PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
*Prog. Photovolt: Res. Appl.* (2012)
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pip.2194

RESEARCH ARTICLE

# Influence of Average Photon Energy index on solar irradiance characteristics and outdoor performance of photovoltaic modules

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## ABSTRACT

Solar spectral irradiance measurements on a routinely basis are relevant to study the influence of solar spectrum on the photovoltaic (PV) module performance, especially for thin film and third generation PV. Two spectroradiometers from EKO were added to the instrumentation available at the ESTER outdoor station of the University of Rome Tor Vergata. A detailed characterisation of the spectral irradiance at the site was carried on during more than 6 months of monitoring activity measuring spectral solar irradiance in the range 350–1700 nm with a time interval of 10 min on a horizontal plane. A wide variety of spectra were acquired in various weather conditions, and indications about the spectra behaviour on a daily and seasonal basis were obtained. Moreover, information about the effect of the weather conditions on the solar radiation spectral distribution were identified. The Average Photon Energy index was used as an indicator of the spectra characteristics. The same index was also used to evidence the solar spectrum influence on polycrystalline and double junction amorphous silicon PV modules. Copyright © 2012 John Wiley & Sons, Ltd.

**KEYWORDS**
solar spectral irradiance; spectral effects; solar spectral variation; PV module

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Received 10 November 2011; Revised 4 January 2012; Accepted 13 February 2012

## 1. INTRODUCTION

The introduction of thin film technology into the market (especially amorphous silicon) and, more recently, the impulse to the study of organic and hybrid solar devices have given higher attention to the solar spectral irradiance measurements and studies. The last generation of photovoltaic devices, in fact, have a narrower spectral response to the solar irradiance than the common crystalline silicon devices, and for this reason, they are more sensitive to the spectral variation in this range [1]. Moreover, although amorphous silicon is now well established in the market, some mechanisms that characterise its behaviour are not completely understood yet: synergic effect of temperature and/or spectral variation seem to contribute to amorphous silicon seasonal variation performances [2–4]. Organic devices as Dye-Sensitized Solar Cells are still in a research phase, and they exhibit a better response at low irradiance levels, under diffuse radiation conditions [5,6] indicating a certain sensitivity to the solar spectral variation. Few authors studied the solar spectrum variation during the time of the day, the season, the weather conditions, the position of the receiver and the location [7–10]. However, to evaluate the potentiality of these new generation devices at a particular location, spectral measurements should be taken routinely [9] to evaluate indices that could uniquely identify the spectral characteristics of the site. To the authors knowledge, very few solar spectral data are available in Italy [11,12] so that more measurements are needed at this particular location. Moreover, most of the spectral characterisations were performed on sloped surfaces that are influenced by the soil reflectance [13] in a way that the information obtained are very peculiar of the system arrangement and location. The University of Rome Tor Vergata was provided with a couple of spectroradiometers installed on February 2009 with the objective to evaluate the spectral characteristics of the solar radiation at the ground for the location and to relate them to the performance of photovoltaic (PV) devices, with special focus on third generation devices such as dye-sensitized solar cells. This work proposes to identify the solar spectral variations induced by the environmental outdoor conditions using the Average Photon Energy (APE) index and to use the same index to correlate the spectral variation with the performance of a double junction a-Si device and a poly-Si module tested at the Rome site. Solar spectral characterisation was conducted analysing spectral data acquired on a horizontal plane to identify a reference position of the receiver, easy to provide and independent from soil reflectance. Spectral influence on the PV devices, instead, was evaluated on a tracking system to eliminate angle of incidence dependence. Lastly, the Performance Ratio (PR) was used as PV performance index to reduce solar radiation intensity dependence.

## 2. EXPERIMENTAL

The ESTER outdoor station, described elsewhere [14], is active since 2007 in the outdoor monitoring of PV modules of various technologies and in the solar irradiance measurements at the ground. In February 2009, the station was upgraded with two spectroradiometers by EKO (MS710 and MS712) for field measurements of solar spectral irradiance in the range 350–1700 nm. The two instruments were located on a horizontal plane in the solar-weather unit of the station, as shown in Figure 1.

