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# Modelling the impact of spectral irradiance and average photon energy on photocurrent of solar modules

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## ABSTRACT

Photocurrent generated by a solar cell depends on environmental conditions as well as electrical and technological parameters of the cell. During this research, a holistic assessment of the performance of solar cell technologies is performed. Measurement of the solar spectrum is carried out from sunrise to sunset using a calibrated spectrometer. Temporal variations in the solar spectrum, spectral content and average photon energy (APE) are discussed. A model is developed to assess the impact of spectral irradiance and temperature on photocurrent from planar pn junction cells. Effect of irradiance, temperature and average photon energy on the photocurrent generated by a poly-Si solar cell is simulated and analysed. Discussions on the performance of other cell technologies are also made. Results show that the APE was 1.94 eV for the 300–1050 nm bin, 1.91 eV for the 350–1050 nm bin and 1.84 eV for the 400–1050 nm wavelength bin of the AM 1.5 solar spectrum. At low intensity of light, the solar spectrum is rich in photons within near Red - IR wavelengths and hence the APE is 1.75 eV. The APE then increases proportionally with an increase in irradiance until a saturation level is reached at approximately 1.95 eV when irradiance exceeds 700 W/m$^2$. Photocurrent is computed for varying spectral irradiance and temperature conditions. First, at low irradiance levels when the solar spectrum is rich in photons from Red-IR regions, the photocurrent is linearly proportional to the APE. Secondly, as the intensity of light increases and Visible-UV components of light increases, an exponential relationship between the photocurrent and APE is exhibited.

## 1. Introduction

Photovoltaic technologies are rapidly penetrating the global market. The total installed capacity of PV around the globe was reported to be 303 GW in 2016 (REN21, 2017) and more than 100 GW is estimated to be installed globally in 2017. As a relatively high investment is required for deployment of PV projects, investors are very concerned with the temporal variations of performance of different PV technologies in specific sites such that the technologies which can lead to least levelized cost of electricity can be selected.

Normally, energy production from a PV array is estimated using information on plane of array insolation at the PV site and peak rating of the PV array. While peak ratings of solar modules are provided for standard test conditions (STC) defined by AM1.5, temperature of 25 °C and total spectral power of 1 kW/m$^2$, such conditions are not generally representative of the actual outdoor environment. Performance of a PV cell is technology dependent, which in turns depends on the absorption spectrum and the spectral responsivity of the PV material used and construction of the cell. It is not always possible to measure the performance of a PV technology at a specific site before its large scale deployment. Therefore, for a detailed analysis of performance of PV cells, it becomes crucial to compute the spectral response or the photocurrent of a solar cell using information on the input solar energy, environmental conditions, and the cell's electrical, material, construction and optical properties. Time varying spectral distribution of solar power and variations of environmental parameters such as temperature and wind speed represent the solar energy and environmental parameters. The material properties of solar cells include energy band gap, level of doping, diffusion coefficients, surface recombination, dielectric constant and the absorption coefficient of the material. The construction properties include the cell's active surface area, the depth of neutral emitter and base layers and the width of depletion zone, the junction ideality factor, the series and the shunt resistance.

Numerous research works have made an attempt to assess impact of spectral distributions on various PV technologies and introduce specific characteristic coefficients of the solar spectrum to assess its impact of on output of PV panels. Eltbaakh et al. (2011) performed a review of measurements made and provided an overview of spectral global solar

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**Abbreviations and nomenclature**

| | |
|---|---|
| APE | average photon energy |
| CIGS | copper indium gallium selenide |
| CIS | copper indium diselenide |
| c-Si | crystalline silicon |
| MMF | module mismatch factor |
| PV | photovoltaics |
| STC | standard test conditions |
| UF | utilisation factor |
| $\alpha(\lambda)$ | absorption coefficient |
| $\phi(\lambda)$ | spectral photon flux - number of incident photons per area per time per unit bandwidth |
| $\lambda$ | wavelength |
| $\mu_n$ | mobility of electron |
| $\mu_p$ | mobility of hole |
| $\tau\alpha$ | effective transmittance-absorbance product |
| $\tau_n$ | electron lifetime $\tau_p$ lifetime of holes |
| $\xi$ | electric field |
| A | device area |
| $D_n$ | diffusion constant for electrons |
| $D_p$ | diffusion constant for holes |
| $E_g$ | energy bandgap |
| $G_n$ | generation rates for electrons |
| $G_p$ | generation rates for holes |
| $J_p$, $J_n$ | hole and electron diffusion current densities |
| k | boltzmann constant |
| $n$ | ideality factor |
| $P_n$, $n_p$ | minority carrier densities |
| $P_{n0}$, $n_{p0}$ | thermal equilibrium minority carrier densities |
| $S_n$, $S_p$ | surface recombination velocity |
| $S_{NOCT}$ | irradiance at NOCT condition |
| $S_{STC}$ | 1000 W/m$^2$ |
| $S_T$ | irradiance at given temperature |
| $T_a$ | ambient temperature |
| $T_c$ | cell temperature |
| $U_l$ | loss coefficient |
| $U_{l,NOCT}$ | loss coefficient at NOCT |

