SPECTRAL CHARACTERISTICS OF SOLAR RADIATION IN TIMISOARA, ROMANIA

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Article Info	Abstract
<p><i>Received: 05.10.2021</i> <i>Accepted: 20.11.2021</i></p> <p>Keywords: Spectral solar irradiance, average photon energy, aerosol</p>	<p>This study deals with the spectral distribution of solar radiation in Timisoara, Romania. Solar spectrum at the ground level was estimated based on Leckner's spectral solar irradiance model and measured atmospheric parameters over the years 2019-2020. The average photon energy index (APE) was used to capture the characteristic signature of the solar radiation spectrum. The results emphasize considerable differences between the solar radiation spectrum in Timisoara and the standard AM1.5G spectrum. During 2019-2020, APE has taken values between 1.841 eV and 1.929 eV, indicating both red- and blue-shift from the standard AM1.5G spectrum. To our best knowledge this is the first study which discusses the signature of solar radiation spectrum in terms of APE for a location in Romania.</p>

1. Introduction

The efficiency of photovoltaic (PV) modules is evaluated at manufacturing level under standard test conditions (STC) which assume 1000 W/m^2 of incident solar irradiance with a spectral distribution AM1.5G [1]. The PV module operates naturally in outdoor conditions, where the spectrum of the incident solar radiation very rarely matches the AM1.5G spectral distribution. Consequently, in outdoor conditions, the efficiency of PV modules may significantly differ from the standard value evaluated under STC, thus becoming a hidden source of uncertainty in the evaluation of a PV plant performance (e.g. [2]).

The effect on PV power production induced by the changes in solar spectrum is a recent topic of research. Some of the current studies are conducted based on solar spectra measured in campaigns with field spectroradiometers. However, such observational spectral information is seldom available [3]. Given the fact that ground measurements are complicated and expensive, computer simulations of solar spectra are used instead (e.g. [3], [4]).

The average photon energy index (APE) is commonly used to capture the characteristic signature of the solar radiation spectrum (see Sec. 2.2 for a definition). Other indexes are also defined, each highlighting both strengths and weaknesses [5]. There are some questions as to whether APE is a unique characteristic of the spectral distribution of solar radiation. The studies performed on this topic have shown that APE is a reasonable index to describe the spectral distribution of solar radiation for evaluating the outdoor performance of PV modules [6], [7].

In this paper the spectral solar radiation distribution in Timisoara, Romania is analyzed. The town of Timisoara (45°46'N, 21°25'E, 85 m asl) has a warm temperate climate, fully humid, with warm summer, typical for the Pannonian Basin. Solar spectrum at the ground level was estimated based on Leckner's spectral solar irradiance model [8] using at its input the atmospheric parameters retrieved from the Aerosol Robotic Network (AERONET) [9].

The paper is organized as follows. Leckner's spectral solar irradiance model and the average photon energy index are briefly introduced in Sec. 2. The characteristics of spectral solar radiation in Timisoara are analyzed in Sec. 3. Section 4 summarizes the main conclusions.

2. Modeling spectral solar irradiance

2.1. Leckner's spectral solar irradiance model

Leckner's model [8] estimates the spectral solar irradiance components at ground level by simple and accessible equations. The direct-normal spectral solar irradiance on a surface faced to Sun at wavelength λ [μm] is expressed as:

$$G_{dn}(\lambda) = G_{ext}(\lambda) \tau_{O_3}(\lambda) \tau_w(\lambda) \tau_g(\lambda) \tau_R(\lambda) \tau_a(\lambda) \quad (1)$$

where $G_{ext}(\lambda)$ is the extraterrestrial spectral solar irradiance [10]. $\tau_{O_3}(\lambda)$, $\tau_w(\lambda)$, $\tau_g(\lambda)$, $\tau_R(\lambda)$ and $\tau_a(\lambda)$ denote the spectral atmospheric transmittances of ozone, water vapor, mixed gases absorption and Rayleigh scattering and aerosol scattering, respectively.

The spectral diffuse solar irradiance is expressed as:

$$G_d(\lambda) = 0.5 G_{ext}(\lambda) \tau_{O_3}(\lambda) \tau_w(\lambda) \tau_g(\lambda) [1 - \tau_R(\lambda) \tau_a(\lambda)] \sin h \quad (2)$$

