

# Effect of seasonal spectral variations on performance of three different photovoltaic technologies in India

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**Abstract** The accuracy of outdoor performance of a photovoltaic (PV) array can be improved by considering the spectral effects. In this paper, the impact of seasonal spectral variations on the three different silicon PV technologies: single junction amorphous silicon (a-Si), Heterojunction with Intrinsic Thin-layer (HIT) and multi crystalline silicon (mc-Si) has been presented first time in Indian environmental conditions. The spectral effect on HIT PV module technology has been presented first time along with the first simultaneous study of variation in spectral indicators by useful fraction (UF), average photon energy (APE) and spectral mismatch factor (MMF), based on monthly and seasonal data. The maximum observed variation in UF was 26.4, 8.2, 10.8 %, while in MMF, variation was up to 24.7, 7.6, 8.2 % for a-Si, HIT and mc-Si, respectively, and in APE variation was up to 15.3 %. Among all three technology modules, first time reported HIT technology showed the least variation while maximum variation was observed in a-Si technology. The observed spectral effect variations have been discussed on Performance Ratio and compared with reported results of other global sites. The value and trends of spectral parameters are important to understand the effect of spectral variation on different technology. This study is especially important in Indian subcontinent perspective because of the strong monsoon season, where observed variation in the

spectrum-related parameter found to be highest among all the seasons.

**Keywords** Photovoltaics · Spectral variation · Average photon energy · Useful fraction · Mismatch factor · Performance ratio

## Introduction

The energy yield from the PV array is the most crucial parameter to assess the viability of any installation. For modeling overall energy yield, the effects of climate during different seasons experienced by the modules need to be considered. Mostly outdoor performance of a PV module is lower compared to its performance at Standard Test Conditions (STC<sup>1</sup>), which normally do not occur in the field environment. Therefore, it is important to know the value of the parameters and their variations, which affect the performance of PV module in actual field conditions. Spectrum is one such important parameter which changes with locations and seasons [1]. The focus of this present work is to study the effect of the spectrum variation in different seasons on different technology modules under Indian environmental conditions. Such a study will be useful to quantify the spectrum related parameter to estimate its effect on the performance of the PV array.

The entire Indian subcontinent features very different climate with different seasonal patterns compared to many other countries. It can be broadly divided into three seasons: summer, winter and monsoon. Each season has a different impact on the spectrum. The region has a very

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<sup>1</sup> STC: Irradiance  $G = 1000 \text{ W/m}^2$ , module temperature  $T_{\text{mod}} = 25 \text{ }^\circ\text{C}$ , perpendicular incidence of irradiance, air mass 1.5 spectrum.

strong monsoon season lasting for several months of the year, which is very different as compared to rest of the world. Monsoon of this region is known to be one of the largest monsoon systems of the world [2, 3]. The monsoon season provides nearly 80 % of the year's rainfall in India [4]. The maximum change in the spectrum, observed in monsoon season, is due to scattering and absorption processes in the presence of clouds and aerosols, which attenuates certain solar radiation wavelengths more compared to other wavelengths. It is important to note that monsoon season is very special to the Indian subcontinent prospective. The current study will be helpful to know the effect of the monsoon on spectral parameters due to change in the spectrum. Other than monsoon season, this study also presents the variation of spectral parameters in the winter and summer seasons, which showed very different trends.

This study of spectrum measurement was conducted at the India's National Institute of Solar Energy (NISE), Gurgaon, located towards North of India near to New Delhi. At this site, a typical year can be broadly divided into four seasons: winter, summer, monsoon and the post-monsoon (or transit period). The winter starts in the beginning of November and continues until the end of February. Summer starts from March and continues till the end of June. The period from July to September is the monsoon and October to beginning of November constitutes the post-monsoon season.

Seasonal change in spectrum affects different technology modules performance in a different way, depending on the absorber material properties, such as band gap, absorption coefficient and device structure. A detailed literature survey shows that several researchers reported spectral effects on PV module performances at different places, using different spectrum parameters, for different module technologies, using spectrum-based models and softwares and in different context, while interrelating with other parameters like temperature, module efficiency, etc. [5–21].

Hirata et al. [5, 6] investigated the influence of seasonal solar spectrum variations in Japan on mc-Si, a-Si and Cadmium sulfide (CdS) PV modules. In this study, "available spectral ratio" (similar to UF) showed the variation of around 5, 14, and 9 % for mc-Si, a-Si and CdS modules, respectively. Gottschalg et al. [7, 8] presented similar spectral variations on three thin film technology modules at UK site, in terms of UF variation of 15, 10 and 3 % for a-Si, cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) module. Further, corrections have been proposed for the incident spectrum at UK site, to include seasonal changes for single and multi-junction a-Si modules [9]. At another site in Germany, annual spectral impact and its uncertainty on a-Si, CdTe, crystalline silicon

(c-Si) and CIGS technologies have been estimated and related with APE and MMF [10, 11]. The highest annual spectral impact and uncertainty were reported in a-Si. The impact of spectral distribution as a result of seasonal variation on PR by considering APE and module temperature on a-Si technology has been analyzed at Japan site [12, 13]. At some other sites of Japan, net effect of the solar spectrum on the annual energy yield of c-Si and a-Si modules has been estimated by parameters related to spectral factor (similar to MMF) and APE [14]. The maximum spectral effect calculated using spectral factor or APE in a-Si (9 %) was much higher than c-Si (1 %). APE was considered as simple and easy parameter to estimate the effect of the solar spectrum on the energy yield of PV modules. Simon and Meyer [15] also studied seasonal spectral effects on c-Si modules in sub-Sahara region, where spectrum is very different from the standard AM1.5 spectrum. In another study conducted in Spain [16], spectral correction parameter (similar to MMF) was used to study the spectral effect on mc-Si and a-Si PV module. Generally in all the study at different places, a-Si technology found to be most susceptible to changes in the spectral variation compared to other technologies.