irradiance observations and of broadband solar irradiance observations from the ultraviolet to the near infrared. The author described equipment used for measurement by various researches. The equipment includes pyrheliometer, pyranometer and reference cells for measurement of broadband irradiance. For measurement of spectral irradiance in the UV, Visible and Near IR ranges sun photometers, radiometers and spectrometers were discussed. The author stated that measurements of the solar spectral irradiance can be obtained with optical filter radiometer instruments that measure irradiance at selected narrow wavebands, and high-resolution scanning spectro-radiometer, that provide full spectral information.

Eke et al. (2017) performed a review of seasonal spectral irradiance effects on performance of photovoltaic modules under outdoor conditions and summarised thoroughly results obtained in previous studies. Key indicators which are commonly used for spectral characterisation such as, Useful Fraction (UF) and Average Photon Energy (APE) are also described in their work. The shape of I-V curves depend on the short circuit current and temperature. Correction of spectrum mismatch or spectral response mismatch (MMF) can be done as per IEC 60904-7 (International Electrotechnical Commission, 2008). IEC 60904-7 standard states that correction is not necessary if either the test spectrum is identical to the reference spectrum or if the test specimen's relative spectral response is identical to the reference cell relative spectral response. Alonso-Abella et al. (2014) studied the impact of variations the solar spectrum on the energy yield of eight different PV technologies. It was reported that a-Si and CdTe panels experience the most noticeable spectral gains. Polo et al. (2017) presented estimations of the spectral factor for 124 worldwide sites uniformly distributed according to the different climatic zones for several PV technologies and showed geographical distribution of the annual spectral factor for seven different PV technologies. The author concluded that the annual spectral factor for crystalline silicon technologies is almost similar worldwide. But, the annual spectral factor for thin film devices displayed a latitudinal pattern with spectral losses occurred mainly in northern hemisphere locations and spectral gains occurring in tropical zones. Both spectral gains and losses may reach up to 10% in the case of amorphous silicon devices. Dirnberger et al. (2015) studied the magnitude of uncertainty of spectral mismatch on performance of different PV technologies. It was reported that uncertainty of spectral mismatch within 350–1050 nm is very low, while between 350 and 1700 nm the uncertainty was less than 2% for a-Si, CdTe, c-Si and CIGS technologies.

A second parameter which is used to reflect fraction of the solar spectrum absorbed by a given PV technology is the utilisation factor or the useful fraction (UF). UF is technology dependent. A large value of UF indicates that a larger portion of the spectrum is being absorbed by the PV material, while a low value indicates that the PV material absorb mainly the blue and visible range of the spectrum. Gottschalg et al. (2005) studied the effect that results from variations in the total irradiance in the spectrally useful range of the device and described in terms of UF. The effect was studied on a-Si and multi junction device. The most widely used parameter is the average photon energy (APE). APE was initially suggested by Jardine et al. (2002). Unlike UF and MMF, APE is not technology dependent and its value depends on the limits of integration. APE has been used in numerous works to classify spectral distributions (Norton et al., 2015; Nofuentes et al., 2017; Eke et al., 2017; Chantana et al., 2017; Minemoto et al., 2007). Minemoto et al. (2007) studied the impact of changes in the solar spectrum and module temperature on the outdoor performance of amorphous Si and wafer type mc-Si PV panels installed at Kusatsu city in Japan. The author reported that the output energy of amorphous silicon panels depends on spectral distribution and is higher for blue-rich solar spectrum while it is less sensitive to module temperature. The output of mc-Si module is sensitive to module temperature but not to spectral variations.

Norton et al. (2015) assessed the spatial variations of APE in two sites in Italy and USA. The author concluded that APE values at a given location correspond to a specific solar spectrum and there is a close match between the solar spectrums measured at different sites but having the same APE values. The author reported that such agreement across all the significant APE values suggests that the APE offers an alternative way with which solar spectral resources can be qualitatively classified. Nofuentes et al. (2017) studied two years of spectral data over two sites and argued that APE cannot be a unique characteristic of the complete spectrum and there are still various factors that need to be investigated. Chantana et al. (2017) assessed the outdoor performance of different types of PV modules using MMF and APE. The author reported that APE value uniquely yields the irradiance and can be used as an index of solar spectral irradiance distribution. It is revealed that the APE is utilized as an indicator of MMF of the outdoor test PV modules. Louwen et al. (2017) performed a comprehensive characterisation of PV module performance under real operation conditions. The authors reported that some effects on performance of module are related to semiconductor material used while angle of incidence effects are attributed to type of front cover on the module.

All the existing research assesses the measured yield of PV technologies against variations of measured irradiance, spectral content and

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