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ScienceDirect

Solar Energy 112 (2015) 469–474

SOLAR ENERGY

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Predicting the spectral effects of soils on high concentrating photovoltaic systems

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Received 28 March 2014; received in revised form 14 November 2014; accepted 21 November 2014
Available online 15 December 2014

Communicated by: Associate Editor Christian Gueymard

Abstract

Soiling losses on high concentrating photovoltaic (HCPV) systems may be influenced by the spectral properties of accumulated soil. We have predicted the response of an isotype cell to changes in spectral content and reduction in transmission due to soiling using measured UV/vis transmittance through soil films. Artificial soil test blends deposited on glass coupons were used to supply the transmission data, which was then used to calculate the effect on model spectra. The wavelength transparency of the test soil was varied by incorporating red and yellow mineral pigments into graded sand. The more spectrally responsive (yellow) soils were predicted to alter the current balance between the top and middle subcells throughout a range of air masses corresponding to daily and seasonal variation.

Keywords: Spectral response; Triple junction limiting current; Soiling losses

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1. Introduction

High-concentrating photovoltaic (HCPV) systems are carefully engineered systems designed to capture as much of the direct (non-scattered) portion of the solar spectrum as possible. Precise sun-tracking hardware and algorithms enable high-concentration optics to focus this light onto triple junction (TJ) receivers, all to improve the efficiency, energy density and cost effectiveness of the system. As a result of this complexity, small deviations from optimal conditions propagate through the system and reduce the overall performance. Due to the substantial capital costs of HCPV systems, any loss in performance is a significant issue. Even small losses can propagate to significant costs, as discussed by Mingguo et al. (2013). In addition to well-known loss mechanisms such as tracking error (Muller, 2009; Stafford et al., 2009) and cloud cover (Viana et al., 2011), the triple junction (TJ) cells used in HCPV systems are sensitive to the uniformity and spectral content of the available light (Victoria et al., 2013). Baig et al. (2012) presented a discussion of non-uniform illumination due to tracking error, collector optical imperfections and spectral response. Of these, spectral response represents a particular challenge. All concentrating optics introduce some spectral effect as they transmit light (Victoria et al., 2013; Cotal and Sherif, 2005); however, environmental factors can exacerbate the effect. Gueymard (2009) has discussed the sensitivity of HCPV systems to spectral variations due to airmass in terms of both elevation of the site and atmospheric aerosol content. In addition to aerosol particles, accumulated soil on the receiver can both absorb and scatter the incident light. Soil decreases photocurrent

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http://dx.doi.org/10.1016/j.solener.2014.11.022
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by reducing the transmission of some wavelengths of light through the optical elements of the device. The total electrical output of HCPV systems has been shown (Vivar et al., 2010) to be more sensitive to soiling than flat plate PV due to the reduction in light reaching the device. However; some wavelengths of light can scatter through the soil, resulting in an altered spectrum at the receiver. The spectral content of the available light influences the limiting current of series-connected TJ devices on a daily and seasonal basis (Torrey et al., 2011).

Soiling effects in the literature have typically emphasized loss in transmission due to the total mass of accumulated material (Miller and Kurtz, 2011; El-Shobokshy et al., 1985). Specific properties of the soil, and thereby spectral quality of transmitted light, have not been discussed in detail with regards to HCPV systems. However, we have shown that the spectrum of transmitted light through soiled glass is dependent upon soil composition (Burton and King, 2014). A neutral density soil would cause predictable losses in the total system output. A wavelength-sensitive soil could induce current mismatch between subcells in TJ cells.