Some of the models in the literature have been used for incorporating the spectral effect, while estimating PV performance. Nann and Emery [17] modeled the spectral effects on PV device rating and found that efficiencies of a-Si cells differ by 10 % between the winter and summer months which was supported by outdoor experimental results [18]. Chegaar and Mialhe [19] discussed variation in intensity and spectral distribution on the short circuit current, and efficiency for a-Si, c-Si and mc-Si technology modules for Algiers site. Parretta et al. [20] developed a four-factor loss model, explaining the condition of solar radiation for the outdoor performance of c-Si modules. Krauter et al. [21] showed the improvements in data precision for the parameters which are responsible for PV yield inaccuracies.

The above-mentioned literature shows that the spectral effect on different technologies at different places has been investigated by different spectrum-related parameters. Most of the reported studies were undertaken at the sites in Europe and Japan. In the current paper, seasonal spectral variations have been performed at the Indian site, which have very different seasonal conditions compared to other sites reported in the literature. As mentioned earlier, India has strong monsoon season which makes a significant effect on the incident spectrum. India is currently implementing Jawaharlal Nehru National Solar Mission (JNNSM), which is one of the largest PV programmes of the world [22]. With all these considerations into account, the current study could be very useful for understanding the relative performance of different PV technologies in

different seasons, which will prove helpful in planning large-scale PV installations.

Many technologies have been investigated in the literature. For this study, mc-Si, a-Si and HIT PV technologies have been chosen while considering the facts that mc-Si have the largest installations in the world as well as in India, a-Si is the most common and oldest technology under a thin film category and HIT is a relatively new and promising technology which seems to have good future potential because of its high performance and reliability. Moreover, the effect of seasonal spectral variations on HIT technology has not been so far reported for any region of the world.

The above literature shows that different spectrum-related parameters have been used in spectral variation studies on PV modules. In most of the studies reported so far, spectral effects have been presented either in terms of APE (also termed as spectral irradiance distribution), UF (also termed as an available spectral ratio) and MMF (also termed as spectral factor), or combination of any of these two parameters. In the current paper, all the three parameters have been simultaneously studied along with PR which is related to the overall electrical performance. Also, these parameters provide a comprehensive comparison of HIT technology with other technologies. In this study, emphasis has been given to find absolute values of spectral parameters instead of their relative values which are rarely found in literature. These absolute values will help to drive other parameters which can be related to other studies.

### Characteristic indicators

The characteristic indicators related to spectrum variation used under the present study are defined below to provide better clarity and to avoid confusion with potentially differing definitions available in the literature.

#### DC performance ratio (PR)

The DC PR was defined as the ratio of the PV array yield ( $Y_f$ ) in terms of DC energy generated by the array, to the reference yield ( $Y_r$ ).

$$PR = \frac{Y_f}{Y_r} \text{ (Dimensionless quantity)} \quad (1)$$

The DC array yield,  $Y_f$ , is the ratio of net DC output energy ( $E$ ) to the name plate (STC) DC power ( $P_o$ ) of the installed PV array.

$$Y_f = \frac{E}{P_o} \text{ (kWh/kW}_p\text{)} \text{ or (hours)} \quad (2)$$

The reference yield ( $Y_r$ ) is the ratio of total in-plane solar irradiance ( $H_t$ ) to the PV's reference (STC) irradiation ( $G$ ), i.e., 1000 W/m<sup>2</sup>.

$$Y_r = \frac{H_t}{G} \text{ (hours)} \quad (3)$$

PR represents an equivalent number of sunshine hours at reference irradiance level. It is a measure of deviation between the actual performance of PV array with respect to theoretical achievable performance under STC. This deviation comes due to various losses under field conditions. PR changes with the location, orientation and time because the performance of the PV array is affected by the environmental parameters, such as variation in temperature, spectrum, and wind speed.