The MS-710 is provided with a CMOS sensor that can measure spectral irradiance in the range 350–1050 nm, whereas the MS-712 has an InGaAs sensor that provides measurements in the range 900–1700 nm. The spectral resolution is $<7.5$ nm, and the wavelength accuracy is $\pm 1.5$ nm. The sensors of both instruments are temperature-controlled (MS-710 at $25\,^{\circ}C \pm 3\,^{\circ}C$ and MS-712 at $-5\,^{\circ}C \pm 0.5\,^{\circ}C$) and exhibit a temperature dependence in the range $\pm 5\%$ for all wavelengths. The spectral intensity is collected by an optical diffuser protected by a glass dome with a cosine error $\leq 5\%$. A shutter can control the exposition time on a grating that separates the wavelength components; the spectral intensity is then measured by a photodiode array. The two spectra are merged with dedicated software so that the final spectral irradiance is in the range 350–1700 nm. The merging procedure used by EKO [15] is briefly described. Owing to different gratings of the two instruments, the measurement data are not taken at the same wavelength. When saved, the MS-710/MS-712 measurements are both lined in the order of wavelength; thus, the measuring wavelength point of MS-710 is not always at the same measuring wavelength point of the MS-712 (or vice versa). Then, the merging procedure is the calculation result of the data combined by the weighting of MS-710 and MS-712 data, in the wavelength range of 900–950 nm. For MS-710, the weighting of data is 100% at 900 nm and 0% at 950 nm, and for MS-712, 0% at 900 nm and 100% at 950 nm. Linear interpolation is used to calculate the weighting between these limits. To check the validity of the described merging procedure, several clear days spectra were examined integrating the spectral irradiance over the range 900–950 nm for each instrument. It was observed that the percentage deviation between the two integrations remained below 5% for all spectra apart from the ones at early morning and late afternoon (data not used for this investigation). Data acquisition is controlled by a dedicated software that collects the spectra every 10 min and stores them in a dedicated computer.

Both instruments are suitable for field measurements and do not require particular maintenance or protection to

**Figure 1.** View of the solar-weather unit of the ESTER station; on the left are the two spectroradiometers.

the weather conditions. However, the instruments were routinely checked, and the glass domes were cleaned when needed. Solar irradiance spectra were collected since February 2009, and data till December 2009 are considered for the spectral characterization. To give an example, the spectral irradiance collected in a clear day of May 2009 for various time of day is shown in Figure 2.

## 3. SPECTRAL INDICES

To illustrate the effect of the solar spectral variations, it is useful to define a parameter that can represent the extent to which a spectrum can shift toward the red or the blue. Different authors use different indices to evaluate this behaviour [4,16,17]. The most used parameters are the Useful Fraction (UF) that is dependent from the PV technology under investigation and the APE. Here, we focus the attention on APE that is independent from the particular technology under consideration, and for this reason, it has a more general significance.

The APE is defined as the average energy per photon of the spectrum, and it is calculated dividing the integrated irradiance by the integrated photon flux density as follows:

$$APE = \frac{\int_0^{\lambda} G(\lambda)\mathrm{d}\lambda}{q\int_0^{\lambda} \Phi(\lambda)\mathrm{d}\lambda} \quad [\mathrm{eV}] \tag{1}$$

where $q$ is the electronic charge, $G$ is the spectral irradiance and $\Phi$ the photon spectral flux density. The APE for the reference spectrum [4] is 1.88 eV in the range 350–1050 nm while for a spectral range of 350–1700 nm is 1.6 eV. A high value of APE corresponds to blue rich spectrum, whereas a low value indicates a redder spectrum. A good correlation agreement was demonstrated between APE and UF for amorphous silicon at a particular location [18] so that these two indices could be used interchangeably. APE calculation is more straightforward because it is a device independent index, and its uniqueness for the spectra measured in a particular location and climate was recently demonstrated [19]. The present work illustrates an approach to the evaluation of the spectral characteristics of a site and to the identification of the solar spectrum influence on different PV technologies. The first part of the activity consisted in the spectral characterization at the site using the APE index as a quantitative indicator of the solar spectral variation because of the time of the day, the season and the weather conditions. In the second part of the work, two PV modules of different technologies (double junction amorphous silicon and polycrystalline silicon) were mounted on a sun tracker together with the spectroradiometers and a poly-Si reference cell. Correlations between APE and PR were identified and discussed for the two technologies.

