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Studying the effect of spectral variations intensity of the incident solar radiation on the Si solar cells performance

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Abstract Solar spectral variation is important in characterization of photovoltaic devices. We present results of an experimental investigation of the effects of the daily spectral variation on the device performance of multicrystalline silicon photovoltaic module. The investigation concentrate on the analysis of outdoor solar spectral measurements carried out at 1 min intervals on clear sky days. Short circuit current and open circuit voltage have been measured to describe the module electrical performance. We have shown that the shift in the solar spectrum towards infrared has a negative impact on the device performance of the module. The spectral bands in the visible region contribute more to the short circuit current than the bands in the infrared region while the ultraviolet region contributes least. The quantitative effect of the spectral variation on the performance of the photovoltaic module is reflected on their respective device performance parameters. The decrease in the visible and the increase in infrared of the radiation spectra account for the decreased current collection and hence power of the module.

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Introduction

The outputs of photovoltaic (PV) devices operating outside under real working conditions are influenced by many environmental factors, such as module temperature, incident irradiance, and spectral irradiance distribution (Shaltout et al.,

1992a,b; Takashi et al., 2007). Characterization of materials is of importance for fabrication of any semiconductor device. Generally, the finished products are tested and characterized in order to improve and or maintain quality control (Kotnala and Singh, 1986). Photovoltaic (PV) devices are usually designed on the basis of standard meteorological data. However, spectral variation is not taken into account in the standard meteorological data which usually gives only the absolute broadband global irradiance (Gottschalg et al., 2003). The physical behaviour of solar cells and photovoltaic modules under varying solar illumination and changing ambient temperature needs to be known. Usually these data are not provided by the manufacturers and suppliers of PV products. Moreover, the data provided most often are taken at test conditions which hardly ever occur in practice (Durisch et al.,

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1996). The importance of spectral effects on PV devices has been investigated by other authors such as Gottschalg et al. (2003) and Kenny et al. (2006), on the basis of computer simulations and indoor measurements. Most of the investigations reported have been based on “useful fractions”, defined as the ratio of the observed spectral irradiance in the useful spectral range of the PV device in question to the observed global irradiance (Durisch et al., 1996; Emery, 1986). In this paper, we present the quantitative effects of the solar spectral variations on the device performance of the multicrystalline silicon (mi-Si) modules. The data used are based on outdoor measurements on cloud free days.

Spectral response (SR) is one of the most important parameters in photovoltaic (PV) device characterization. It is defined as the ratio of the wavelength dependent photo-generated current density to the incident photon flux. The mathematical representation of SR is

$$SR(\lambda) = J_{ph}(\lambda)/G(\lambda) \quad (1)$$

where $J_{ph}(\lambda)$ is the total photo-generated current density at a given wavelength λ and $G(\lambda)$ is the spectral irradiance of the incident light measured in $\text{W m}^{-2} \text{nm}^{-1}$. However, in state-of-the-art solar modules, the measured short-circuit current density (J_{sc}) approximates J_{ph} (Silvestre et al., 1999). Measurement of the wavelength dependent $J_{sc}(\lambda)$, which approximate the spectral response of the solar module is of prime importance in evaluating the material and device characteristics of a PV module (Bell, 1978). Spectral response of PV devices is in most cases reported in terms of quantum efficiency (QE), which is a measure of how efficiently a device converts in coming photons to charge carriers in an external circuit (Shaltout et al., 2000).

$$SR(\lambda) = QE(\lambda) \cdot \frac{q \cdot \lambda}{h \cdot c} \quad (2)$$

From Eq. (1), we can express the short-circuit current $I_{SC} \text{ A/m}^2$ in terms of incident photon flux $G(\lambda)$ as

$$J_{sc}(\lambda) = \frac{q}{h \cdot c} \int SR(\lambda) \cdot G(\lambda) \cdot \lambda \cdot d\lambda \quad (3)$$

where q is the electron charge, 1.6×10^{-19} coul., λ is the wavelength, h is planks constant, 6.63×10^{-34} J s, c is the speed of light, 3×10^8 m/s, and $QE(\lambda)$ is the external quantum efficiency of the cell, which is defined as the ratio of the current of the photo generated carriers to the photon flux incident on the surface of the solar cell (Singh et al., 2003). The short circuit current is dependent on the spectral distribution of the incident radiation. If any modification of the spectrum of the incident radiation is done, subsequent modification of the short circuit current should be noticed.