#### Useful fraction (UF)

UF is defined as the ratio of energy in the useful spectral range of the PV device to the total energy in the entire spectrum [7, 23, 24].

$$UF = \frac{\int_c^d E(\lambda) d\lambda}{\int_a^b E(\lambda) d\lambda} \quad (4)$$

where  $E$  is the spectral irradiance (Wm<sup>-2</sup>),  $a$  and  $b$  are wavelength ( $\lambda$ ) ranges of spectroradiometer from 350 and 1700 nm, while  $c$  and  $d$  are wavelength ( $\lambda$ ) ranges of useful spectral range of the PV device. UF varies with the incident spectral irradiance and is specific to the absorber material of the solar cell. UF changes to some extent with the operating temperature and the age of the PV device due to change in the material properties with temperature and defect formation by aging. UF has a close relation with the short circuit current ( $I_{SC}$ ). The dependency of  $I_{SC}$  on UF was explained with experimental results by Gottschalg et al. [25]. The main advantage of using UF as spectral indicator is that it provides direct feedback of a particular device performance and quantifies spectral influence on PV devices [15]. In this study, three technology modules of a-Si, mc-Si and HIT were used, which have active wavelength bands (i.e., useful spectral range) of 350–780 nm [23], 350–1150 nm [23], and 350–1200 nm [24], respectively.

#### Average photon energy (APE)

APE is defined as the ratio of integrated solar irradiance to integrated photon flux density. It represents average energy per photon [13].

$$APE = \frac{\int_a^b E(\lambda) d\lambda}{q \int_a^b \phi(\lambda) d\lambda} \quad (5)$$

where  $q$  is the electronic charge (C),  $E$  is the spectral irradiance ( $\text{Wm}^{-2}$ ) and  $\phi$  is a spectral photon flux density ( $\text{m}^{-2} \text{s}^{-1}$ ). For this study,  $a$  and  $b$  are wavelength ( $\lambda$ ) ranges of spectroradiometer from 350 to 1700 nm. APE is an index that indicates a spectral irradiance distribution of the solar spectrum [14]. It gives an idea of blue and red fractions available in the spectrum.

### Mismatch factor (MMF)

MMF is a correction factor applied to the short circuit current by taking into consideration the spectral mismatch between standard AM1.5 spectrum to the actual spectrum measured under outdoor condition at the time of measurement [10].

$$\text{MMF} = \frac{\int_a^b \text{SR}_{\text{PVdevice}}(\lambda) E_{\text{meas}}(\lambda) d\lambda}{\int_a^b \text{SR}_{\text{PVdevice}}(\lambda) E_{\text{ref}}(\lambda) d\lambda} \times \frac{\int_a^b \text{SR}_{\text{ref}}(\lambda) E_{\text{ref}}(\lambda) d\lambda}{\int_a^b \text{SR}_{\text{ref}}(\lambda) E_{\text{meas}}(\lambda) d\lambda} \quad (6)$$

where  $\text{SR}_{\text{PVdevice}}(\lambda)$  and  $\text{SR}_{\text{ref}}(\lambda)$  are the relative spectral response of PV module and pyranometer ( $\text{AW}^{-1}$ ), respectively,  $E_{\text{meas}}(\lambda)$  is the measured relative spectral irradiance under site condition ( $\text{Wm}^{-2}$ ),  $E_{\text{ref}}(\lambda)$  is the reference spectral irradiance ( $\text{Wm}^{-2}$ ) according to standard IEC 60904-3 [26],  $a$  and  $b$  are wavelength ( $\lambda$ ) ranges of spectroradiometer from 350 nm and 1700 nm. MMF is the factor which expresses the quantity more or less irradiance observed by the device under test at current conditions compared to the reference device [10].

### Instrumentation

The three test beds consisting of a-Si, HIT and mc-Si technology modules were used in this study as shown in Fig. 1. These test beds were located at NISE, Gurgaon, towards North of India near New Delhi. Details of these test beds and module used in these test beds are given in Tables 1 and 2, respectively. To measure the maximum power generated by PV test beds, an  $I$ - $V$  Scanner, array analyzer and multiplexer were installed as part of the test beds. A comprehensive weather station was present at the site of a test bed which was used for measuring and recording the horizontal surface and in-plane solar radiation on a test bed, the solar spectrum, ambient temperature, humidity, wind speed and wind direction [27]. The description and specifications of instruments used in the weather station are given in Table 3.

The schematic of a-Si, HIT and mc-Si technology PV test bed arrays is given in Fig. 2 which shows the series and parallel connections of modules in each test bed. In each test bed, one sample module was kept under open circuit condition (refer Fig. 2) and one sample module was connected to the  $I$ - $V$  tracer to measure  $I$ - $V$  data once in every 10 min. These sample modules (marked by symbol 'O') were kept under open circuit condition to perform a comparative degradation study with reference to the PV array which was always kept under load condition. The a-Si test bed was of 1.2 kWp capacity, consisted of 16 single junction a-Si modules, each of 75 Wp. These a-Si modules were connected in 4 strings and each string was made of 4 modules. The HIT test bed was of 1.68 kWp capacity,



**Fig. 1** Photograph of the PV module outdoor test bed used for collecting data

**Table 1** Specifications of three different technology modules used in test bed

Technologies	Modules configuration	Open circuit Voltage $V_{oc}$ (V)	Short circuit current $I_{sc}$ (A)	Maximum power $P_{max}$ (W)	Voltage at maximum power $V_{pm}$ (V)	Current at maximum power $I_{pm}$ (A)
a-Si	4 series 4 parallel	367.2	5.6	1200	268.0	4.4
HIT	4 series 2 parallel	294.4	7.5	1680	238.8	7.0
mc-Si	10 series	256.0	8.4	1600	212.8	7.5

which comprises 8 modules, each of 210 Wp. These HIT modules were connected in 2 strings and each string was made of 4 modules. The mc-Si test bed was of 1.6 kWp capacity, comprising 10 series connected modules, each of 160 Wp.