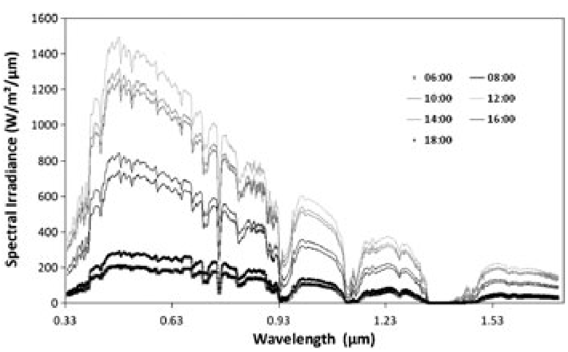


**Figure 2.** Solar spectral irradiance at different hours of a clear day of May 2009.

## 4. SITE SPECTRAL CHARACTERIZATION USING AVERAGE PHOTON ENERGY

To evaluate the spectral characteristics of the solar spectra measured at various irradiance intensities, a normalisation procedure was considered. In this work, the spectral irradiance was normalised with respect to the intensity value measured at 560 nm [4]. The intensity at this wavelength is least affected by environmental conditions especially related to the water vapour content into the atmosphere (absorption and scattering). The normalised spectra were studied to evaluate their variation during the day, during the year and for an overcast day to characterise the spectra behaviour at the location in the period March–December 2009.

The APE parameter was chosen as a spectral index for the evaluation of the average colour of the solar spectrum measured on a horizontal plane in the area of Rome. As already mentioned, the APE index is related to the colour of the spectrum: high APE values indicate a spectrum shifted toward the blue, whereas a lower value is correlated to a redder spectrum. To verify this for our measurements, we took all the spectral measurements taken during the period considered, and we calculated the APE values. For each month, the spectra at noon were related to the correspondent APE, and the spectral irradiances were graphed. Figure 3 shows some of these spectra for the month of June 2009.

In this case, APE was calculated for the spectral range 350–1050 nm. It can be observed as the spectrum with the highest energy in the blue part (bluest spectrum) with respect to the red part is the one with highest *APE* and that as the *APE* decreases, the blue content of the spectrum also decreases. This behaviour was observed when comparing spectra of the same month, whereas if spectra for different months and different APE are compared, the previous considerations do not hold.

Figure 4 shows the normalised solar spectral irradiance measured for clear days at noon for the month of July and December 2009. The air mass effect on the spectral variation can be noted; indeed, the December spectrum appears more reach in the high wavelengths (red shift),

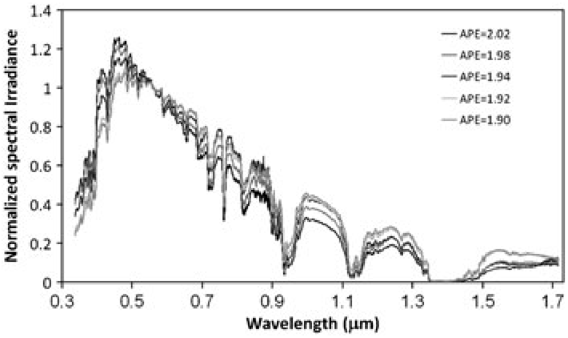


**Figure 3.** Irradiance spectra at different Average Photon Energy (APE) taken at noon for the month of June 2009.

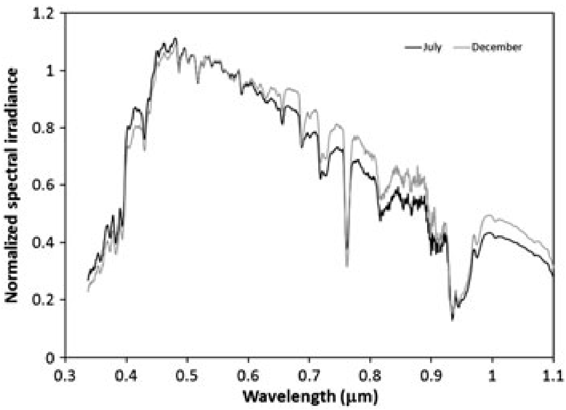


**Figure 4.** Normalized spectra for July and December 2009.

and this is due to the longer path the solar radiation covers to reach the ground (higher AM) in the winter months than in the summer months. This behaviour was confirmed by the analysis of various clear days spectra measured at noon, and it was proved for all the months.

To quantify this assumption, the APE index for the spectral range 350–1700 was calculated for the spectra showed in Figure 4. The July spectra has an APE of 1.72, whereas for December, a value of 1.59 has been calculated. Considering an average APE value of 1.64 for the period, July exhibits a 5% bluer spectrum than the average, whereas for December, a 2.6% redder spectrum than the average; moreover, between the two seasons, a spectral variation of the order of 8% was observed. These findings confirm a consistent seasonal effect on the spectral irradiance.