Experimental procedure

We investigated the effects of spectral variation on the performance of multicrystalline (mi-Si) module. The module was mounted on a fixed tilted plate along with a Pyranometer at the outdoor above the building of the National Research Institute of Astronomy and Geophysics (NRIAG) at Helwan, Egypt as shown in Fig. 1(a). The plate is mounted South facing at an inclination of 32° which is the optimum tilt angle in September month of this site (Elminir et al., 2006; Shaltout et al., 1992a,b). Measurements of the module were performed for a

whole day to collect adequate data for spectral variations for the day. The equipments of the experiment for the spectral variation measurements and its impacts on mc-Si module performance are shown in Fig. 1.

Current–voltage measurements

The measurement of solar module short circuit current I_{SC} and open circuit voltage V_{OC} data was performed by a visual basic program automatically acquires all the module $I_{SC} - V_{OC}$ data together with global radiation from a Pyranometer through a 14Bit data logger, which is connected to a PC (Ghitas and Sarby, 2009; Mageed et al., 2010). The program saves the data in appropriate files. To determine the effects of spectral variation and its impacts on mc-Si module physical parameters, the $I_{SC} - V_{OC}$ data for the module was measured at every 10 s intervals for the whole day.

Spectral irradiance measurements

The spectral measurements were performed by using a Fibre Optic Spectrometer (USB650) (Fig. 1b and c) which was mounted next to the solar module on the same site. Spectral measurements were made at the beginning and end of the day with the $I_{SC} - V_{OC}$ measurement. This enabled us to ensure that there was no significant change in spectral irradiance during the $I_{SC} - V_{OC}$ measurement. The spectral Sensitivity of the CCD of the Spectrometer (Fig. 1c) is 75 photons per count at 400 nm and the bandwidth of the instrument is 350–1000 nm. The glass dome covering and base mounting of the spectrometer sensor for environmental protection (Fig. 1b) is designed by the author and calibrated for field testing. The Spectrometer sensor has a cosine corrected head which enables it to correctly respond to and measure spectral irradiance at various angles of incidence. Each characteristic spectrum measured comprises 651 measurement points at 1 nm steps across the spectral range 350–1000 nm. The incident solar radiation is recorded by using CMP3 Kipp & Zonen pyranometer (Fig. 1a). The CMP3 is used in order to measure solar radiation with high quality blackened thermopile that provides a flat spectral response for the full solar spectrum range.

Results and discussion

The measured of solar spectra from morning to before solar noon during a typical clear sky day of 15 September 2012 is shown in Fig. 2. For comparison, we have overlaid the tabulated global spectrum in different air mass. It can be observed that the absorption peaks by ozone, oxygen, and water molecules in the measured spectra. Different parts of the spectrum change differently with time of the day. The visible (VIS) part of the spectrum (380–780 nm) experiences major variations compared to the variations in the ultraviolet (UV) and the infrared (IR) regions. We note that the absorption peaks do not change significantly with time but the integrated power changes. This is because while the absorption by specific gasses in the atmosphere changes the spectral content of the solar radiation, they have a relatively minor impact on the integrated power. Instead, the major factor reducing the power from solar radiation is the absorption and scattering of light due to air molecules and dust. This absorption process does

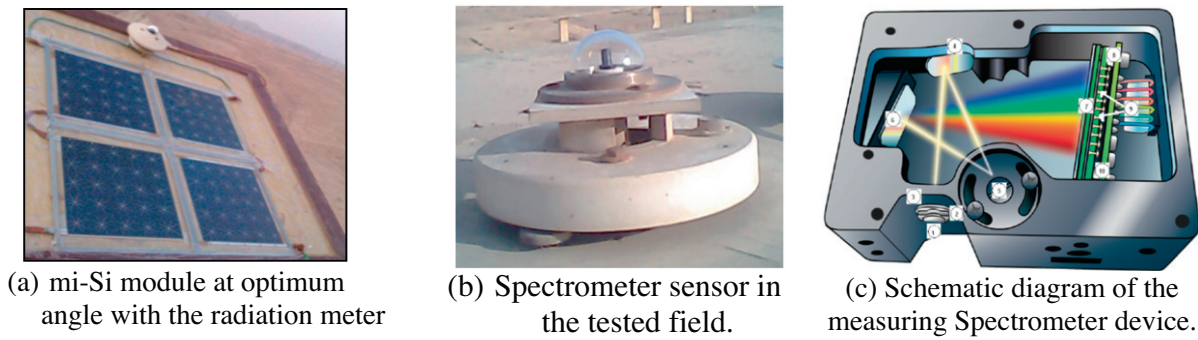


Fig. 1 Field test equipments for the spectral variation measurements (b and c) and mc-Si module physical parameters measurements (a).

