Solar Energy Materials & Solar Cells 127 (2014) 179–187

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

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

Analysis of the spectral variations on the performance of high concentrator photovoltaic modules operating under different real climate conditions

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ARTICLE INFO

Article history:
Received 9 March 2014
Received in revised form
24 April 2014
Accepted 29 April 2014
Available online 21 May 2014

Keywords:
High concentrator photovoltaic
Spectral effects
Climate conditions

ABSTRACT

Multi-junction (MJ) solar cells show an important dependence on the incident spectrum due to the internal series connection of several cells with different band gap energies. The influence of spectral variations on the performance of HCPV modules or systems is different from that in MJ solar cells since they use optical devices to concentrate the light on the solar cell surface. The spectral distribution of irradiance is affected by atmospheric parameters and changes during the course of day, month or year. Because of this, several authors have done different studies to analyse and quantify the spectral effects on the performance of HCPV modules. However, there are still important issues that have not been addressed. In this paper, a deep analysis of the spectral effects on the performance of different HCPV modules with different multi-junction solar cells and Fresnel lenses on an annual time scale and their study and comparison at locations with different climate conditions is conducted. In order to address this issue, ground-based climatologies at the locations studied, spectra simulations with the SMARTS model and the spectral factor of a HCPV module have been used. Results show that the annual spectral losses vary from 6% to 51% depending on the climate conditions of the location and the HCPV module.

1. Introduction

Photovoltaic devices are influenced by the spectral distribution of the incident solar irradiance. But, due to the internal series connection of several cells with different band gap energies, multi-junction (MJ) solar cells show a significantly greater spectral dependence than single-junction solar cells [1,2].

The spectral distribution of solar irradiance is determined by multiple time-varying atmospheric factors, and several methods have been proposed to quantify the influence of the spectral variations of solar irradiance on the performance of MJ solar cells under real operating conditions [1,3–6].

Nowadays, high concentrator photovoltaic (HCPV) modules and systems are largely based on the use of MJ solar cells [7]. HCPV modules use optical devices, usually Fresnel lenses, to concentrate the light on the solar cell surface and may use secondary optical elements such as homogenizers [8]. The assembly of optical devices alters the spectral distribution of the solar irradiance that strikes the solar cell surface. Hence, the influence of incoming spectral variations on the performance of HCPV modules is inherently different to that in MJ solar cells [9].

Recently, the influence of spectral variations in the incident solar irradiance on the performance of HCPV modules has been evaluated by different authors. The spectral effects on various HCPV mono-modules and systems during a clear and a very clear day have been studied by Hashimoto et al. [9] in Okayama (Japan) from measurements gathered with a spectro-radiometer. However, as is pointed out in [10], the use of spectro-radiometers is complex and presents multiple disadvantages for long-term analyses. As a consequence, an alternative method based on isotype cells has been proposed by Peharz et al. [10]. Isotype cells register the solar irradiance spectral variations and quantify their effects on the electrical parameters of the HCPV modules. This approach has also been used in [11] to gauge the annual spectral losses of different HCPV systems in Madrid (Spain). However, although the methods based on isotype cells are robust and simple, they are difficult to apply in remote sites for long-term studies. The use of ground-based long-term observations of atmospheric properties in conjunction with the Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS [12–14]) poses an alternative

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http://dx.doi.org/10.1016/j.solmat.2014.04.026
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modelling approach for long-term studies. It allows evaluating the spectral effects at different locations if the atmospheric parameters are available. This approach has been used to study the influence of air mass, aerosol optical depth and precipitable water on the performance of different HCPV modules in Golden (USA) over 9 months [15] and in a HCPV module in Toyohashi (Japan) over a year [16].

Nonetheless, a deeper analysis of the influence of the time-varying solar irradiance spectrum on the performance of HCPV modules at locations with disparate climate conditions is required. This is crucial to leverage our understanding of the annual performance of HCPV modules under real operating conditions [17]. To address this issue, the effects of solar irradiance spectral variations on the annual performance of different HCPV modules at five locations with different climate conditions have been analysed based on high-quality ground-based climatologies at the sites studied and spectra simulations with the SMARTS model. A detailed analysis of the influence of air mass, aerosol optical depth and atmospheric water vapour content is presented.

2. Method and materials

2.1. The spectral factor of a HCPV module

The spectral factor of a single-junction PV device can be defined as [18–20,17]

$$SF = \frac{\int E(\lambda)\mathrm{SR}(\lambda)d\lambda \int E_{ref}(\lambda)d\lambda}{\int E_{ref}(\lambda)\mathrm{SR}(\lambda)d\lambda \int E(\lambda)d\lambda} \tag{1}$$

where $E(\lambda)$ is the incident spectrum on the PV device, $E_{ref}(\lambda)$ is the reference spectrum and $SR(\lambda)$ is the spectral response of the PV device. The spectral factor quantifies the differential performance of a PV device between the incident and reference spectra: an SF higher than 1 represents a better performance (spectral gains) and an SF lower than 1 (spectral losses) indicates a worse performance.

The spectral factor as defined in Eq. (1) is not valid for HCPV modules since the combined use of MJ solar cells and optical devices modifies the incident spectral distribution [9,21,22]. Therefore, the spectral factor needs to be reformulated for use in HCPV modules.

