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Photovoltaic yield: correction method for the mismatch between the solar spectrum and the reference ASTM G AM1.5G spectrum

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Abstract We propose a method for a spectral correction of the predicted PV yield and we show the importance of the spectral mismatch on the solar cell. Indeed, currently predicted PV yield are made considering solar irradiation, ambient temperature, incidence angle and partially (or not) the solar spectrum. However, the solar spectrum is not always the same. It varies depending on the site location, atmospheric conditions, time of the day... This may impact the photovoltaic solar cells differently according to their technology (crystalline Silicon, thin film, multi-junctions...). This paper presents a method for calculating the correction of the short-circuit current of a photovoltaic cell due to the mismatch of the solar spectrum with the reference ASTM AM1.5G spectrum, for a specific site, throughout the year, using monthly data of AERONET (AEROSOL ROBOTIC NETWORK established by NASA and CNRS) and the model SMARTS (simple model for atmospheric transmission of sunshine) developed by the NREL. We applied this correction method on the site of Palaiseau (France, 48.7°N, 2.2°E, 156 m), close to our laboratory, just for comparison and the example of Blida (Algeria, 36°N, 2°E, 230 m) is given for one year. This example illustrates the importance of this spectral correction to better estimate the photovoltaic yield. To be more precise, instead of modeling the solar spectral distribution, one can measure it with a spectro-radiometer, and then, derive the spectral mismatch correction. Some of our typical measurements are presented in this paper.

1 Introduction

Nowadays, the rated performance of photovoltaic (PV) modules is evaluated under standard test conditions (STC), that is to say at an irradiance of 1000 W m^{-2} , a PV cell temperature of $25 \text{ }^\circ\text{C}$ and a spectral energy distribution according to the reference spectrum AM1.5. This reference AM1.5 solar spectral distribution, adopted by the International Electrotechnical Commission (IEC), corresponds to a global irradiation (direct and diffuse) of incident sunlight on a flat surface facing the sun, tilted at 37° to the horizontal, under precise atmospheric conditions [1,2]. In outdoor conditions, the solar spectral distribution varies continuously mainly due to (i) the path length through the atmosphere, named Air Mass (AM),

(ii) the amounts of atmospheric water vapor (w) and (ii) the aerosol volume (AOD). All those parameters depend on the considered site and the date.

The solar spectrum has a direct impact on the portion of sunlight absorbed by PV cells, more specifically, on the short-circuit current (I_{sc}). The spectral photoresponse of a PV cell depends on the band gap energy, which is technology dependent. Thus, the effects of the solar spectral distribution should be different according to the PV technology considered [3,4]. Then, it may be useful to calculate the correction in I_{sc} due to the spectral mismatch (M) of the real solar spectrum compared to the reference solar spectrum for a given site and the considered PV cells. Currently, predictions of PV yield are made considering solar irradiation, ambient temperature, tilt and orientation of the panels. A few models take into account the effect of solar spectrum (e.g., PVsyst) [5] and when it is the case, not

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for all the PV technologies. Furthermore, the only parameter taken into account is AM . But the solar spectrum not only varies with AM and can be very different according to the site (pollution for instance). We propose a method for a spectral correction of the predicted PV yield.

This paper proposes a method for estimating the correction of I_{sc} due to the spectral mismatch, of any PV module knowing the spectral response of its unit cells. We explain how to reconstruct the solar spectrum with precise atmospheric data provided by AERONET (AErosol RObotic NETwork) [6], if available, or directly measure it with a spectro-radiometer.

The first part of this paper presents the tools used to study the solar spectrum and to recover the solar spectrum from atmospheric data. We also simulated the influence of atmospheric conditions on the solar spectrum through key parameters such as AM , w and AOD. Then, we study the spectral mismatch correction for 3 years (2008–2010) on the site of Palaiseau (France, 48.7°N, 2.2°E, 156 m) for 2 PV technologies (crystalline Silicon (c-Si) and thin film Silicon (a-Si:H)). For comparison, the same exercise is made for Blida (Algeria, 36°N, 2°E, 230 m) during one year (2009). Then, we present some solar spectrum measurements and derived mismatch factor M . The last part proposes a method, non PV technology dependant, to derive M from atmospheric data.

