Solar Energy 165 (2018) 148–158

Contents lists available at ScienceDirect

Solar Energy

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

Potential energy yield increase of a solar spectra down-converter equipped photovoltaic device in real operational conditions

Bartosz Fetliński*, Michał Malinowski

Institute of Microelectronics and Optoelectronics, Warsaw University of Technology, ul. Koszykowa 75, 00-662 Warsaw, Poland

ARTICLE INFO

Keywords:
Photovoltaics
Down-conversion
Spectral irradiance
PV system performance

ABSTRACT

In this work, we evaluate the impact of solar spectrum down-converter (DC) on an energy yield of solar cells working in real world meteorological conditions. For this purpose, a simple model of PV device with a down-converting layer is used, with inputs (spectra, irradiance, temperature) taken from the public NREL database for their outdoor test facility. The model assumes ideal external quantum efficiency (EQE). The analysis showed that in these conditions the energy yield increase from the use of DC system is 23.64% which is bigger than improvement due to DC calculated for the standard test conditions (20.1%). This effect is more profound in summer (24.8% for June-August) than winter months (22.1% for December-February). The average photon energy (APE) turned out to reasonably well reflect the overall impact of the DC layer on the energy yields with $R^2 = 0.96$. The primary conclusion is that the impact of spectral converters on PV device performance should be analyzed not only in the standard test conditions as in the real operating conditions the result of spectra converting layer may turn out substantially better, lowering the bar for commercialization and broad application of such layers.

1. Introduction

Solar spectrum conversion, especially down-conversion (DC) and down-shifting (DS), are among the most feasible methods of increasing efficiency of photovoltaic (PV) devices. We define DC as an effect in which from a single photon of incident irradiation more than one longer wavelength photon is emitted, while in DS process a single incident photon results in no more than one photon emitted at a longer wavelength. Application of down-converting layer theoretically permits an increase of single junction PV device efficiency from around 31% (Henry, 1980) to 38.9% (Trupke et al., 2002). Some experimental devices utilizing down-shifting layers have been presented in the literature (Klampaftis et al., 2011; Rothemund, 2014), but vast majority of authors investigate only the impact on the external quantum efficiency (EQE) that the DS has on photovoltaic device and the data on their performance in the real world meteorological conditions is rather scarce (Ross et al., 2012). Much fewer down-conversion based photovoltaic devices were presented (Vivaldo et al., 2017; Zhou et al., 2012).

Properties of the devices utilizing spectrum converting layer are usually measured in Standard Test Conditions (STC, irradiance 1000 W/m^2, spectrum AM1.5G, cell temperature 25 °C) using sunlight simulator or EQE measurement. Reliability of the DC and DS layer measurements is often questionable, as even the AAA class simulators allow for ± 25% deviation of power contained in a part of the spectrum, which has to be taken into consideration when measuring the efficiency. Even this lenient requirement is waived for wavelengths below 400 nm, where requirements for simulators are not specified but which are of greatest importance for down-converting or down-shifting applications.

Most of the down-conversion systems' analyses are focused on efficiency increase potential under reference spectrum. In the literature on PV devices efficiency limits calculation many different spectra are used: beginning from spectrum referred to AM1.5 or AM1.5G, definition of which changed over time, and is not always normalized to 1000 W/m^2 or 1000.37 W/m^2 as given in the ASTM G173-03 reference spectrum, AM0, blackbody emission spectra at temperatures of 6000 K, 5800 K, 5760 K) and other (approximation of AM1.5G with Gaussian peaks (ten Kate et al., 2013)). The term AM1.5G will be used interchangeably with ASTMG173-03 as a customary synonym.

Significant effort had been dedicated to evaluating the impact of changing solar spectrum on energy yields (Behrendt et al., 2013; Dirnberger et al., 2015a; Nofuentes et al., 2014). Since calculations of the spectral mismatch on measurement point by measurement point basis over a long period of usually at least a year is computationally intensive many authors seek methods of simplifying this calculation for example by use of Average Photon Energy (APE) (Liu et al., 2016; Minemoto et al., 2009). The APE is often indicated as a convenient parameter for describing the solar spectra. This parameter is commonly used for evaluation of solar spectrum impact on the performance and

---

* Corresponding author.
E-mail address: b.fetlinski@imio.pw.edu.pl (B. Fetliński).

https://doi.org/10.1016/j.solener.2018.02.071
Received 19 November 2017; Received in revised form 2 February 2018; Accepted 26 February 2018

efficiency of various photovoltaic cell technologies in real-world operating conditions. Work of Minemoto et al. (Minemoto et al., 2009) relying on analysis of over 10,000 sample spectra strongly supported a relation between APE and unique shape of spectra in the APE range of 1.86–2.04 eV. However, these simplifications are not always justifiable and their validity has been questioned (Dirnberger et al., 2015a, 2015b).

Other approaches to simplification of solar spectra representation include airmass calculation (Zdanowicz et al., 2004), which however is limited to clear sky irradiance, spectral mismatch factor (Dirnberger et al., 2015a; Polo et al., 2017), which requires assumptions regarding external quantum efficiency (EQE) of considered photovoltaic devices or useful fraction of photons (Gottschalg et al., 2003, 2004).