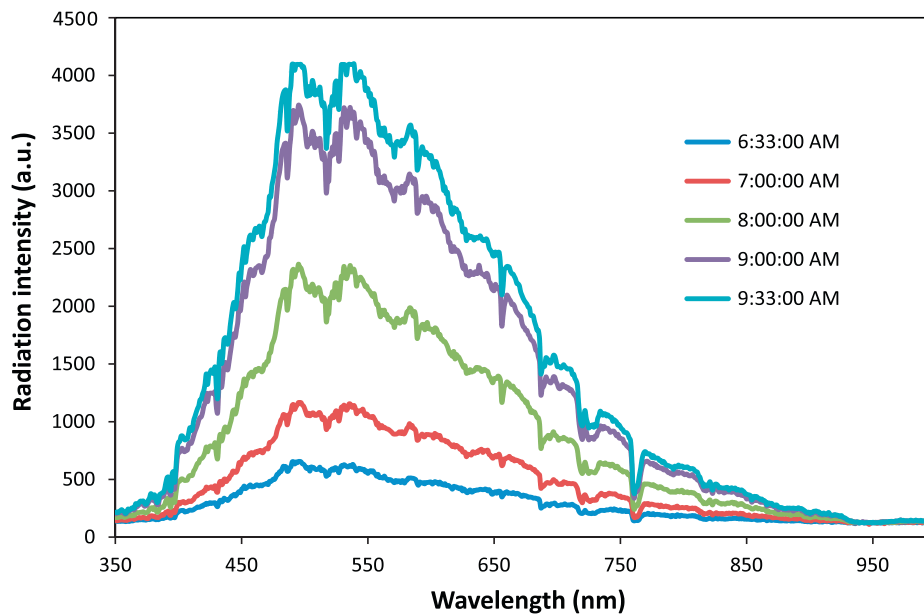


Fig. 2 Spectral irradiance variation versus time (A.Ms) on a clear sky measurement day.

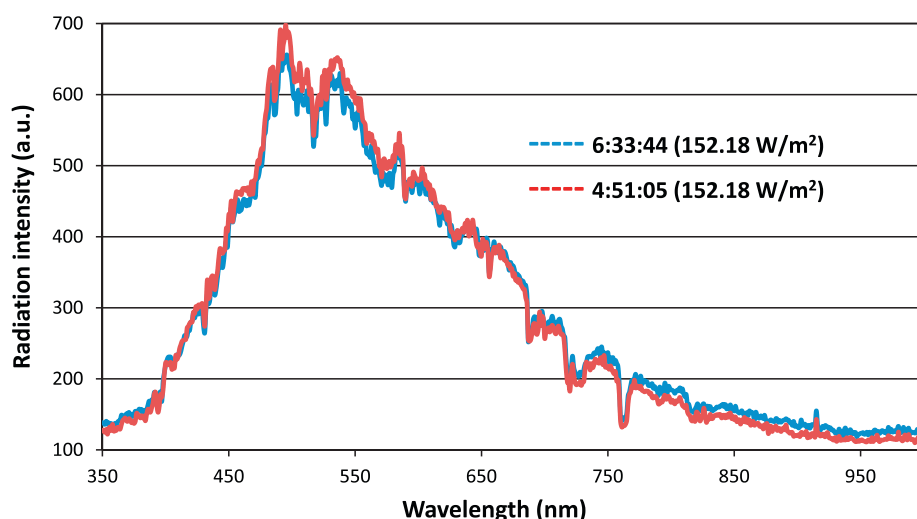
not produce the deep troughs in the spectral irradiance, but rather causes a power reduction dependent on the path length through the atmosphere. At solar noon, the absorption due to these atmospheric elements causes a relatively uniform reduction across the visible spectrum, so the incident light appears white. However, for longer path lengths, higher energy (lower wavelength) light is more effectively absorbed and scattered. Hence in the morning and evening the sun appears much redder and has a lower intensity than in the middle of the day (Okullo et al., 2011). The effects of these variations on the electrical output of the mi-Si PV module are shown in Table 1. It can be noted that as the radiation increases, the corresponding $I-V$ changes, with I_{SC} increasing with irradiance. Note that Fig. 3 shows the spectra of solar radiation at time 06:33:44 and 16:51:05 on one of the measurement days (15/9/2012). The values of irradiance at these times were comparatively similar but the corresponding spectral distribution was different. The relative difference between the two spectra is presented in Fig. 4. It can be noted that from the 375 nm to the wavelength of about 650 nm, the values of the spectrum at 16:51:05 were greater than those at time 06:33:44. However,