2 Tools for studying the solar spectral distribution

In this part, we present first, a mathematical index, the average photon energy (APE), calculated to quantify the amount of energy available in the solar spectrum. Then, to take into account the spectral response of the PV cell, we define the spectral mismatch correction in I_{sc} (M). Next, the modelization of the solar spectrum is described, based on the SMARTS model. We need geographical and atmospheric input parameter for this model. The AERONET atmospheric data are presented in the last paragraph of this part.

2.1 Average photon energy

APE has been first introduced by Betts et al. [7]. This index is defined as the sum of the light energy in the spectrum divided by the total density of the photon flux:

$$APE = \frac{\int_a^b E(\lambda) d\lambda}{q \int_a^b \phi(\lambda) d\lambda}. \quad (1)$$

q is the electronic charge (C), E is the solar spectral irradiance ($\text{W m}^{-2} \text{nm}^{-1}$), and Φ is the spectral photon flux density ($\text{photon m}^{-2} \text{s}^{-1} \text{nm}^{-1}$). In this study, a and b are equal to 300 nm and 1100 nm, respectively, corresponding to the lower and upper wavelength of the spectral response of most PV cells.

The main advantages of this tool are:

- easy indication of the “color” of the sunlight: $APE > 1.895$ for blue-rich sky; $APE < 1.895$ for red-rich sky;
- non device-dependent indicator.

2.2 Spectral mismatch correction

The second tool is the spectral mismatch correction developed in equation (2):

$$M = \frac{\int_a^b E_{ref}(\lambda) S_{ref}(\lambda) d\lambda}{\int_a^b E_t(\lambda) S_{ref}(\lambda) d\lambda} \frac{\int_c^d E_t(\lambda) S_t(\lambda) d\lambda}{\int_c^d E_{ref}(\lambda) S_t(\lambda) d\lambda} \quad (2)$$

where E_t and E_{ref} are the test and reference spectra ($\text{W m}^{-2} \text{nm}^{-1}$), S_t and S_{ref} are the spectral response (A W^{-1}) of the test and reference cell, a and b , and c and d , are the wavelength limits (nm) of the spectral response of the reference cell and of the test cell, respectively. In this study, an ideal pyranometer is considered as reference, with a flat response over the entire solar spectrum, that is to say that $S_{ref} = 1$.

Moreover, we can derive I_{sc} by convoluting the spectral response of the PV cell with the incident solar spectrum, using the following equation:

$$I_{sc} = A \int_0^{\lambda(E_g)} S(\lambda) E(\lambda) d\lambda \quad (3)$$

where I_{sc} is the short-circuit current (A), A the cell area (m^2), $S(\lambda)$ the spectral response of the PV cell (A W^{-1}), $E(\lambda)$ the irradiance ($\text{W m}^{-2} \text{nm}^{-1}$), λ the wavelength (nm) and E_g the band gap energy (eV) of the PV cell.

In our study, equation (2) becomes:

$$M = \frac{E(AM1.5)}{E(t)} \times \frac{I_{sc}(t)}{I_{sc}(AM1.5)} \quad (4)$$

where $E(AM1.5)$ and $E(t)$ are the irradiation of the reference spectrum and test spectrum, between 300 nm and 1100 nm, respectively. $I_{sc}(AM1.5)$ and $I_{sc}(t)$ are the short-circuit current for the considered PV cell for the AM1.5 spectrum and for the test spectrum, respectively.

The spectral mismatch correction adjusts the I_{sc} of a PV cell, for a given spectrum, from the rated I_{sc} measured under STC.

This tool is device dependent, which means that the spectral response of the PV cell must be known.