The short-circuit current density of each junction of a MJ solar cell can be expressed as

$$J_{\mathrm{sc},i} = \int E_b(\lambda)\eta(\lambda)SR_i(\lambda)d\lambda \tag{2}$$

where the index i represents the junction considered, $E_b(\lambda)$ is the spectral distribution of direct normal irradiance (E_b) or direct normal spectrum (HCPV modules react only to direct normal irradiance due to the use of lenses), and $\eta(\lambda)$ is the optical efficiency of the HCPV module.

As junctions of a MJ solar cell are interconnected in series, the short-circuit current density of the whole device is given by [23]

$$J_{sc} = \min(J_{sc,i}) \tag{3}$$

From Eqs. (1)–(3), the spectral factor of a HCPV module should be rewritten as

$$SF = \frac{\min(\int E_b(\lambda)\eta(\lambda)SR_i(\lambda)d\lambda)\int E_{b,ref}(\lambda)d\lambda}{\min(\int E_{b,ref}(\lambda)\eta(\lambda)SR_i(\lambda)d\lambda)\int E_b(\lambda)d\lambda} \tag{4}$$

where $E_{b,ref}(\lambda)$ is the reference spectrum AM1.5d ASTM G-173-03 at which MJ solar cells and HCPV modules are rated [24].

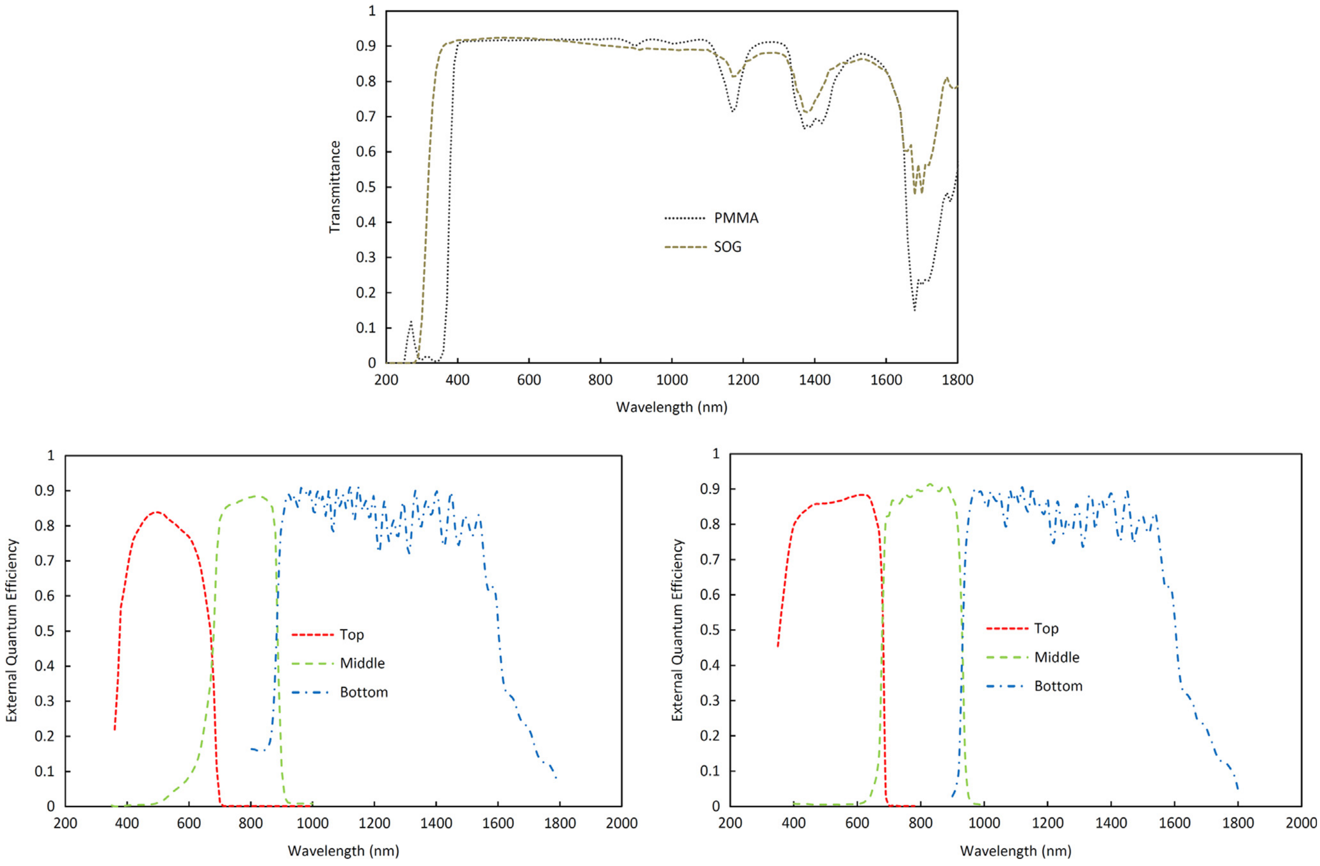

Fig. 1. External Quantum Efficiency of the lattice-matched (bottom left) and the metamorphic (bottom right) multi-junction solar cells at 298 K. (Top) Transmittance of the Fresnel lenses (PMMA and SOG) at 293 K.