It is known that the spectral variation is strongly dependent on the water vapour content into the lower atmosphere and that this content varies during the day; in particular, water vapour is generally lower in the morning than in the afternoon, providing a redder spectrum in the morning than in the afternoon [7]. To prove this assumption, a series of clear days for each month were considered; for each day, three spectra were chosen: one in the morning, one at midday and one in the afternoon.

The morning and afternoon spectra were taken at the same air mass to be independent from its variation.

Figure 5 shows the three normalised spectra for the month of March, May, July and December 2009. It can be observed that in all cases, the normalised morning spectral irradiances have higher intensities in the red part of the spectrum, whereas in the afternoon, the intensities are higher in the blue part, confirming the previous assumption. This behaviour was systematically observed for each clear day considered. The only anomaly was observed for the month of November 2009, and this behaviour has not been completely understood. However, the amount of energy delivered in the red part and in the blue part of the spectrum expressed as fraction of the global solar irradiance in the range 350–1700 nm shows only an average variation of the order of 0.5% between morning and afternoon for the examined spectra with a standard deviation of the average that is of the same order of magnitude of the observed variation. This can be due to higher errors in the morning and afternoon spectra, induced by temperature differences between morning and afternoon and also by the high angle of incidence of solar radiation over the glass dome for the same periods. More quantitative evaluations are necessary to confirm or reject these hypothesises.

Analogous considerations can be carried out comparing spectra taken in a clear day with spectra taken in an overcast day. Nann and Riordan [8] carried on a study on the behaviour of the solar spectrum in the overcast sky conditions.

They conclude that the relative spectral transmission is enhanced in the ultraviolet and blue region of the spectrum in an overcast day, whereas a consistent reduction is observed for the wavelength in the 700–950 nm range where some water vapour absorption bands are present.

Between the 950 and 1000 nm, even if other vapour bands are present, they observed an increase in spectral transmission essentially because of albedo effects from the clouds and the ground. To find a confirmation to what is exposed, a series of spectra of overcast days and clear days taken at noon in the different periods of the year considered were compared.

Figure 6 shows, as an example, the comparison of two normalised spectra measured in a clear and in an overcast day for the month of December. The behaviour confirms the Nann and Riordan considerations for what concerns the blue enrichment of the spectrum in the overcast day, whereas no increment was observed at higher wavelengths. For each month, the APE index of the overcast and clear day spectrum at noon was calculated. The values were compared with the monthly average APE at noon. For the overcast days, the increment in APE with respect to the average varies from a maximum of 24% in June and a minimum of 3.5% in May. For the clear days, the variation is of the order of 3.5% less than the average (redder spectrum). For each month, considering the average of the spectra at noon of the overcast days, an increment in APE of approximately 10% with respect to the clear days was observed.