The weather data were recorded once in every minute, whereas *I–V* data of each PV module test bed along with its

temperature were measured and recorded once in every 10 min. PV arrays were kept under load conditions PV Scanner except during *I–V* measurement. All the data were stored on a PC and downloaded to the memory module once in every month.

### Results and discussion

The measurement site falls under the composite climate, which shows a wide variation in environmental conditions with the changing seasons. The solar spectrum incident on the modules varies due to changing seasons. To study the spectral variation in different parts of the spectrum, the entire spectrum was divided into five different wavelength bands. For simplicity, the peak time of clear days was

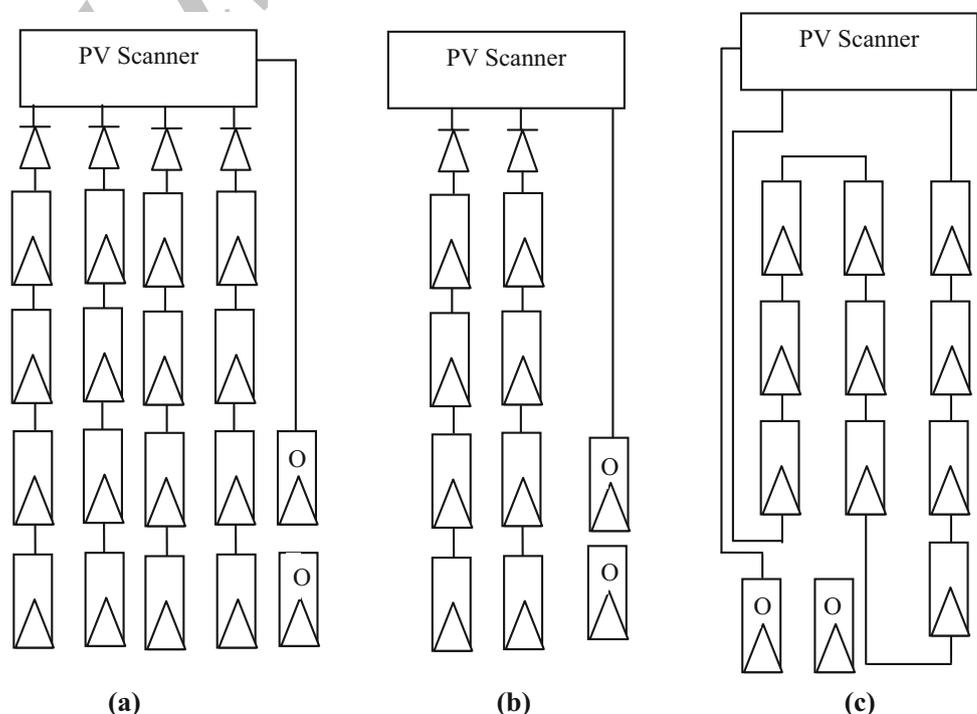
**Table 2** Specifications of individual modules used in the test bed under STC

Technologies	$V_{oc}$ (V)	$I_{sc}$ (A)	Fill factor (FF)	$P_{max}$ (W)
a-Si	91.8	1.4	0.64	75
HIT	73.6	3.7	0.78	210
mc-Si	25.6	8.4	0.74	160

**Table 3** Description of weather station instruments and specification

S. No.	Instrument name	Function	Accuracy	Company/make
1	Pyranometer MS-802	To measure solar radiation intensity on module (tilt) and horizontal surface with wavelength range 305-2800 nm	$\pm 10 \text{ W/m}^2$	EKO
2	MS-710 and MS-712 Spectroradiometer	To measure spectral distribution of the sun radiation. MS-710 covers region of visible and near infra-red (NIR) (i.e., 350-1000 nm) and MS-712 covers NIR only (i.e., 900-1700 nm)	Wavelength accuracy $\pm 0.2 \text{ nm}$	EKO
3	Wind sensor	To measure wind speed and direction	Accuracy $0.5^\circ$	Young
4	Humidity and temperature sensor	To measure relative humidity (RH) and temperature	$\pm 1.7 \%$ for RH, $\pm 0.20 \text{ }^\circ\text{C}$ for temperature	Vaisala

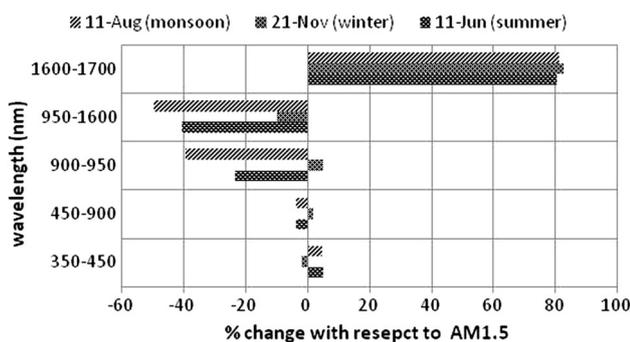
**Fig. 2** Schematic of a PV test bed **a** a-Si, **b** HIT, **c** mc-Si



