     | 1543               | 12:48:56            |
| January 13\textsuperscript{th}, 2020 | 5                                     | 1472               | 12:08:32            |
| October 25\textsuperscript{th}, 2019 | 8                                     | 1479               | 12:14:21            |

Figure 2 illustrates the irradiances measured by all instruments during March 23\textsuperscript{rd}, 2020, when the overall highest EOI event was observed with 1543 W/m² at 12:48:56 hours. The solar irradiance calculated using the extrapolated spectroradiometer data resulted in 1444 W/m² at 12:48:56 hours. The slight difference between these two instruments could be explained by the following factors: (1) All instruments measure simultaneously within a time interval of 1-3 seconds, which may result in a slight time difference between the measurements of both instruments; within this time interval the EOI values may change. (2) The difference may also originate from the extrapolation of the measured spectrum due to the distinct spectral responses of the pyranometer and the spectroradiometer. However, we can consider that all instruments measured practically simultaneously, as seen in the high correlation of the irradiance data confirming the detections of the EOI events by all instruments.

Furthermore, figure 2 shows a mostly clear and sunny sky until noon with a continuous increase of the irradiance curve. Only between 7:00 and 8:00 hours a slight enhancement of the irradiance can be
observed, possibly due to minor CE. However, between 12:00 and 14:00 hours, clouds appeared leading to a rapid change of the irradiance, leading to values lower than expected for a sunny day with 549 W/m² at 12:30:11 hours, as well as values much higher than expected with 1543 W/m² during the EOI. The difference between highest and lowest irradiance value within one hour is almost 1000 W/m². In the afternoon, after 15:00 hours more irradiance enhancement events can be observed.

Figure 2. Irradiance values on March 23rd, 2020 measured by four instruments at PV Research Laboratory – PUCP.

For comparison, table 2 lists the maximum values of EOI events reported worldwide that we found in our literature search. The maximum value recorded to date was 1891 W/m² in Colorado-USA, while in Lima it was 1543 W/m². Clearly, EOI events may occur anywhere in the world. Their occurrence does not seem to be restricted to specific latitudes, altitudes nor climatic regions.

| Reference                        | EOI (W/m²) | Location          | Altitude (MASL) | Latitude (°) |
|----------------------------------|------------|-------------------|-----------------|--------------|
| Gueymard (2017)                  | 1891       | Colorado, USA     | 1829            | 40° N        |
| Do Nascimento et al. (2019)      | 1845       | Ceará, Brazil     | 32              | 03°41’ S     |
| Emck and Richter (2008)          | 1832       | Andes, Ecuador    | 3400            | 04° S        |
| Yordanov et al. (2015)           | 1600       | Grimstad, Norway  | 60              | 58°20’ N     |
| **This work**                    | **1543**   | **Lima, Peru**    | **54**          | **12°04’ S** |
| Tapakis and Charalambides (2014) | 1533       | Cyprus            | 360             | 34.7° N      |
| Ramgolam and Soyjaudah (2014)    | 1532       | Mauritius         | 200             | 20° S        |
| Piacentini et al. (2003)         | 1528       | Atacama, Argentina| 3900            | 23.30° S     |
| Pfister et al. (2003)            | 1450       | Lauder, New Zealand| 370            | 45.04° S     |
| Inman et al. (2016)              | 1380       | Hawaii, USA       | 3               | 21°18’ N     |
Figure 3 takes a closer look at the GTI and GHI measured by the two pyranometers from 12:00 to 14:00 hours, the time interval in which the highest EOI event of interest occurred. For a more detailed analysis of the irradiance values and the respective spectral distribution, we chose 3 points A, B and C in the GTI curve, which correspond to 3 different categories: “A” for a clear sky as a reference with 1013 W/m², “B” for cloudy sky with 654 W/m², and “C” for the EOI event with 1543 W/m².

![Solar irradiance graph](image)

**Figure 3.** Irradiance values on March 23rd, 2020. Presence of clouds between 12:00 p.m. and 14:00 p.m. causes sudden changes in solar irradiance.

In figure 4, the corresponding spectral distributions for the aforementioned 3 points A, B and C are depicted. First, we compare point C, the EOI event detected on March 23rd, 2020 at 12:48:56 p.m., with the extra-terrestrial solar spectrum AM0. In the UV band (300 nm – 400 nm) the AM0 spectrum is above the EOI, between 400 nm to 450 nm they are similar, and from 450 nm to 1100 nm, the EOI is higher than the AM0 except for the absorptions bands of oxygen (760 nm) and water vapour (940 nm). We conclude that the EOI is more pronounced in the visible (VIS) and near infrared (NIR) regions (500 nm to 1100 nm).

