Solar Energy Materials & Solar Cells 163 (2017) 73–90

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Quantification of the spectral coupling of atmosphere and photovoltaic system performance: Indexes, methods and impact on energy harvesting

Pedro M. Rodrigo[a,*], Eduardo F. Fernández[b,*], Florencia M. Almonacid[b], Pedro J. Pérez-Higueras[b]

[a] Universidad Panamericana, campus Aguascalientes, Facultad de Ingeniería, Josemaría Escrivá de Balaguer 101, Aguascalientes, Aguascalientes 20290, Mexico

[b] Centro de Estudios Avanzados en Energía y Medio Ambiente, Universidad de Jaén, s/n Las Lagunillas Campus, 23071 Jaén, Spain

ARTICLE INFO

Keywords:
Photovoltaic devices
Spectral characterization
Mathematical procedures
Outdoor performance

ABSTRACT

Photovoltaic system performance is affected by changes in the input sunlight spectrum. Moreover, the different photovoltaic materials employed show different spectral responses, having different spectral behaviour as a result. Many authors have developed methods and proposed indexes for quantifying the spectral influences in photovoltaic systems under the time-varying weather variables. These methods use different equipment, different procedures and assumptions, present different levels of complexity and accuracy, and have advantages and disadvantages in each specific context and application. In this paper, for the first time, a systematic review of the available methods and photovoltaic spectral indexes is presented. Each alternative is analysed in detail and a comparative study is done. In addition, as several authors have measured and/or calculated the spectral impact on the energy yield of the different photovoltaic technologies at particular locations and climates, the existing results are summarized and discussed in order to elucidate the spectral behaviour of each technology as a function of the relevant atmospheric parameters, i.e. air mass, aerosol optical depth and precipitable water. The presented study covers non-concentrating and high-concentrating photovoltaic technologies and is intended for clarifying the methods available for the spectral analysis and the spectral impact on energy harvesting of the photovoltaic technologies.

1. Introduction

A solar cell could be considered as a quantum converter based on the use of one or various semiconductor materials. The Spectral Response (SR) is widely accepted as the most relevant magnitude to understand the conversion of the incident photons into electricity of photovoltaic (PV) devices. It can be defined as the amperes generated per watt of incident light of a given wavelength. As an example, Fig. 1 shows the SR, also known as spectral absorption band, of some of the most wide-spread PV materials nowadays. At the same time, the energy of the photons received from the sun is distributed according to their different wavelengths, as given by the well-known Planck–Einstein relation: $E = h{\cdot}\nu = h{\cdot}c/\lambda$. The approximately constant energy distribution of the photons at the top of the atmosphere (TOA) of the planet Earth is affected through its pass over the atmosphere by different interaction physical phenomena. Hence, the wavelength distribution of the photons, hereafter defined as spectral irradiance or spectral distribution, which reaches the Earth surface is inherently variable and different than the received at the TOA. As a result, the output of photovoltaic systems is going to be affected by the unavoidable spectral irradiance variations caused by the different attenuation processes produced in the atmosphere as a function of their different spectral abortion bands.

The changes in the input spectral distribution have demonstrated to play a relevant role on the electrical performance of PV systems under real operating conditions since early in the 1990s [1]. Bearing this in mind, the PV community has agreed a reference spectral distribution, or reference spectrum, to rate photovoltaic devices under the so-called standard test conditions (STC). This spectrum has been established by using different spectral models and from a rigorous study of the different extinction processes that occur in the atmosphere [2–4]. Nowadays, the most widely adopted spectral distribution to evaluate photovoltaic devices under STC is the ASTMG-173-03 reference spectrum provided by the American Society for Testing and Materials (ASTM) [5]. However, this spectrum rarely happens in outdoors where the main value of interest is not the efficiency under STC, but the

* Corresponding authors.
E-mail addresses: prodrigo@up.edu.mx (P.M. Rodrigo), fenandez@ujaen.es (E.F. Fernández).

http://dx.doi.org/10.1016/j.solmat.2017.01.018
Received 19 August 2016; Received in revised form 10 January 2017; Accepted 13 January 2017
Available online 19 January 2017