In this work, we attempt to evaluate potential increase of the energy yield obtainable by equipping photovoltaic devices with the down-converting layer relative to yield of devices not equipped with such layer. The model itself, its justification and methodology of data processing are described in Section 2, with results calculated in STC presented in Section 3 for reference. In Section 4 the meteorological data in the considered location is presented and analyzed, with stress on the short-wavelength part of the solar radiation particularly important for DC processes. In Section 5 impact of DC on efficiency is presented and used to estimate the impact on energy yields in Section 6. In addition, in Section 7, we look if APE may be used to estimate this impact.

2. Method

The solar cell operation model we use is a classical model proposed by Henry (Henry, 1980). This detailed-balance based model includes both spectral and thermodynamic effects affecting solar cells efficiency and permits calculation of maximal obtainable efficiency of PV cell of given temperature exposed to the irradiance of given spectral power density. The model assumes ideal EQE equal to unity in a range limited only by the bandgap of the cell's material. Since the goal of this work is to estimate possible relative energy yield increase we find that the general nature of Henry's model is better suited for this application than more elaborate models. Such models take into consideration numerous detailed properties of different semiconductor material (such as Tiedje-Yablonovich model (Tiedje et al., 1984)) or at least require assumptions regarding EQE. Thus, using simpler model offers a better trade-off between generality of the analysis and precision of the calculated efficiency. For this reason, the scope of this work is limited to DC system, as without assumed non-ideal EQE the DS processes don't provide any improvement.

Limiting the cell model to spectral response only is often the case in works aiming to evaluate spectral effects on photovoltaic devices performance. Yet, even in the case of general energy yields analysis temperature effects are of critical importance and cannot be neglected. The Henry's model taking into account both temperature and radiation power density enables more detailed, yet still general analysis. The model doesn't consider angular losses (sunlight angle of incidence).

In order to evaluate the impact of down-conversion of the incident spectra, we assumed the existence of the external two-step down-converting layer of ideal properties in front of the photovoltaic cell. The layer absorbs and converts each photon of energy larger than two times bandgap energy of considered cell into two photons, and all emitted photons are absorbed by the PV cell. For photons of energies smaller than twice bandgap energy, the layer is assumed to be completely transparent. This solution is of course among the simplest model possible, yet it does not require any assumptions about the absorption properties of the solar cell material or the down-converting mechanism.

There are some available sources of meteorological data which include regularly measured solar spectra (Polo et al., 2017). The analysis of the potential yield increase for devices with down-converting layers was conducted using publicly available data from the National Renewable Energy Laboratory, Solar Radiation Research Laboratory (Andreas and Stoffel, 1981). The extensive meteorological station belongs to one of the most reputable institutions, downtimes are rare and well-marked in the documentation and the instruments are regularly calibrated ensuring very high reliability of the data. The meteorological station used is located at 39.74 N, 105.18 W at an elevation of 1829 m above sea level. The data from selected meteorological instruments was acquired from ("www.nrel.gov/midc/srrl_bms/") for a complete three-year period of January 1st 2009 to December 31st 2011, which was dictated by the availability of records from the chosen instruments. The data which was used in this chapter originates from the following instruments:

- LICOR Li-1800 Global 40-South Spectral Data – spectra measured in a plane oriented south at a tilt of 40°. It ceased to be operated in 2012, but provides a wider usable spectral range of 300–1100 nm and narrower 6 nm bandwidth in comparison with the currently operated device.
- Global 40-South LI-200 – south facing Licor LI-200 silicon pyranometer measuring global irradiance in the same plane as the spectrometer.
- Dry Bulb Temp (Tower) – Ambient air temperature measured in a radiation shield 2 m over natural vegetation.
- Wind Speed (6′) – wind speed measured 6 feet over the ground level.

The spectral irradiation data was available at 5 min intervals and corresponding data points of global irradiation, wind speed and ambient temperature measurement were assigned. All the calculations, including those conducted for ASTM G-173-03, were limited to the 300–1100 nm range unless explicitly stated otherwise.

The spectra and the other meteo data were downloaded separately and merged according to timestamps. The spectral data were recorded with 1-min resolution while other data was recorded at 5 min interval. Thus, the spectral data was appropriately downsampled.

Since the NREL laboratory does not provide data on PV modules temperature measurement at the exact same location we had to approximate the PV cell temperature by using model presented in (Tamizhmani et al., 2003), which was developed for photovoltaic modules located in the NREL laboratory basing on available data on ambient temperature, global irradiation and wind speed. The modules temperature was calculated using the following equation:

$$T_m(K) = 0.943T_{ambient} + 0.028Irradiance - 1.528\,Windspeed + 4.3 + 273.15 \quad (1)$$

Irradiation taken for temperature calculation purpose is measured by the Licor LI-200 pyranometer.

Then the dataset was reduced with the removal of data sets which fulfilled the following criteria:

- Pyranometer irradiance or integral of the spectrum $< 15\,\mathrm{W/m^2}$.
- Pyranometer irradiance or integral of the spectrum $> 1600\,\mathrm{W/m^2}$.
- Module temperature outside of 250–375 K range.

Apart from these conditions several data points containing obviously faulty values (for example the ambient temperature of −6666 K, impossibly huge values of the spectral irradiance, data points with non-numeric or void content) were removed. The primary reason for the elimination of the low irradiance data points is to reduce excessive errors introduced by the instrumentation in such conditions.

Energetic availability defined as the proportion of irradiation measured by the pyranometer in the cleaned data to irradiation in the raw data is about 95%, which means that the cleanup should not adversely affect the further analysis in a significant way and that the remaining data are representative for the whole dataset. After the cleanup the dataset consists of 140,308 individual measurement points, each containing measured spectrum and the mentioned meteorological parameters.