When we compare the spectral distribution of the EOI “C” with the clear sky spectral distribution “A” we can see that the EOI’s spectral distribution is higher than clear sky’s spectrum in all wavelengths. This is particularly the case in the visible (VIS) and near infrared (NIR) regions. Furthermore, the EOI event has the lowest APE (1.900 eV) compared with the clear sky (1.925 eV) and cloudy sky (1.934 eV) respectively. This shows that the EOI event leads to a red-shift of the solar spectrum, whereas the cloudy sky leads to a blue-shift of the solar spectrum. This observation may help understand the physical origin of these EOI events, such as cloud enhancement and/or strong forward Mie-scattering. A more detailed analysis of their spectral distributions is currently in progress.
4. Conclusions
The EOI events are not only of theoretical scientific interest, but also of practical as demonstrated by prior scientific publications in this field. In this work we present, for the first time in Lima (Peru), EOI events that exceed the solar constant. During the months between spring and autumn we observed several EOI events, with the highest value reaching 1543 W/m². In addition, we analysed the respective spectral distribution of this particular event. The information from the spectroradiometer allows a more detailed analysis of the spectral bands. The enhancement occurs within the entire measured spectral region, from UV (300 nm) to near IR (1100 nm). However, the enhancement is stronger in the VIS and near IR, thus, red-shifting the spectral distribution in reference to one at clear sky conditions for Lima. This red-shift is observed as a reduction of the average photon energy. We recommend further detailed studies of the spectral changes during EOI events to better understand this phenomenon.

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References
[1] Gueymard C A 2004 The sun’s total and spectral irradiance for solar energy applications and solar radiation models *Sol. Energy* **76** 423–53
[2] Muneer T 2004 *Solar radiation and daylight models* (Amsterdam: Elsevier)
[3] Almeida M P, Zilles R and Lorenzo E 2014 Extreme overirradiance events in São Paulo, Brazil *Sol. Energy* **110** 168–73
[4] Emck P and Richter M 2008 An Upper Threshold of Enhanced Global Shortwave Irradiance in the Troposphere Derived from Field Measurements in Tropical Mountains J. Appl. Meteorol. Climatol. 47 2828–45
[5] Gueymard C A 2017 Cloud and albedo enhancement impacts on solar irradiance using high-frequency measurements from thermopile and photodiode radiometers. Part I: Impacts on global horizontal irradiance Sol. Energy 153 755–65
[6] Yordanov G H, Saetre T O and Midtgārd O-M 2015 Extreme overirradiance events in Norway: 1.6 suns measured close to 60°N Sol. Energy 115 68–73
[7] Piacentini R D, Salum G M, Fraidenraich N and Tiba C 2011 Extreme total solar irradiance due to cloud enhancement at sea level of the NE Atlantic coast of Brazil Renew. Energy 36 409-12
[8] Tapakis R and Charalambides A G 2014 Enhanced values of global irradiance due to the presence of clouds in Eastern Mediterranean Renew. Energy 62 459–67
[9] Yordanov G H, Saetre T O and Midtgārd O-M 2013 Optimal temporal resolution for detailed studies of cloud-enhanced sunlight (Overirradiance) 2013 IEEE 39th Photovoltaic Specialists Conference (PVSC) 2013 IEEE 39th Photovoltaic Specialists Conference (PVSC) pp 0985–8
[10] Chase O A, Teles M B, De Jesus dos Santos Rodrigues M, De Almeida J F S, Macêdo W N and Da Costa Junior C T 2018 A Low-Cost, Stand-Alone Sensory Platform for Monitoring Extreme Solar Overirradiance Events Sensors 18 2685
[11] do Nascimento L R, de Souza Viana T, Campos R A and Rüther R 2019 Extreme solar overirradiance events: Occurrence and impacts on utility-scale photovoltaic power plants in Brazil Sol. Energy 186 370–81
[12] do Nascimento L R, Braga M, Campos R A, Naspolini H F and Rüther R 2020 Performance assessment of solar photovoltaic technologies under different climatic conditions in Brazil Renew. Energy 146 1070–82
[13] Järvelä M, Lappalainen K and Valkealahti S 2020 Characteristics of the cloud enhancement phenomenon and PV power plants Sol. Energy 196 137–45
[14] Järvelä M and Valkealahti S 2020 Operation of a PV Power Plant during Overpower Events Caused by the Cloud Enhancement Phenomenon Energies 13 2185
[15] Tiba C and Silva Leal S da 2017 Enhancement of UV Radiation by Cloud Effect in NE of Brazil Int. J. Photoenergy 2017 e8107435
[16] Piacentini R D, Cede A and Bárcena H 2003 Extreme solar total and UV irradiances due to cloud effect measured near the summer solstice at the high-altitude desertic plateau Puna of Atacama (Argentina) J. Atmospheric Sol.-Terr. Phys. 65 727–31
[17] Feister U, Cabrol N and Häder D 2015 UV Irradiance Enhancements by Scattering of Solar Radiation from Clouds Atmosphere 6 1211–28
[18] Conde L A, Montes-Romero J, Carhuaivica A, Perich R, Guerra J A, Angulo J, Muñoz E, Töfflinger J A and De la Casa J 2019 Performance evaluation and characterization of different photovoltaic technologies under the coastal, desertic climate conditions of Lima, Peru Conf. Proc. 11
[19] Martín N and Ruiz J M 1999 A new method for the spectral characterisation of PV modules Prog. Photovolt. Res. Appl. 7 299–310
[20] Jardine C N, Betts T R, Gottschalg R, Infield D G and Lane K 2003 Influence of spectral effects on the performance of multijunction amorphous silicon cells 3rd World Conf. on Photovoltaic Energy Conversion May 11-18 (Osaka)
[21] Minemoto T, Nakada Y, Takahashi H and Takakura H 2009 Uniqueness verification of solar spectrum index of average photon energy for evaluating outdoor performance of photovoltaic modules Sol. Energy 83 1294–9
[22] Norton M, Amillo A M G and Galleano R 2015 Comparison of solar spectral irradiance measurements using the average photon energy parameter Sol. Energy 120 337–44