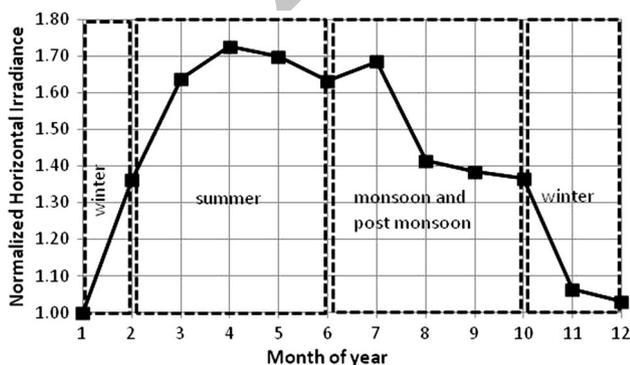
chosen from different seasons to estimate the percentage change in those five wavelength bands with respect to standard AM1.5 spectrum. Figure 3 shows this percentage change with respect to standard AM1.5 spectrum at the site for a clear day of summer (11th June), monsoon (11th August), and winter (21st November) for the year 2010.

Figure 3 shows that spectrum variation is more in the infrared region compared to the visible region. It is interesting to note that winter season shows the least variation and has an opposite trend in the spectrum, where most of the solar energy is concentrated in the wavelength range of 350–950 nm. Monsoon, which is a special season in the Indian context, shows the maximum variation in the solar spectrum, especially in infrared region due to the presence of clouds which affects the spectrum significantly. The percentage change in the wavelength band of 1600–1700 nm is highest in all seasons, but its effect is not severe because it contains a very small portion of solar energy (around 13 %). The large variation in this band could be partially due to the uncertainty of spectroradiometer at higher wavelength.

To give clarity of annual solar spectrum intensity variation on the site, the normalized horizontal irradiance for this site is plotted in Fig. 4. It presents the monthly median



**Fig. 3** Percentage change in five different wavelength bands with respect to standard AM1.5 spectrum at peak time of the day



**Fig. 4** Monthly median of daily normalized horizontal irradiance

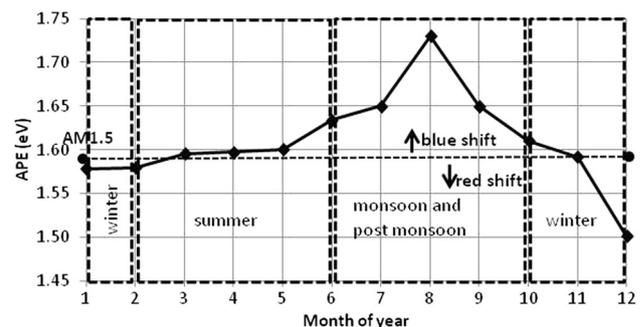
of the daily normalized horizontal irradiance variation in the year 2010, which is normalized by January month's median horizontal irradiance. This figure shows that the annual variation is up to 70 %. To give an idea about seasons, bands of different seasons are marked by dotted lines in Fig. 4. It shows that there is an appreciable change in intensity of solar irradiance in different seasons. The monsoon season shows intermediate average irradiance, where it is maximum in the summer and minimum in the winter seasons. This is mainly due to air mass (AM) effect which is low in summer and high in winter as discussed in a subsequent section.

In the following section, the seasonal variations using different characteristic indicators with a comparison among different PV technology modules are being discussed. The effect of seasonal variations is useful information pertaining to a specific technology, which is likely to dominate seasonally and annually.

### Variations in average photon energy (APE)

APE is a spectral index parameter which indicates the average energy of photons in the spectrum, which essentially represents the shift in the spectrum. A high value of APE indicates a shift towards the blue color of spectrum and low values indicates a shift towards the red color of the spectrum. At a particular location, APE depends on the measured spectral range and the climatic conditions at that time. As a reference, the APE value for standard AM1.5 spectrum in the range of 350–1050 nm and 350–1700 nm is 1.88 and 1.58 eV, respectively.

Figure 5 presents a plot of the monthly variation of measured APE values in the wavelength range of 350–1700 nm. The monthly variation of APE with respect to the annual average value of APE was +7.7 to –6.6 %. The actual APE values varied between 1.50 and 1.73 eV (15.3 %) during the whole year. In contrast to these values, Ishii et al. [14] observed the large APE variation of around 1.3–1.9 eV (46.1 %) at four outdoor sites of Japan in the similar wavelength range of 350–1700 nm. This large



**Fig. 5** Monthly variation of average photon energy (APE)



variation may be due to the oceanic effect on air mass variation which is not present at the Indian site. For another site located in Germany, the APE value variation was reported to be from 1.8 to 2 eV (11.1 %) for the wavelength range of 350–1050 nm [10]. In this case, the measurement spectral range was limited up to 1050 nm, which could be one of the main reasons of this small variation. As shown in Fig. 3, variation in spectral change was less at lower wavelength.