beyond 650 nm the spectral values at 06:33:44 were higher than the corresponding values at 16:51:05 and the relative difference increased to 10% as shown in Fig. 4. There is more IR and less VIS in the later spectrum. To quantify the spectral effects on the electrical output of the module, we present the device parameters of the mc-Si module in Table 1. It can be observed that the most affected parameters are I_{SC} , Power and the least affected parameter is V_{OC} . The electrical output therefore depends largely on the VIS part of the spectrum and less on the IR. Fig. 5 shows the spectral response (SR) of a typical mc-Si module overlaid on the spectra presented in Fig. 4. The SR curve shows a decrease in the long wavelength conversion into current. Note that the spectra presented have very small values in the wavelength range of 750–1000 nm while SR have maximum peak. We used the SR in Fig. 5 to calculate asymptotically the contributions by different parts of the solar spectrum to the photo-generated current, which is usually estimated by the measurable I_{SC} . The results are presented in Table 1.

Taking into account the area of the module, the calculation was based on Eq. (1) and the spectra were partitioned into

Table 1 Electrical parameters of multicrystalline (mc-Si) module with versus time.

Time	Radiation (W/m ²)	I_{SC} (A)	V_{OC} (V)	Power (W)
06:33:34	152.18	1.535	2.155	3.31
16:51:36	152.18	1.62	2.0407	3.306
Differences (%)	00	5.25	-5.6	-8.3
07:00:05	266.28	2.9588	2.193	6.489
16:22:32	266.28	3.1945	2.08178	6.65
Differences (%)	00	7.4	-5.3	2.4
07:15:36	345.069	3.9533	2.2004	8.699
16:08:50	345.069	4.038	2.0844	8.4175
Differences (%)	00	2.1	-5.5	-3.3
08:15:09	633.039	7.6673	2.18579	16.759
15:0:29	633.0398	7.8699	2.0949	16.487
Differences (%)	00	2.5	-4.34	-1.65
09:27:09	904.7	11.2247	2.1286	23.8958
13:46:17	904.7	11.334	2.0613	23.3628
Differences (%)	00	0.964	-3.26	-2.28
10:30:08	1050.05	12.9507	2.1057	27.2705
12:44:56	1051.4	12.8706	2.0700	26.641
Differences (%)	0.12	-0.622	-1.7	-2.36

**Fig. 3** Comparatively similar irradiance but different solar spectra recorded at different times on the same day (15/9/2012).

bands of UV, VIS and IR, that is the wavelength ranges of 350–380, 380–750 and 750–1000 nm, respectively. The results indicate that the VIS band of the spectrum at 16:51:05, contributed to I_{SC} more than the corresponding band in the spectrum at 06:33:44. However, the IR band of the spectrum at 06:33:44 gave more contribute on to I_{SC} than the corresponding band from the spectrum at 16:51:05. This is because as shown in Fig. 3 there is more IR in the spectrum at 06:33:44 than in the spectrum at 16:51:05. But the increased contribution by IR does not appreciably offset the decrease in I_{SC} caused by the decrease in the VIS part of the spectrum. The most important reason is that the electrical performance of PV mc-Si modules is heavily influenced by the visible part of the spectrum, and any shift in the spectrum results in significant non-linear impacts on I_{SC} and other parameters. The

spectrum at 06:33:44 has less visible but more infrared components, accounting for the decreased current collection and hence power. The blue part of the spectrum enhances charge carrier collection at the emitter or n-type region of the solar cell, which in turn depends upon the surface recombination velocity and the junction depth (usually close to the surface). The minority carrier life time in the p-type region of the module governs the long wavelength response (Shaltout et al., 2000).