Global spectral solar irradiance on a horizontal surface is simply computed as the sum of beam and diffuse solar irradiances:

$$G(\lambda) = G_{dn}(\lambda) \sin h + G_d(\lambda) \quad (3)$$

The spectral atmospheric transmittances are expressed as functions of the optical atmospheric mass m [8]:

$$\tau_{O_3}(\lambda) = \exp[-ml_{O_3}K(\lambda)] \quad (4a)$$

$$\tau_w(\lambda) = \exp\left(-\frac{0.2385mwK_w(\lambda)}{[1 + 20.07mwK_w(\lambda)]^{0.45}}\right) \quad (4b)$$

$$\tau_g(\lambda) = \exp\left(-\frac{1.41mK_g(\lambda)}{[1 + 118.3mK_g(\lambda)]^{0.45}}\right) \quad (4c)$$

$$\tau_R(\lambda) = \exp(-0.008735\lambda^{-4.08}mp/p_0) \quad (4d)$$

$$\tau_a(\lambda) = \exp(-m\beta\lambda^{-\alpha}) \quad (4e)$$

The model requires at input four atmospheric parameters: the ozone column content l_{O_3} [cm·atm], the water vapor column content w [g/cm²] and the Ångström parameters α and β [11]. The absorption coefficients $K(\lambda)$ [cm⁻¹], $K_w(\lambda)$ [cm²g⁻¹] and $K_g(\lambda)$ [km⁻¹] are tabulated in Leckner's paper [8] for 144 wavelengths, covering the entire Sun's optical spectrum.

2.2. Average photon energy - APE

APE is defined as the average energy per photon evaluated over a spectral domain $[\lambda_{\min}, \lambda_{\max}]$:

$$APE[\text{eV}] = \frac{\int_{\lambda_{\min}}^{\lambda_{\max}} G(\lambda) d\lambda}{\frac{q}{hc} \int_{\lambda_{\min}}^{\lambda_{\max}} \lambda G(\lambda) d\lambda} \quad (5)$$

where $G(\lambda)$ is the spectral solar flux density, q denotes the elementary charge, c denotes the speed of light and h denotes the Planck's constant. The reference value of APE is 1.88 eV, calculated over the spectral domain $[\lambda_{\min} = 0.35\mu\text{m}, \lambda_{\max} = 1.05\mu\text{m}]$ and considering the reference AM1.5G spectrum (ASTM G-173) for $G(\lambda)$. A higher value of APE indicates a

blue-shift in spectrum while a smaller value of APE indicates a red-shift in spectrum. This is well illustrated in Fig. 1, where the solar spectrum estimated with the Leckner model is plotted for three values of APE.

In this study APE was calculated on the basis of Leckner's model considering the extraterrestrial solar spectrum from [10] and the typical integration domain $[\lambda_{\min} = 0.35\mu\text{m}, \lambda_{\max} = 1.05\mu\text{m}]$. Under these assumption for the AM1.5G spectral distribution of solar irradiance we obtained the reference value $APE = 1.892\text{ eV}$.

Figure 1. Spectral solar irradiance $G(\lambda)$ estimated by Eq. (3) corresponding to three different values of APE in eV. The black curve corresponds to AM1.5G spectrum

It should also be noted that APE is highly sensitive to the domain of integration $[\lambda_{\min}, \lambda_{\max}]$. For example, for the AM1.5G spectrum, preserving $\lambda_{\min} = 0.35\mu\text{m}$ and increasing successively $\lambda_{\max}$ to $1.1\mu\text{m}$, $2.0\mu\text{m}$ and $4.0\mu\text{m}$, APE decreases to 1.850 eV , 1.559 eV and 1.440 eV , respectively.

3. Results and discussions

3.1. Input parameters

In order to run the spectral solar irradiance model, the input parameters (ozone column content, water vapor column content and the Ångström parameters) were taken from the Aerosols Monitoring Station of the Polytechnic University of Timisoara. The atmospheric parameters are derived by a standard processing of the measurements performed with a CIEMEL318 Sun Photometer connected in the global AERONET network [9]. For this study, data recorded during 2019-2020 were retrieved from AERONET 2.0 level (quality assured). The final database contains 12823 lines, each line including the time stamp and the instantaneous values of the atmospheric parameters. Figure 2 displays the histograms for the

Ångström turbidity coefficient β and the Ångström exponent α . Both distributions are unimodal and skewed (to the right for β and to the left for α). The mode of β is 0.034 indicating a fairly low loading of the atmosphere with aerosols while the mode of α is 1.64, indicating that the urban-industrial aerosols are prevailing [12]. The water vapor column content has an almost uniform distribution (not shown here) in the range $0.5\text{g/cm}^2 < w < 3\text{g/cm}^2$.

Figure 2. Distributions of the (a) Ångström turbidity coefficient and (b) Ångström exponent recorded by the AERONET station of Timisoara during 2019 – 2020.

3.2. Spectral solar irradiance in Timisoara

The study was focused on global spectral solar irradiance, evaluated at an atmospheric air mass $m = 1.5$. This assumption allows an objective graphical comparison of the different spectra and their signature quantified by APE. Figure 3 shows the spectral solar irradiance estimated by Eq. (3) at an atmospheric air mass $m = 1.5$ for the atmospheric parameters sets recorded at the minimum, maximum and the most frequent values of β , α and w . These sets of parameters are listed in Table 1. For example, the first column includes the values of β , w and I_{O_3} recorded simultaneously with the minimum value of α . Figure 3 emphasizes that the atmospheric parameters range is large enough to cause visible changes in the solar radiation spectrum. For the extremes values of the Ångström turbidity coefficient, minimum (low aerosol loading) and maximum (high aerosol loading), APE takes the values 1.890 eV and 1.915 eV, respectively. For the extremes values of the Ångström exponent, minimum (prevalent desert dust) and maximum (prevalent biomass burning), APE takes the values 1.915 eV and 1.894 eV, respectively. For the minimum (dry atmosphere) and maximum (humid atmosphere) values of the water vapor column content, APE takes the values 1.887 eV and 1.893 eV, respectively.