As the season changes, the shifting in solar spectrum can be seen in the magnitude of APE. Figure 5 shows that APE values were low in the winter season, indicating more energy in higher wavelength spectrum bands. As a result, solar spectrum shifts towards the red wavelength which could be due to high air mass and fog during this period. The calculated monthly average air mass for this site is plotted in Fig. 6 [28], which shows high air mass values in winter. The average APE value in the winter months was 3.3 % lower compared to yearly average APE of 1.6 eV. The trend of air mass variation is also supported by the average monthly data of Clearness Index (CI or Kt) for the year 2010, which was measured and is being plotted in Fig. 7. The CI data show low values in winter months which support spectrum shifting in the red region.

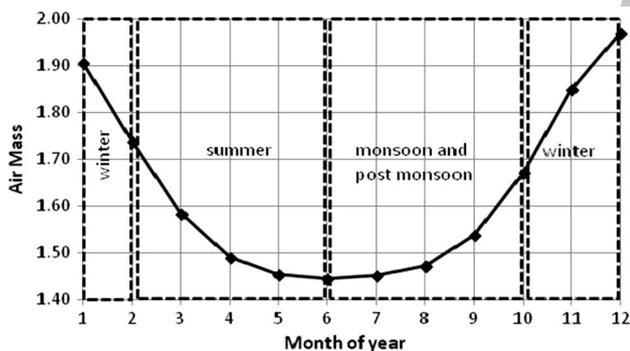


Fig. 6 Monthly variation of air mass (AM) at the site

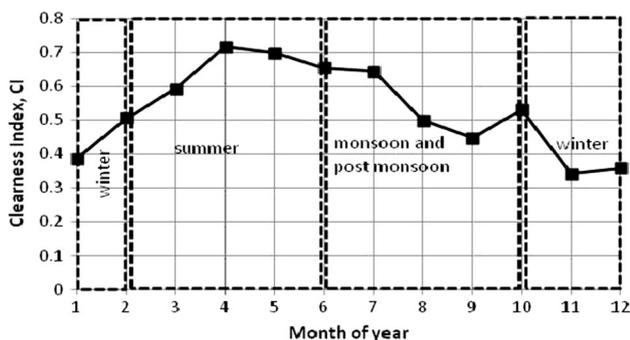


Fig. 7 Monthly variation of Clearness Index at the site

During summer months, observed average APE was 1.61 eV which was close to the yearly average. Further, Fig. 5 shows a strong blue shift during monsoon and post-monsoon months, with peak APE of 1.73 eV in August, which was 8.1 % higher than the yearly average value of APE, indicating more energy in the low wavelength spectrum. The main reason behind this strong shift in APE is due to cloudy weather conditions in monsoon, which block portion of infrared radiation and low air mass value [13]. The average APE value during the monsoon period was 7 % higher than standard AM1.5 spectrum.

This spectrum shifting primarily affects PV technologies which have a narrow spectral band response, like a-Si single junction, whereas its effect is marginal on technologies which have a broad spectral band response like mc-Si and HIT modules.

**Variations in useful fraction (UF)**

The effect of seasonal spectrum variation on PV technologies can also be quantified through UF measurement [5–8]. UF is a parameter which strongly depends on the PV technology. It primarily signifies the fraction of energy content in the spectral band of particular PV technology. It is affected by the seasonal changes due to change in the solar spectrum with the seasons. For the standard AM1.5 spectrum, values of UF for a-Si, HIT and mc-Si are 0.6, 0.86 and 0.84, respectively. Variation of UF value above standard AM1.5 spectrum value is called blue shift, whereas UF variation below AM1.5 spectrum is called red shift. In the field conditions, this variation in UF is mainly due to air mass and clouds, which also affects the irradiance, as discussed by Gottschalg et al. [29].

Figure 8 shows the monthly variation of measured UF value for a-Si, HIT and mc-Si PV technologies. It indicates that the PV technologies which have broad spectral band give higher UF value compared to technologies which have narrow spectral band. However, seasonal variation of

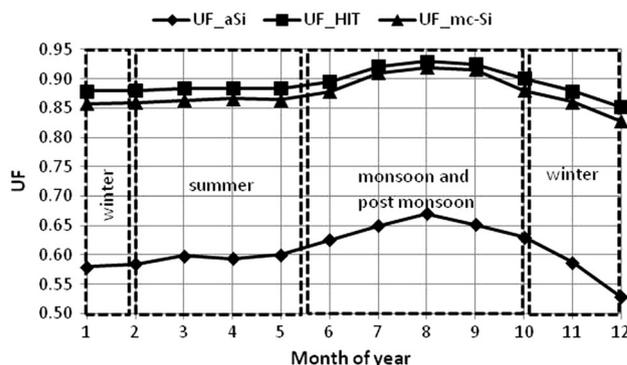


Fig. 8 Monthly useful fraction (UF) variation of a-Si, HIT and mc-Si PV technologies

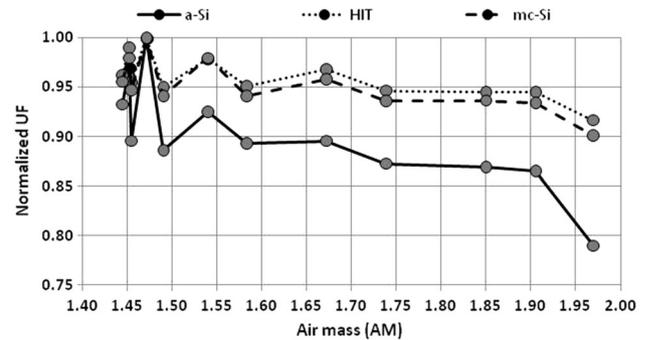
different technologies is different due to spectrum shift. The highest UF variation of 26.4 % was observed in a-Si case, due to its narrow spectrum response which makes it more sensitive to change in the spectrum shift. The maximum UF variation in HIT and mc-Si was 8.2 and 10.8 %, respectively, both the values are close, the reason being a small difference in spectrum range of these two technologies.