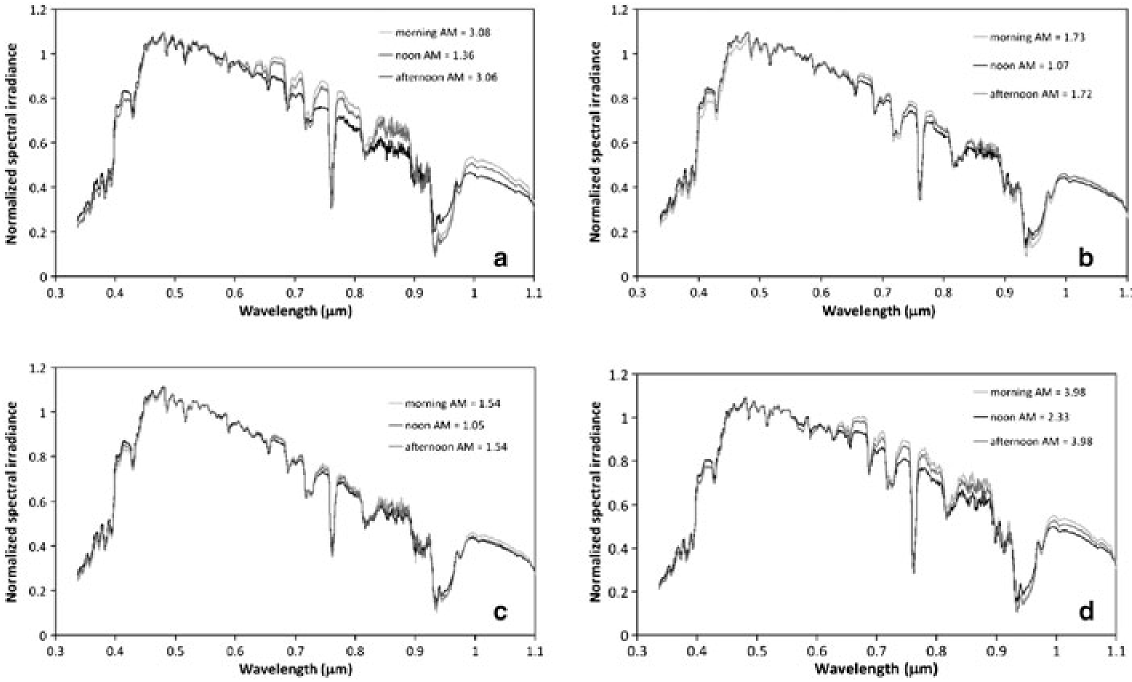


**Figure 5.** (a) Daily spectra variation of a clear day in March 2009; (b) daily spectra variation of a clear day in May 2009; (c) daily spectra variation of a clear day in July 2009; and (d) daily spectra variation of a clear day in December 2009.

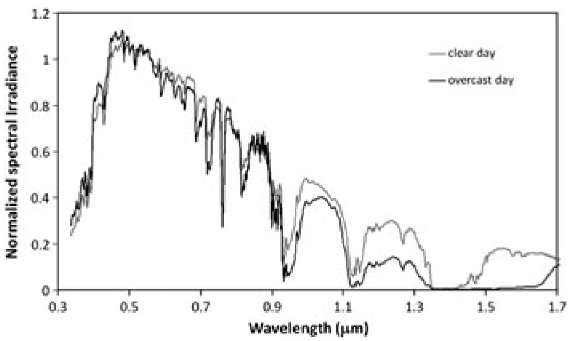


**Figure 6.** Irradiance spectra taken on the fifth (clear day) and eighth (overcast day) days of December 2009.

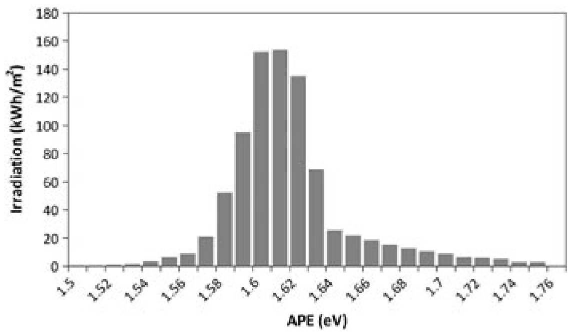


**Figure 7.** Energy delivered under different Average Photon Energy (APE) at the Rome site for the period March–December 2009.

To characterise the site for the period of interest, the solar energy delivered under different values of APE (spectral range 350–1700 nm) was calculated, and it is shown in Figure 7. The APE values were separated in 0.01 eV bins, and for each bin, the solar energy (irradiation) was calculated, integrating the irradiance. It can be seen how the energy peaks at an APE of 1.61 and that approximately 60% of the total energy for the period is delivered with APE higher than 1.6 indicating a slighter enrichment in the blue wavelengths. It has also to be considered that, owing to a failure in the measurement system, the August, September and October data were not considered for the analysis. A higher percentage of energy at higher APE could be expected taking into account also for the contribution of the missing data that are mostly concentrated in the summer period where bluer spectra are observed.

## 5. EFFECT OF APE ON A-SI AND POLY-SI MODULE OUTDOOR PERFORMANCE

To evidence the spectral dependence of the PV module performance, a suited test was carried on for 2 months during summer 2011. It is well known that the performance of PV modules depends on various environmental parameters. In particular, PV module efficiency, defined as the ratio of the maximum power produced by the module over its surface area multiplied by the incident solar irradiance, is a parameter that depends on radiation intensity, module temperature, angle of incidence of the solar radiation and solar spectral variation. To study the effect of one of these parameters with respect to the others, it is necessary to eliminate the multiple dependence by fixing the not-interesting variables or arranging the experiment in a way that some of these dependences could be eliminated.