APE indicates a largely blue-shift of the solar spectrum due to aerosols, even if this is not visible with the naked eye in Figs. 3a, b. Differently, the changes in the water vapor column content generates a visible shift of the spectrum color (Fig. 3c).

Figure 3. Spectral solar irradiance $G(\lambda)$ estimated by Eq. (3) at an atmospheric air mass $m = 1.5$ for those sets of atmospheric parameters recorded at the extremes and the most frequent values of: (a) Ångström turbidity coefficient β ; (b) Ångström exponent α and (c) water vapor column content w . The vertical dotted lines delimit the spectral domain [$\lambda_{\min} = 0.35 \mu\text{m}$, $\lambda_{\max} = 1.05 \mu\text{m}$]

Figure 4. Solar spectrum at the extreme values of APE recorded in Timisoara during 2019-2020. The standard AM1.5G spectrum is displayed as reference.

Table 1. The atmospheric parameters recorded when the Ångström exponent, Ångström turbidity coefficient and water vapor column content reached the extreme and most probable values (highlighted on a grey background).

Parameter	Min	Max	Mode	Min	Max	Mode	Min	Max	Mode
α	0.147	2.075	1.642	1.539	0.147	1.558	1.449	1.738	0.981
β	0.402	0.031	0.089	0.005	0.402	0.034	0.009	0.108	0.106
w [g/cm ²]	1.843	1.806	3.340	0.235	1.843	1.311	0.161	4.128	2.442
l_{O_3} [cm·atm]	0.360	0.359	0.344	0.353	0.360	0.288	0.353	0.323	0.340

Table 2. The atmospheric parameters recorded when APE took extreme values.

APE [eV]	α	β	w [g/cm ²]	l_{O_3} [cm atm]
1.915	0.147	0.402	1.843	0.360
1.867	2.031	0.166	1.780	0.288

Figure 4 compares the standard AM1.5G spectrum with the solar radiation spectra estimated by the Leckner model for the extreme values of APE recorded in Timisoara during 2019-2020. The Leckner model was run for an atmospheric air mass $m = 1.5$ with the actual measured atmospheric parameters at the moments when APE reached the extreme values (minimum on October 18, 2019, at a zenithal angle 73.18° and maximum on May 18, 2020, at a zenithal angle 72.75°). While the red-shift is mainly due to the changes in the water vapor column content, the blue-shift is the result of many influential factors.

Figure 5. Time variation of APE in Timisoara during 2019 - 2020. The horizontal black line marks the value of $APE = 1.892$ eV under AM1.5G spectrum.

Table 2 displays the atmospheric parameters recorded when APE took extreme values. The maximum value of APE was recorded when the Ångström exponent reached its minimum value while the minimum value of APE was recorded for a high value of the Ångström exponent, suggesting a possible inverse proportionality. The water vapor column content took similar values on both days when the extreme values of APE were reached. Surprisingly, on the day with maximum APE the ozone column content was higher than average, which would indicate a red-shift, not a blue-shift, as calculated. This can suggest that the ozone column content has a relatively low influence on the value of APE, compared to the aerosol parameters.

The variation of APE in Timisoara during 2019-2020 is displayed in Fig. 5. Unlike all the previously studied cases, Fig. 5 was built considering the actual values of the Sun elevation angle and, consequently, the actual values of the atmospheric air mass. Visual inspection shows that the solar spectrum in Timisoara experiences a preponderantly red-shift ($APE < 1.892$ eV). Also, a clear seasonal behavior is observed. In the winter months, there is more a pronounced red-shift while in the summer months blue- and red-shift coexists.

4. Conclusions

This study was devoted to the analysis of solar radiation spectral distribution in Timisoara, Romania. The methodology combined numerical simulation of solar spectrum with experimental measurements of the atmospheric parameters during 2019-2020. The results

emphasize considerable differences between the solar radiation spectrum in Timisoara and the standard AM1.5G spectrum. During 2019-2020, the average photon energy index had taken values between $APE = 1.841$ eV and $APE = 1.929$ eV, indicating both red- and blue-shift from the standard AM1.5G spectrum. This is probably the first study which deals with the signature of solar radiation spectrum in terms of APE for a Romanian location. A future research is needed to assess how these changes in the solar spectrum influence the efficiency of solar systems.

Acknowledgements

The authors thank dr. Delia Gabriela Trif-Torday for the effort of maintaining the AERONET station of Timisoara, Romania.

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