The estimated monthly variations in UF values with respect to annual average value were +11.2 to −12.2 %, +4.3 to −4.4 % and +5.9 to −5.2 % for a-Si, HIT and mc-Si, respectively. However, reported UF variation of a-Si by Gottschalg et al. [7] at the UK site and Hirata and Tani [5] at Japan site was less than the observed variation of (+11.2 to −12.2 %) at the Indian site.

It is interesting to observe that monsoon season shows the maximum variation in UF due to cloudy weather and low AM value. The maximum UF value in all the three technologies was observed in the month of August, which is a peak month of the monsoon period in which spectrum shift is maximum. To understand the impact of monsoon, the monthly variations with respect to annual averaged UF without monsoon and post-monsoon was calculated which comes out to be only +3.7 to −12.2 %, +0.3 to −4.4 %, +0.5 to −5.2 % for a-Si, HIT and mc-Si, respectively, which shows significant impact of monsoon under Indian conditions. It also shows that without considering the monsoon season, UF variation of a-Si at Indian site (15.9 %) is comparable to the other reported UF variation for a-Si, by Gottschalg et al. [7] at UK site (15 %) and Hirata and Tani [5] at the Japan site (14 %). Similarly, the observed variation in mc-Si technology (5.7 %) is comparable to Hirata and Tani [5] at Japan site (5 %).

Among three technology modules, a-Si modules showed a maximum increase in UF during monsoon due to its narrow spectral response which is affected more severely by a strong blue shift in APE during this season (Fig. 5).

Figure 9 shows a plot between normalized UF (with respect to the highest value of UF) and AM for the present site. The overall relation between AM and UF was found to be non-linear for the present site. Similar, non-linear variation between UF and AM was also reported by Gottschalg et al. [7] in a cloudy environment, while Berman et al. [30] observed a linear relationship between AM and UF in a desert environment. The observed non-linearity was mainly due to the cloudy environment in monsoon and partially due to fog in the peak winter months. Gottschalg et al. [31] and Betts et al. [32] also demonstrated similar effects based on spectro-radiometric and outdoor device measurement data of different technologies. This indicates that spectral irradiance corrections for monsoon of the Indian climate require cloud modifiers [33, 34]. The simple sinusoidal (AM-based) corrections such as

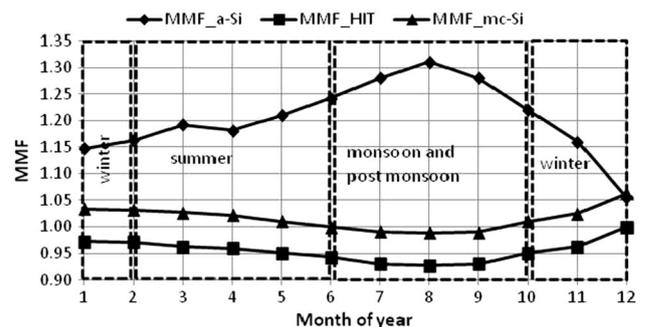


**Fig. 9** Relation between air mass (AM) and normalized useful fraction (UF) for all PV technologies

Berman et al. [30] and King et al. [35] or cloudless transfer models [36] may introduce a bias, which could mislead analysis or simulation results.

### Variations in mismatch factor (MMF)

For understanding the seasonal variations of the three PV technologies, another important spectral indicator, mismatch factor (MMF) has been calculated from measured parameters at the site. Spectral mismatch depends on the difference of the measured spectral irradiance distribution (at outdoor) with respect to the standard AM1.5 spectrum. It influences the short circuit current ( $I_{SC}$ ), because the spectral response of the module differs by some extent with the spectral response of the reference cell. Figure 10 shows the calculated monthly variation of MMF for a-Si, HIT and mc-Si technologies. The highest MMF variation of 24.7 % was observed for a-Si, whereas the variation of HIT and mc-Si was only 7.6 and 8.2 %, respectively, which are comparable and much lower than a-Si. In contrast to these values, Ishii et al. [14] observed MMF variation up to 50 % for a-Si at the Japan site in the similar wavelength range of 350–1700 nm. This large variation of a-Si may be due to the oceanic effect on the air mass variation which is not present at the Indian site. For another site located in



**Fig. 10** Monthly mismatch factor (MMF) variation of a-Si, HIT and mc-Si PV technologies

Germany, the observed variation in MMF was up to 44.4 % for a-Si in the wavelength range of 350 nm to 1050 nm [10]. In this case, the measurement spectral range was limited up to 1050 nm.

