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# Average photon energy assessment based on modelled spectra from the National Solar Radiation Database for Lima, Peru

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**Abstract.** The photovoltaic performance under operating outdoor conditions is affected by the variability of the solar spectrum. The spectral distribution is quantifiable using the average photon energy (*APE*). In the present study, we characterize the spectral distribution in a low-latitude location such as Lima - Peru through a decade of simulated solar spectra obtained on demand from the National Solar Radiation Database and taking as a reference one year of ground-based experimental data following the decade of theoretical spectra. This characterization utilizes annual and monthly averages of irradiance-weighted *APEs*. The results indicate a difference of only 0.2% between the average annual *APE* for the decade and the annual ground-based experimental *APE*. Additionally, the theoretical monthly *APEs* for the decade show a seasonality consistent with our experimental data for the summer months but not for the winter months.

## 1. Introduction

The spectral distribution under operating outdoor conditions generally differs from the AM1.5G spectrum under standard test conditions (STC) at which the photovoltaic (PV) modules are rated by the manufacturers. Consequently, considering the spectral distribution of the solar resource can positively impact the estimation of the power of operating PV generators [1]. In contrast, its disregard can be a source of uncertainty in the economic models of PV projects. The temporal changes and fluctuations of the spectral distribution are subject to the air mass and local weather conditions, respectively. Weather atmospheric components, such as clouds, aerosols, precipitable water, ozone, are responsible for selectively altering the spectrum. The magnitude of the spectral impact on PV performance depends on the spectral response of the photovoltaic technology; it has been reported that wide-bandgap technologies are more significantly impacted in their performance by spectral fluctuations than smaller bandgap technologies [2]. Thus, there is a need to characterize the spectral distribution quantitatively. Various indices have been proposed for this purpose [3]; among them, the solar spectrum's average photon energy (*APE*) is a device-independent index that reduces the wavelength-dependent spectrum distribution to a scalar value [3–5]. The *APE* bijectivity with the spectral shape is still a topic of discussion in the photovoltaic community [6–8]. However, the *APE* shows the blueness or redness of a solar spectrum concerning the AM1.5G spectrum. The scarcity of ground-based measurements makes evident the need for alternatives to evaluate the spectral distribution in a location of interest [1,9]. In this



sense, atmospheric models allow obtaining information on the spectral distribution based on the atmospheric components commonly derived from satellites.

However, the precision of many of these models has a compromise with their computational efficiency. The National Renewable Energy Laboratory (NREL) has recently released spectral data on-demand integrated into the National Solar Radiation Database (NSRDB) Data viewer [10]. The spectral on-demand data currently available is for longitudes from  $-25^{\circ}\text{E}$  to  $-175^{\circ}\text{W}$  and latitudes from  $-20^{\circ}\text{S}$  to  $60^{\circ}\text{N}$ . The spectral data provided by the NSRDB is computed based on a novel radiative transfer model called Fast All-sky Radiation Model for Solar applications with Narrowband Irradiances on Tilted surfaces (FARMS-NIT). FARMS-NIT obtains the optical properties of the atmosphere using SMARTS; from these parameters, it solves the radiative transfer equation based on a pre-computed look-up table, giving a theoretical solar spectrum for an all-sky condition. In this way, this model integrates the existing advantages in models used in meteorology and solar energy. However, as every theoretical model is subject to validation and comparison with ground-based data, this is still an open research topic [11–14].

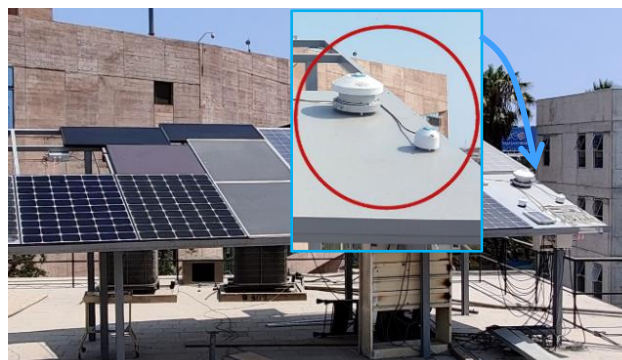
Thus, the present work reports the characterization of the spectral distribution for a low latitude location such as Lima-Peru for a decade based on the theoretical spectral data of the NSRDB, having as the comparative reference one year of experimental data following the decade of theoretical data.