In this work a poly-Si and a double junction a-Si module were mounted on a sun tracker together with the two spectroradiometers and a poly-Si reference cell, as shown in figure 8. The reference cell is from IKS, and the calibration was achieved by the supplier using a reference element (quality grade A, constructed in an identical fashion) from an accredited test laboratory in W/m² by IWS/Kassel. The irradiance data considered in this study were corrected for cell temperature variations. The modules were kept at the maximum power point, and solar spectral irradiance, module power and temperature were recorded every 10 min for 2 months during summer 2011. The sun tracker mounting was chosen to eliminate the angle of incidence influence on the PV module efficiency. Moreover, the PR index was used instead of efficiency as performance indicator. PR is defined as the ratio of the effective PV module efficiency evaluated at the maximum power point and the efficiency of the same module at Standard Test Conditions. This index was chosen because it is fairly sensitive to the solar radiation intensity, and it is more influenced by the temperature reached by modules and by the spectral variations. Therefore, to isolate the sole spectral dependence on PR, three module temperatures were chosen ($40 \pm 1.5\,°C$, $50 \pm 1.5\,°C$ and $60 \pm 1.5\,°C$), and for each of them, the PR calculated for poly-Si and a-Si PV modules was correlated with the APE index. For both modules, the PR was calculated in two ways. $PR_{ref}$ was calculated using the solar radiation intensity measured by the poly-Si reference cell positioned on the plane of the modules, whereas PR was calculated using the spectroradiometers positioned on the same plane. Figure 9 shows the PR evaluated with the reference cell ($PR_{ref}$) and with the spectroradiometers (PR) versus APE for the poly-Si module. It can be observed as almost no dependence from APE is present using $PR_{ref}$. This can be explained by the fact that the spectral response of the reference cell is the same as the PV module so that the spectral dependence is eliminated by the measurement itself. Different behaviours can be observed for PR where the solar radiation intensity was measured considering a wider spectral range (350–1700 nm, with the spectroradiometer). In this case, a decrease in PR is observed at the three module temperatures. This means that bluer spectra reduce the performances of poly-Si, and this is explained considering that this material is more sensitive to the high wavelengths than to the short wavelengths. In figure 10, the same indexes are showed for the a-Si PV module. Both PR and $PR_{ref}$ show an increase as APE increases (bluer spectrum), but this trend is more evident for $PR_{ref}$

**Figure 8.** Experimental set-up for the test carried out in June–July 2011.

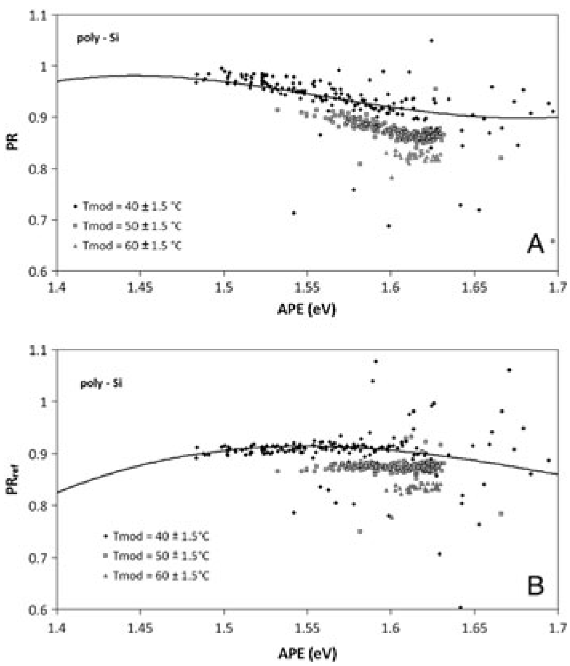


**Figure 9.** (A) Performance Ratio (PR) for the poly-Si module, evaluated using the integrated spectral irradiance versus Average Photon Energy (APE) evaluated in the range 0.35–1.7 μm, for different module temperatures and (B) PR for the poly-Si module, evaluated using the reference cell irradiance versus APE evaluated in the range 0.35–1.7 μm, for different module temperatures.