The maximum variation with respect to annual average MMF values was observed in the peak month of monsoon (August) for all the three technologies, but the trends of a-Si were found to be different compared to HIT and mc-Si. It was reported that the technology with a large band gap indicates spectral improvements in summer and spectral losses in winter, and vice versa for small band gap technologies [10]. An estimated monthly averaged MMF values with respect to an annual average MMF varied from +8.8 to −12.4 % for a-Si, +4.7 to −5.7 % for HIT and +4.5 to −2.6 % for mc-Si PV modules. Among all the three PV technology modules, the variation in a-Si during the monsoon season showed the highest spectrum mismatch.

The above results show that highest seasonal variations in terms of UF and MMF were observed in a-Si modules and least seasonal variations were observed in the first time reported HIT technology. HIT comes out to be the best technology among all the three technologies in terms of spectral variation for this site.

### Variations in performance ratio (PR)

Impression of seasonal variations of APE, UF and MMF on the performance of different technology PV modules can be seen in Performance Ratio (PR) parameter. Figure 11 shows monthly variation of PR for a-Si, HIT and mc-Si PV technology for the year 2010 [27]. It shows that during monsoon season, a-Si has higher PR compared to HIT and mc-Si technologies, the reason being high APE value during this season, which significantly shifts the spectrum towards the blue region as shown in Fig. 5. Thick cloud cover during monsoon season blocks some part of infra-red radiations which shift the spectrum towards the blue region [37]. UF and MMF values for a-Si are also high during the

monsoon period (Figs. 8, 10) which supports a good performance of a-Si during the monsoon period.

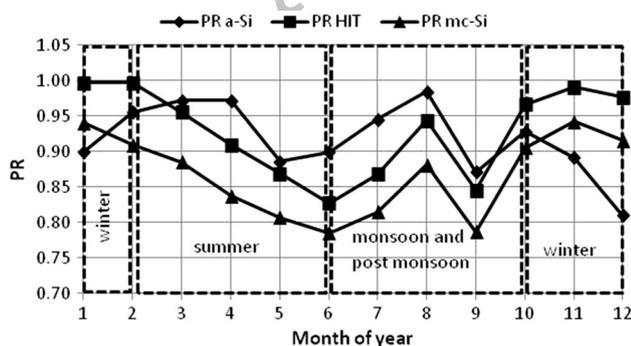
From the above analysis, it is interesting to note that, if APE decreases, spectrum shifts towards the red region (Fig. 5), which is more favorable condition for mc-Si and HIT technology compared to a-Si, whose effect can be seen strongly in the winter season on PR, where HIT and mc-Si showed highest PR (Fig. 11).

PR is affected by many parameters other than spectrum; therefore, its variation would not be exactly similar to spectrum parameters. Module temperature is another important parameter which affects PR significantly. Wafer-based technologies have stronger temperature dependence compared to a-Si-based thin film technology. All the three technologies have negative temperature coefficients in decreasing order from mc-Si > HIT > a-Si. The module temperature effect can be seen in the PR plot during the summer season. It shows that wafer-based technology modules give a much more reduction in PR compared to a-Si in the summer season, where the temperature goes up to 45 °C, which improves a-Si PR better than other technologies.

The effect of seasonal spectral variation was found to be more in a-Si PV technology followed by mc-Si and HIT technologies, which was explained on the basis of variations in MMF and UF. However, the observed PR variation in Fig. 11 was 21, 20.7, 20.5 % for a-Si, HIT and mc-Si, respectively, which was comparable due to the high temperature effect at the site. This indicates that a-Si PV technology modules are more sensitive to seasonal spectral variations than the module temperature, while HIT and mc-Si PV technology modules are more sensitive to module temperature than seasonal spectral variations.

### Conclusions

The current paper presents the comparative effect of seasonal spectral variations on a-Si, HIT and mc-Si technology PV modules under Indian environment. The spectral effect on the above-mentioned PV technologies has been first time quantified simultaneously in absolute value on a monthly basis and discussed qualitatively and quantitatively on a seasonal basis by average photon energy (APE), utilization factor (UF) and MMF along with performance ratio (PR). This is a first seasonal spectral effect-related study on different PV technology modules under Indian environmental conditions, in which spectral effects on HIT technology have been explored first time in the global context. It was observed that MMF variation was 24.7, 7.6, 8.2 %, while UF variation was 26.4, 8.2, 10.8 % for a-Si, HIT and mc-Si, respectively, and APE variation was 15.3 %. It shows that first time reported seasonal spectral variation of HIT technology has least variations among all



**Fig. 11** Monthly performance ratio (PR) of a-Si, HIT and mc-Si PV technologies

the three technologies. In this study, the maximum change in the annual spectrum was measured under higher wavelength bands. The observed spectral parameter showed the maximum variation with respect to annual average value in the monsoon season and least in the summer season, where it was lower and had an opposite trend in the winter season compared to monsoon. The presented results showed a very dominant effect of the monsoon season on the measured spectral parameters, which is a special season in Indian subcontinent perspective as compared to rest of the world.

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#### Compliance with ethical standards

**Conflict of interests** The authors declare that they have no conflict of interests.

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