## 2. Methodology

### 2.1. Spectral datasets

This study was carried out for Lima-Peru, taking as location the Outdoor PV-performance laboratory at the Pontificia Universidad Católica del Perú (latitude:  $-12.07168^{\circ}$ , longitude:  $-77.08038^{\circ}$ ) given the availability of experimental spectral data (see Figure 1). The theoretical spectral on-demand data was obtained from the NSRDB Data viewer for the available decade 2009–2018 and the coordinates mentioned above. This theoretical data based on FARMS-NIT compute efficiently the radiative transfer equation producing a spectral irradiance in all-sky condition transposed to a tilted surface in an hourly resolution in wavelength steps from 0.5 to 5 nm and in the wavelength range from 280 to 4000 nm.

As a reference, the experimental spectral data in Conde et al. [15] is considered. This campaign includes one year of solar spectra with a temporal resolution of less than 1 minute and broadband irradiances, measured in the location mentioned above between 03.2019 and 02.2020. The spectra were recorded by an EKO MS-711 spectroradiometer tilted at  $20^{\circ}$ , north-oriented, in a wavelength range between 300 and 1100nm in steps of 0.4nm. An EKO MS-80 pyranometer measured the broadband irradiance at the same tilted angle and orientation. The experimental spectral data was used as a comparative reference. Additionally, both spectral data sets are filtered by the angle of incidence ( $AoI$ ) to minimize the influence of larger air mass with predominant diffuse radiation on the global spectral irradiance. Here, we discarded data for  $AoI > 50^{\circ}$ , as seen in [15].



**Figure 1.** The outdoor PV-performance laboratory at the Pontificia Universidad Católica del Perú. The inset shows the meteorological instruments: The EKO MS-711 spectroradiometer and the EKO MS-80 pyranometer.

## 2.2. Spectral distribution assessment

The spectral distribution can be represented in a one-dimensional way by the *APE* index (in eV). It is defined as the integrated spectral distribution of the solar spectrum divided by the integrated photon flux density of that spectrum, as shown in Equation 1,

$$APE = \frac{\int_{\lambda_a}^{\lambda_b} E(\lambda) d\lambda}{q \int_{\lambda_a}^{\lambda_b} \varphi(\lambda) d\lambda} \quad (1)$$

Where  $E(\lambda)$  (in  $\text{Wm}^{-2}\text{nm}^{-1}$ ) is the spectral distribution,  $\varphi(\lambda)$  is the photon flux density (in  $\text{m}^{-2}\text{nm}^{-1}\text{s}^{-1}$ ) and  $q$  is the elementary electric charge ( $1.602 \times 10^{-19}$  C) which serves as a conversion factor. Additionally,  $\lambda_a$  and  $\lambda_b$  represent the range of integration, in this case, 350 and 1050 nm, respectively. The *APE* of the AM1.5G standard spectrum is 1.876 eV, considering the mentioned wavelength range. For the experimental data, the calculated instantaneous *APE*s and measured broadband irradiances were resampled to 5-min averages.