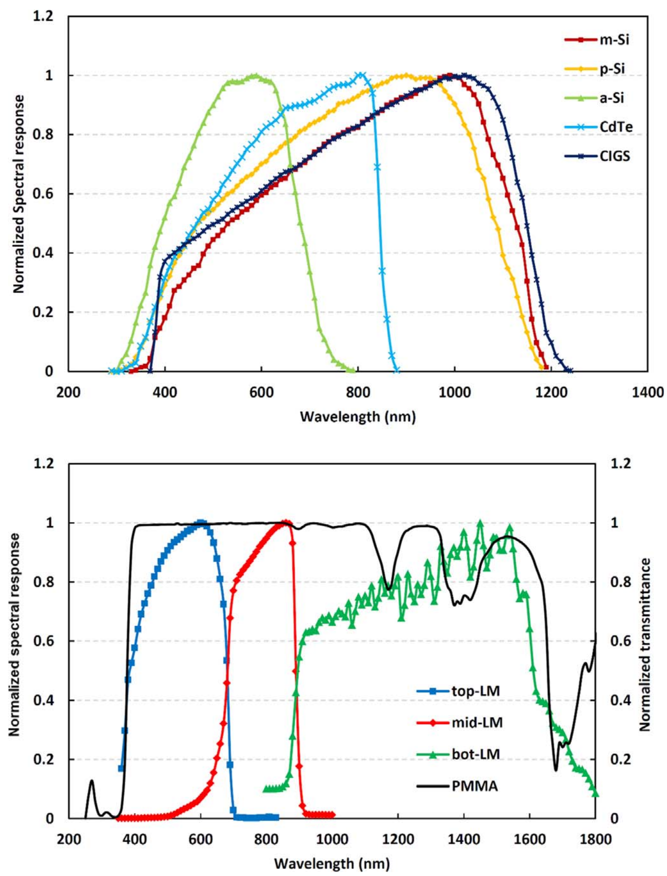

Fig. 1. Top: normalized spectral response of five kinds of PV materials: m-Si: monocrystalline silicon; p-Si: poly-crystalline silicon; a-Si: amorphous silicon; CdTe: cadmium telluride; CIGS: copper indium gallium selenide. Bottom: normalized transmittance of a poly(methylmethacrylate) (PMMA) material and normalized spectral response of a triple-junction lattice-matched (LM) solar cell made up of: top junction: gallium indium phosphide (GaInP), middle junction: gallium indium arsenide (GaInAs), bottom junction: germanium (Ge). The normalized spectral response and transmittance is the ratio of the spectral response/transmittance to the maximum value of the spectral response/transmittance for each material.

electrical output under realistic operating conditions [6]. Because of this, the PV community has devoted big efforts in order to quantify and understand the impact of spectral changes on the output of the different solar devices developed over the last decades. This includes non-concentrating c-Si, a-Si, CIGS, CIS and CdTe [7–11], as well as non-concentrating dye-sensitized and perovskite [12,13], and concentrating, lattice-matched and metamorphic-mismatched [14,15], solar materials.

This papers aims to cover the most relevant studies concerning the spectral analysis of PV systems conducted within the last three decades. The review of the existing contributions reveals that different authors proposed different methods which use specific equipment and assumptions. While some authors have presented partial reviews of the state-of-the-art, nowadays there is not a systematic analysis of all of these procedures and it is not clear what the relations are between the different defined spectral indexes, what are the advantages and disadvantages of each one, and finally, what method is more convenient in each particular context and application. For instance, there are three recent works which include partial reviews of spectral indexes: Alonso-Abella et al. [16] cited some contributions regarding the “useful fraction”, the “spectral effective responsivity” and the “average photon energy” indexes for non-concentrating PV devices in order to introduce the method employed (“spectral factor”), but the reviewed methods are not defined in detail, neither compared and only a brief discussion on them can be found; Dirnberger et al. [17] made a historical overview of some articles focused on the spectral analysis of non-concentrating PV devices and mentioned the use of “average photon energy”, “useful fraction”, “integrated electric charge” and “spectral mismatch factor” as spectral indicators; Fernández et al. [15] focused on concentrating PV technologies and cited some works emphasizing the instruments used for the spectral characterization but not the methodologies employed. In general, authors present partial reviews focused on introducing their own methods but there is lack of a systematic and comprehensive study of the available methods and indexes for the different PV technologies. Moreover, the proposed indexes have not a unified nomenclature, and present different levels of complexity and accuracy which have not been discussed in many of the cases. So, there is confusion both in the PV researchers and developers when selecting the most suitable method for analysing the spectral influences in PV systems. In this paper, an in deep analysis on the available alternatives is conducted, supported by measurements and calculations carried out by the authors. The aim is to provide a reference framework on the quantification of the spectral coupling of atmosphere and PV system performance for the future works of the PV community in this field.

The impact of this spectral coupling on the energy yield of PV systems has also been investigated by different authors in particular locations and climatic conditions for different PV materials. However, these contributions have not been analysed together and therefore general conclusions about the spectral impact on each PV technology have not yet been established. Moreover, the majority of these studies are based on pure experimental analyses and they usually lack a discussion of the fundamental phenomena involved in their findings by considering the weather variables at each site. This leads to a clear poorer understanding of the spectral performance of the different PV devices under the time-varying spectral changes. In this paper, the results available in the literature are summarized and discussed in order to elucidate the spectral behaviour of the different PV technologies as a function of the most relevant atmospheric parameters influencing the sunlight spectrum, i.e. air mass, aerosol optical depth and precipitable water. As will be shown, results provided by different researchers are consistent, in spite of using different methods and equipment, so that the general conclusions found will be of application in future solar cell development and PV system design.

The study is structured as follows: Section 2 introduces the fundamentals of spectral solar radiation, presents the main atmospheric parameters and physical mechanisms which modify the solar spectrum that reaches the Earth surface and overviews the influence of changing spectra on the different PV materials; Section 3 develops the review, classification, analysis and comparison of the spectral indexes and methods available in the literature; Section 4 summarizes the annual spectral energy gain or loss values reported in the literature and draws the characteristic spectral behaviour of each PV technology as a function of the air mass, aerosol optical depth and precipitable water atmospheric parameters; finally, Section 5 details the findings and conclusions of the research.

2. Spectral solar radiation

The Sun can be considered as a black body at a temperature of T≈5770 K. According to the Stefan-Boltzmann's law, $E = \sigma \cdot T^4$, and by considering the average radius of the Sun, $R_S \approx 6.96\times10^8$ m, and the distance from the sun to the planet Earth, $d_{S\text{-}E} \approx 1.496\times10^{11}$ m, the total radiation that reaches the TOA is approximately 1360 W m^{-2}. This value is usually defined as the solar constant (SC) and the wavelength irradiance distribution at the TOA as the extraterrestrial solar spectrum (E_{TR}). At the same time, the atmosphere acts as a filter that modifies the amount and spectral distribution of the E_{TR} spectrum by scattering and absorption phenomena. This attenuation depends on the amount of substance traversed by the solar rays in their course through the atmosphere and on the optical properties of the different atmospheric constituents (e.g. CH_4, O_2, CO_2, O_3, water vapour,