Therefore the red part of the spectrum penetrates the p–n junction into the base of the module. Infrared, however, contributes little to I_{SC} . This is most likely due to incomplete absorption of the long wavelength photon. Most of the energy of these long wavelength photons is given as heat to the PV module, which in turn has a negative impact on its

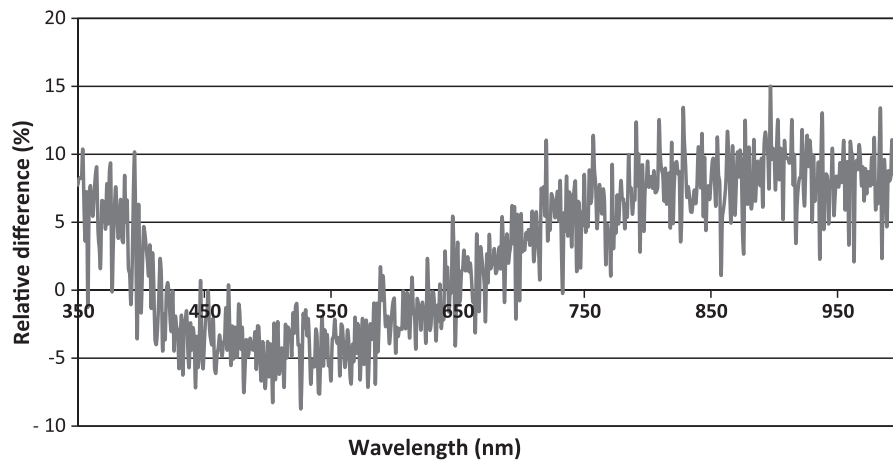


Fig. 4 The Relative differences between the spectra at the same amount of radiation.

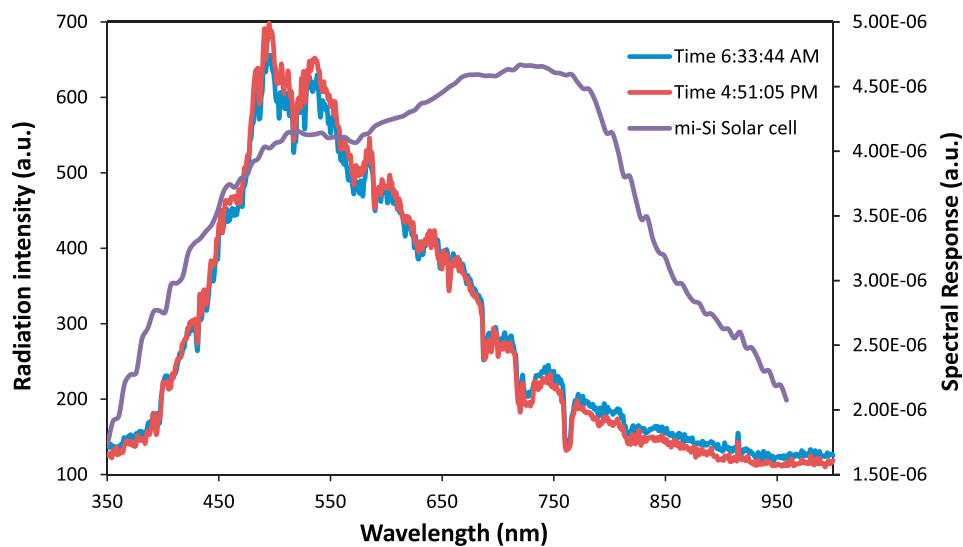


Fig. 5 Spectra of comparatively same irradiance at different times on the same day with spectral response of multicrystalline cell mi-Si.

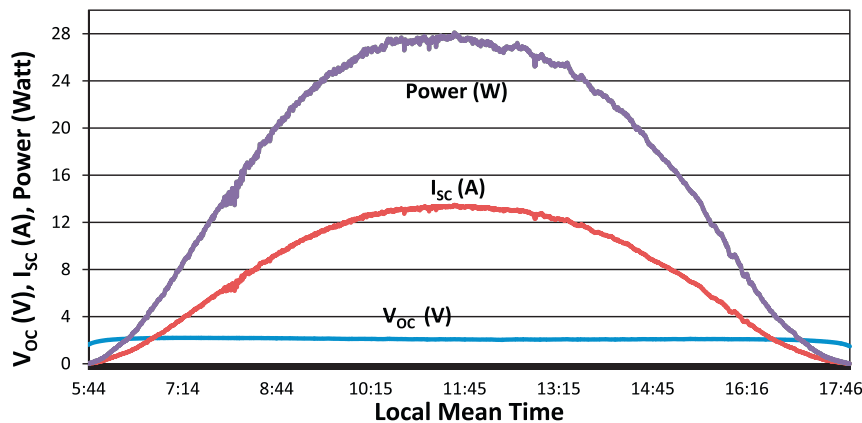


Fig. 6 Daily profile of the measured solar module short circuit current, open circuit voltage and electrical output power.