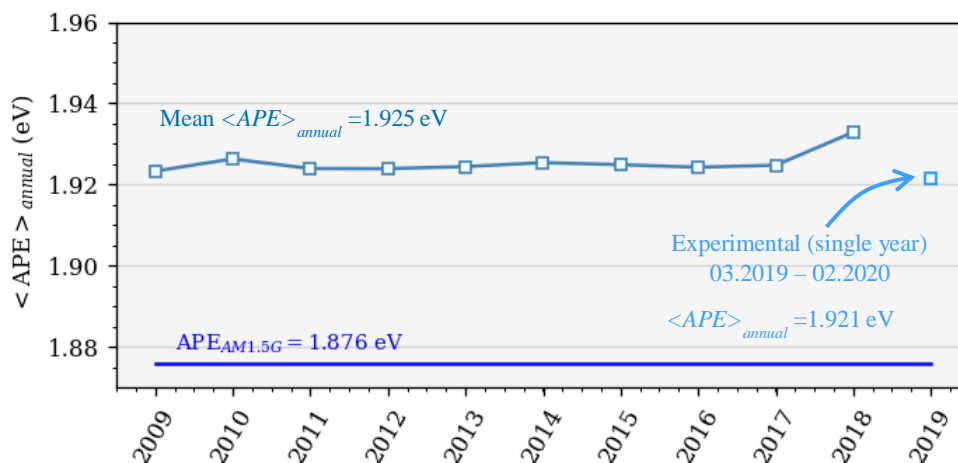
In addition, we use the average irradiance-weighted *APE* on a monthly and annual basis to obtain a representative value during those periods. The latter is defined in Equation 2.

$$\langle APE \rangle_{\mathcal{T}} = \frac{\sum_{i=1}^{N_{\mathcal{T}}} APE_i \times GTI_i}{\sum_{i=1}^{N_{\mathcal{T}}} GTI_i} \quad (2)$$

Where  $GTI$  (in  $\text{Wm}^{-2}$ ) is the global tilted irradiance. For the theoretical data, the irradiance corresponds to the integrated spectrum, whereas for the experimental data, we use the global tilted irradiance measured by the pyranometer.  $\mathcal{T}$  represents the period (annual or monthly) and  $N_{\mathcal{T}}$  is the total number of spectra in the respective period.

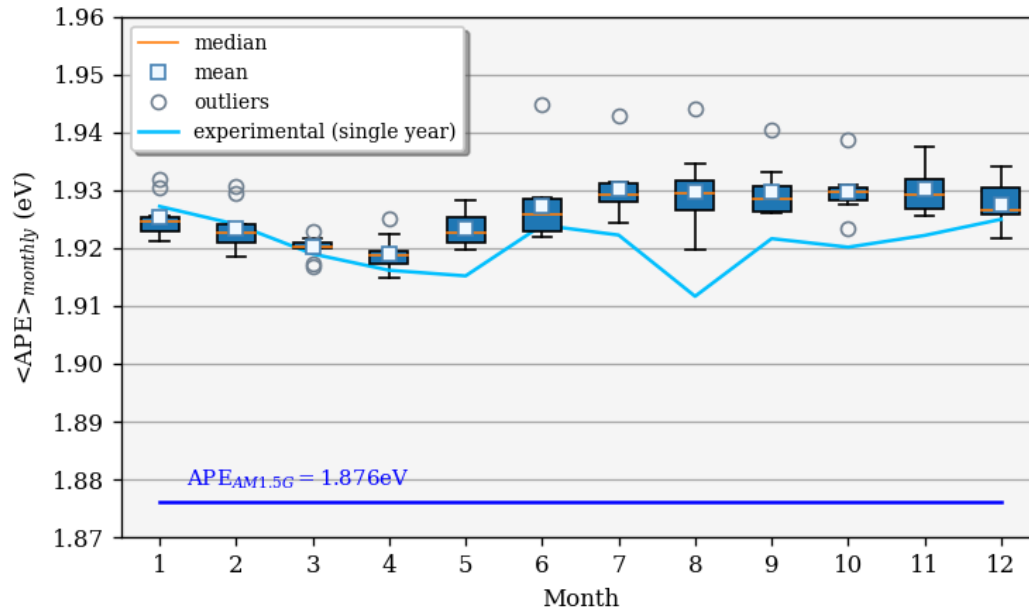
## 3. Results and discussions

To characterize the spectral distribution in Lima, we use the annual irradiance-weighted *APE*  $\langle APE \rangle_{\text{annual}}$ , shown in Figure 2. Note that the periods of theoretical (2009-2018) and experimental (03.2019 to 02.2020) data do not coincide. We observe that the mean of the theoretical  $\langle APE \rangle_{\text{annual}}$  with 1.925 eV differs only slightly from the experimental one for one year with 1.921 eV.