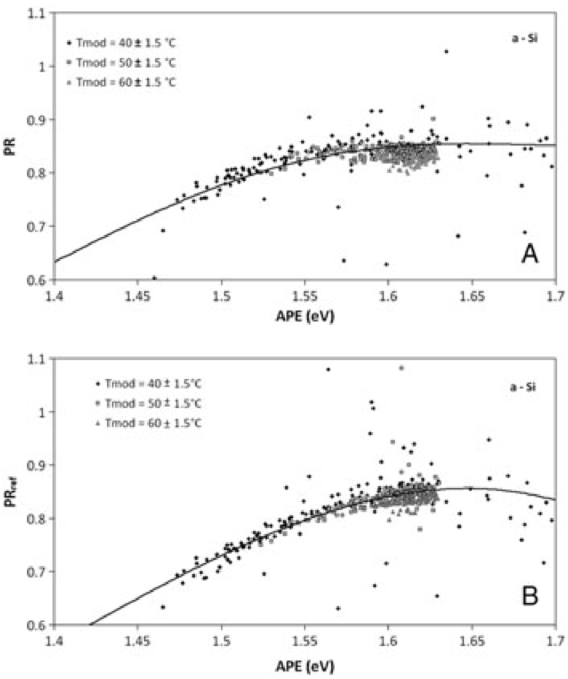


**Figure 10.** (A) Performance Ratio (PR) for the a-Si module, evaluated using the integrated spectral irradiance versus Average Photon Energy (APE) evaluated in the range 0.35–1.7 μm, for different module temperatures and (B) PR for the a-Si module, evaluated using the reference cell irradiance versus APE evaluated in the range 0.35–1.7 μm, for different module temperatures.

than for PR. This is due to the fact that the double junction a-Si spectral response is restricted to a narrower spectral interval (more similar to the spectral response of the reference cell than of the spectroradiometer), and therefore, $PR_{ref}$ is more sensitive to the spectral variation in the blue part of the spectrum.

The PR dependence from the module temperature is clearly identified for the poly-Si module where the temperature coefficients are more negative than for the a-Si devices. In fact, a stronger spectral dependence than a module temperature dependence is observed for the double junction a-Si module. Furthermore no annealing effect was observed because the module did not reached temperature values higher than 68°C owing to the open rack mounting configuration. The data, in this particular configuration and at this site, show that for double junction a-Si module, the spectral effect is predominant over the temperature effect justifying the seasonal PR variation typical of amorphous silicon devices observed at various sites, which exhibits higher PR in summer (bluer spectrum) than in winter and higher performances under diffuse radiation conditions (bluer spectrum) [20].

## 6. CONCLUSIONS

Spectral irradiance measurements in the spectral range 350–1700 nm were collected on a horizontal plane at the outdoor monitoring station of the University of Rome Tor Vergata since February 2009. Data analysis evidenced the dependence of the solar spectrum from the time of the day, the period of the year and the presence of clear sky or cloudy sky. APE index was calculated for the considered spectra, and it was used as an indicator of the blue enrichment of the spectrum. A variation in APE of around 7% is observed between summer and winter period (summer is bluer), whereas for the overcast days, a blue enrichment proved by an increment of APE of approximately 10% with respect to the clear days is observed. For the period March 2009 to December 2009, a spectral characterization of the site was made, considering the amount of solar energy delivered under different APE. A solar energy peak was observed at an APE value of 1.61 eV, very near to the APE calculated for the Standard Spectrum (1.6 eV). A slight shift towards blue enriched energy is observed with approximately 60% of the total energy delivered at APE higher than 1.6 eV for the data considered. Some missing data in the summer period would probably have contributed to increase the energy delivered at high APE.

The same APE index was used to evaluate the spectral dependence of performance of poly-Si and double junction a-Si modules positioned on a sun tracker for 2 months. For the a-Si module, fixing three different values of the module temperature, an increase in PR was observed as the APE increased, whereas the poly-Si did not show a clear trend with APE evidencing a stronger temperature dependence. In this case, the solar spectral dependence for the double junction a-Si appears stronger than its temperature dependence.

## ACKNOWLEDGEMENT

This work was supported by the Lazio Region within the frame of the Centre for Hybrid and Organic Solar Energy (CHOSE).

## NOMENCLATURE

| | |
|---|---|
| $G$ | Spectral Irradiance [W/m$^2$μm] |
| $\lambda$ | Wavelength [μm] |
| $\Phi$ | Photon Spectral Flux Density [μmol/m$^2$/s] |
| $APE$ | Average Photon Energy [eV] |
| $PR$ | Performance Ratio |
| $q$ | Electron charge [C] |

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