performance. Fig. 5 shows the variation of SR of mc-Si module with wavelength against spectra. It can be observed from this figure that the bands in the UV gave very little contribu-

tions to I_{SC} but the wavelength ranges 380–930 nm in both spectra gave large contributions to I_{SC} . However, the VIS contributions to I_{SC} from the spectrum at 16:51:05 were more than

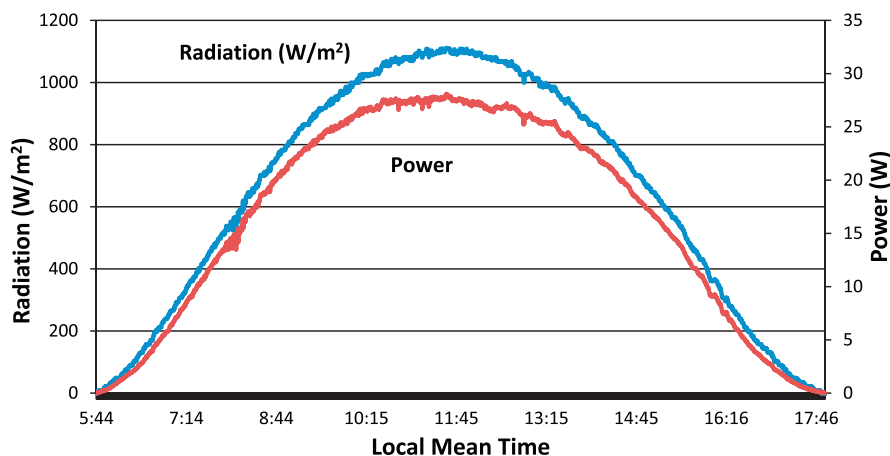


Fig. 7 Daily profile of incident solar radiation along with module output power.

the contribution in the corresponding band from the spectrum at 06:33:44. The total values of I_{SC} integrated overall wavelengths from 350 to 1000 nm at 16:51:05 and 06:33:44 were, respectively, 1.62 and 1.535A as indicated in Table 1. Fig. 6 shows the daily profile of the recorded solar module short circuit current I_{SC} , open circuit voltage V_{OC} and electrical output power P_{out} .

The maximum module open circuit voltage value is about 2.2 V for the series connection of the four solar cells (V_{OC} of each cell is ~ 0.55 V). In the meantime, the module reaches its maximum short circuit current (~ 14 A) to achieve about 28 W output power around the true noon time. Fig. 7 demonstrates the module electrical output power P_{out} along with the incident solar radiation intensity P_{inc} on its module surface in case of the optimum tilted orientation. The differences of the short circuit current from morning to near the noon are always positive with comparative values, except at noon is negative, as tabulated in Table 1. The differences of the open circuit voltage are always negative with nearly same values except at noon. This is because; the defences of the ambient temperature have negative impact on the module voltage. The increasing of the current does not offset the detrimental decrease of the voltage and consequently the output power is decreased.

Conclusion

The presented work is the effects of variation in solar spectrum on the performance of multicrystalline mc-Si module. The morning spectra have more infrared compared to the late afternoon spectra and this shift from VIS to IR has a small negative impact on the device parameters of the module. The spectral bands in the VIS region contribute more to I_{SC} than the bands in the IR region. This is because the blue part of the spectrum enhances charge carrier collection at the emitter of the solar cell, which in turn depends upon the surface recombination velocity and the junction depth (usually close to the surface). Also, the long wavelength (red) response is, in part, determined by the minority carrier lifetime in the p-type region of the module. Infrared on the other hand contributes little to I_{SC} due to incomplete absorption of the long wavelength photons whose energy is mostly given as heat to the PV module. The UV region contributes least to the I_{SC} because most of the short wavelength photons are absorbed on

the surface of the module before they generate charge carriers. The quantitative effect of the spectral variation on the performance of the PV module is shown on their respective device performance parameters. For mc-Si, most affected device parameter is I_{max} , and P_{max} . The effect of the decrease in the VIS of the second spectra is not appreciably offset by the increase in IR, accounts for the decreased current collection and hence power of the module. It can therefore be concluded from this work that for a thorough understanding of the outdoor performance of mc-Si device spectral data are important.

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