Since many reports discuss the importance of spectral content to HCPV systems, a theoretical study was undertaken to predict the effect of observed light transmission through soil on TJ cells. Emphasis was placed on understanding the effect of soil as an optical element of *any* HCPV system, so the soil was treated as a stand-alone element. In addition to the magnitude of the soil effect at standard (AM1.5D) conditions, changes in the incident light throughout a typical day and year were considered. Performance predictions of soiled HCPV could improve the expected cost effectiveness of cleaning regimens, or spectrum enhancing technologies such as secondary optics. For example, Victoria et al. (2013) have shown improved spectral tolerance by using secondary optics, but noted the additional manufacturing cost is a significant consideration. A more thorough understanding of the performance changes induced by soil could provide insight to the cost effectiveness of soil mitigation technologies, or O&M costs for large HCPV plants. In the present work, we examine the potential spectral effects of soil analogues typical of the US southwest on calibrated isotype cell data. The change in spectral response was used to predict the limiting current condition of an HCPV device. Premature current limiting behavior, relative to performance at standard conditions, was considered as a system loss. Performance predictions of HCPV devices were made using measurements from prior work (Burton and King, 2014).

2. Methods

This work used experimentally collected transmission data (Burton and King, 2014) to predict the spectral response of TJ GaInP/GaInAs/Ge (noted as **T**op/**M**iddle/**B**ottom junctions, respectively) photovoltaic devices. Light transmission through a soil film previously collected by UV/vis spectroscopy (Burton and King, 2014) was used to simulate direct normal irradiance (DNI) reaching the HCPV cell. These measured values were used to calculate the expected short circuit current density (J_{SC}) of a hypothetical device under a similar soil coverage. A nominal baseline for DNI spectral behavior was determined by multiplying the standard AM1.5D spectrum (ASTM, 2012) by the reported device response. The percent transmission due to each soil type and mass loading measured by the spectrophotometer was applied as a reduction factor to the calculated baseline, as shown in (1).

The subcell spectral response ($SR(\lambda)$) of an isotype spectral sensor (BPI-IT1, Black Photon International) at each calibrated wavelength was used to predict the effects of soil on a TJ device. In the isotype sensor, each independent subcell collects the full spectrum allowed by its respective bandgap; however, only the active cell is connected to an external circuit. As a result, the current reported by each subcell is exaggerated compared to the performance of a series-connected device, which would be limited to the current of the lowest output subcell. Since the emphasis of this study was the relative impact of various soil types on TJ devices, an artificial constraint was imposed by scaling the middle cell response to equal the top cell at AM1.5D. A multiplicative factor of 90.68% was applied to the integrated area of the middle subcell.

The baseline was calculated as the integral over wavelength (λ) of the standard AM1.5D spectrum ($E_{ASTM}(\lambda)$) multiplied by the $SR(\lambda)$ of each subcell. The ratio of $J_{\mathrm{SC}}^{\mathbf{T},ASTM}/J_{\mathrm{SC}}^{\mathbf{M},ASTM}$ was applied to subsequent calculations for the middle subcell under soiled conditions, as shown in (2).

$$J_{\mathrm{SC}}^{T,soiled} = \int_{\lambda_{T_1}}^{\lambda_{T_2}} E_x(\lambda) \cdot SR(\lambda) \cdot \%T(\lambda) d\lambda \tag{1}$$

$$J_{\mathrm{SC}}^{M,soiled} = \frac{J_{\mathrm{SC}}^{T,ASTM}}{J_{\mathrm{SC}}^{M,ASTM}} \int_{\lambda_{M_1}}^{\lambda_{M_2}} E_x(\lambda) \cdot SR(\lambda) \cdot \%T(\lambda) d\lambda \tag{2}$$

The effect of soil was calculated by multiplying the spectrum by the measured light transmission ($\%T(\lambda)$) to account for the light reaching the device. Changes in spectrum throughout a typical day were predicted using a DNI spectrum ($E_{AM}(\lambda)$) calculated using the Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS) (Gueymard, 1995, 2001). The SMARTS inputs for an ASTM 173-G spectrum were used over a range between AM1.0D to AM15.0D in 0.5 increments to roughly approximate the spectrum of a typical day. Each spectrum was used as an input as described in (2). A similar approach has been described by Qasem et al. (2012) to evaluate the effects of tilt angle on flat-plate systems. Seasonal effects were modeled using the extreme conditions of each season; i.e. the solstices, to capture the greatest possible variation between data sets. In order to calculate the spectra for specific dates, the standard inputs were replaced with location-specific data collected in Albuquerque, NM (35.05°N, 106.54°W). Summer and winter solstice calculations were performed using SMARTS with inputs modified