**Figure 2.** Theoretical (from 2009 to 2018) and the experimental (single year) annual average irradiance-weighted *APE*'s.

Furthermore, the  $\langle APE \rangle_{annual}$  in the theoretical data indicates a blue shift of the spectral distribution in Lima for the entire decade, varying from 1.923 eV (2009) to 1.933 eV (2018) with respect to the  $APE$  for the AM1.5G spectrum, which is in accordance with the experimental observation for the following year.



**Figure 3.** Boxplots of the theoretical (NSRDB) average monthly irradiance-weighted  $APE$  along with the experimental one superposed in the light blue line.

Next, we analyze the monthly behaviour of the spectral distribution for the decade of theoretical data. In Figure 3, a monthly boxplot, consisting of ten data points each, represents the theoretical  $\langle APE \rangle_{monthly}$  distribution for the decade. The experimental  $\langle APE \rangle_{monthly}$  of the single year is represented by the light blue line. The theoretical results indicate a slight seasonality, with the lowest mean  $\langle APE \rangle_{monthly}$  during the autumn months around April and the highest mean  $\langle APE \rangle_{monthly}$  during the winter months around July. To explain such seasonality in the spectral distribution would require knowledge about various factors, such as air mass, cloud cover, diffuse irradiance fraction, albedo and the atmospheric parameters that define the spectral distribution in a clear and cloudy sky condition. That analysis is outside the scope of this work. However, the experimental  $\langle APE \rangle_{monthly}$  shows a similar seasonality trend and similar values as the theoretical during the first half of the year, including December, but a different behaviour and distinct values from July to November. The former corresponds to the summer months (December, January, February and March), consisting of predominantly clear-sky days with high irradiance values. We can assume that the  $APE$  values corresponding to clear sky conditions and high irradiance contribute more significantly to the  $\langle APE \rangle_{monthly}$  during these months. As stated before, FARMS-NIT obtains the optical properties of the atmosphere from SMARTS, which has demonstrated a high spectrum prediction accuracy for clear-sky [9]. The latter may explain the observed accordance between theoretical and experimental  $\langle APE \rangle_{monthly}$ . When low irradiance values are predominant for the other months, the necessity to include atmospheric constituents for cloudy-sky conditions may enhance their spectrum simulation uncertainty.

#### 4. Conclusions

We evaluate the spectral distribution in Lima, Peru, based on theoretical spectral data obtained from NSRDB Data viewer for a decade (2009 - 2018), taking as reference experimental spectra for a single year (03.2019 - 02.2020). This evaluation was made based on the average photon energy ( $APE$ ) index, which simplifies the spectrally resolved irradiance to a single value. We used the monthly and annual

average irradiance-weighted *APE*, where the broadband irradiance was the integrated spectrum in the theoretical case. For the experimental data, the irradiance measured by the pyranometer was used. The experimental *APEs* and irradiances were resampled to 5-min averages. We found that the average theoretical annual irradiance-weighted *APEs* for the decade show a small relative error of only 0.2% with respect to the experimental annual irradiance-weighted *APE* for a single year.

Additionally, we observe a seasonality when calculating the monthly values for the theoretical data during the decade. The experimental monthly irradiance-weighted *APEs* coincide with the theoretical ones during the summer months, suggesting that this good agreement could be due to the predominant contribution of clear-sky conditions to the monthly *APE*.

To better evaluate the precision of the theoretical data, we propose as a future study a comparative analysis between experimental and theoretical data for the same year, once the latter is available. Furthermore, experimental spectral data from other locations should be contrasted with available theoretical data from the NSRDB.

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