2.3 SMARTS solar spectrum model

The FORTRAN code “simple model for atmospheric transmission of sunshine” (SMARTS) [8–12] is the program used to model the solar spectrum under clear sky conditions by injecting atmospheric and geographic input parameter. It covers the whole wavelengths range of the solar spectrum (280 nm to 4000 nm). It is the program used by the American Society for Testing and Materials

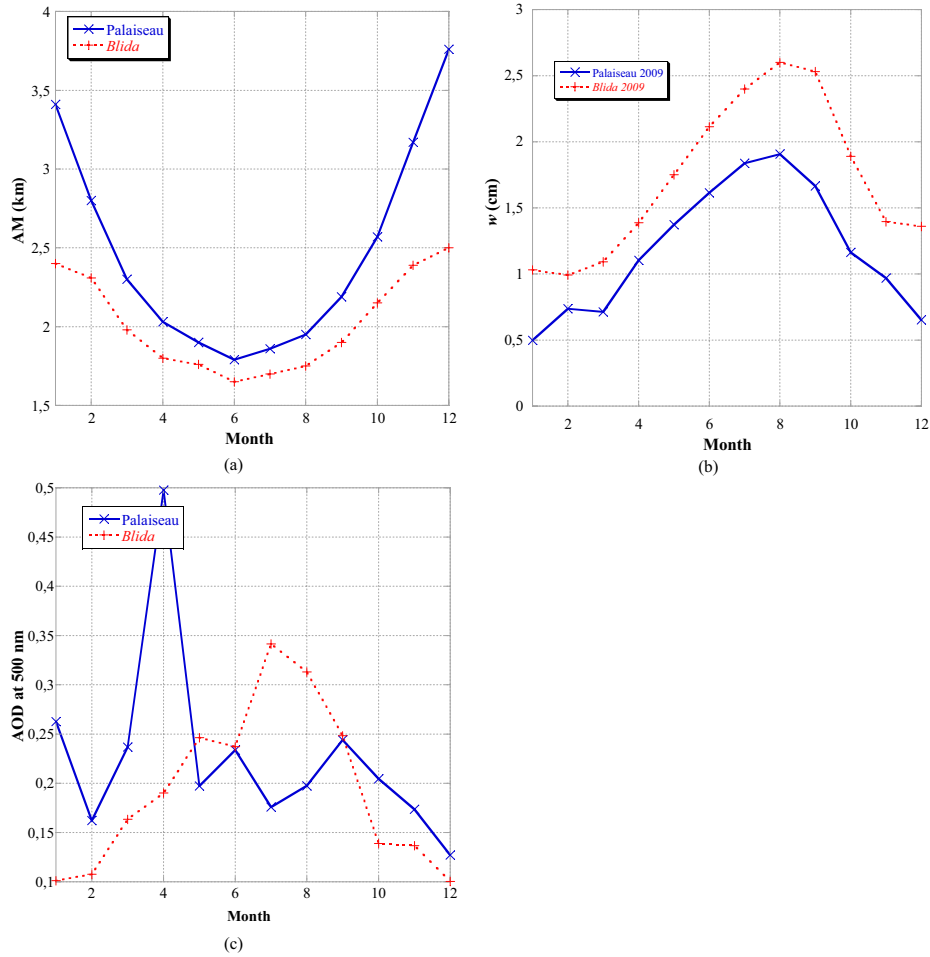


Fig. 1. Monthly average calculated AM (a), w (b) and AOD at 500 nm (c) derived from AERONET data for Palaiseau and Blida during 2009.

(ASTM) to model the reference solar spectrum AM1.5, ASTM G 173-03 [2]. This model is based on parameterizations of transmittance and absorption function for atmospheric constituents include molecular (Rayleigh), ozone, water vapor, mixed gases, trace gases and aerosol transmittances.

2.4 Atmospheric data of AERONET

Sun photometer measurement-derived parameters from the AERONET database are considered in this study as input to the model. In particular we consider:

- aerosol optical depth (AOD) at 500 nm;
- angstrom's alpha parameter for two wavelength intervals (380–500 nm and 500–870 nm);
- integrated water vapor (w).

The single scattering albedo and the asymmetry parameters are set constant to 0.9 and 0.7 in the model, respectively, as typical values for a semi-rural site [13].

These data are entered into the SMARTS model to recover the solar spectrum distribution at a given time and

for a considered site. Moreover, the AM must be calculated from the zenith angle derived from the solar equation.

In this paper, only less than 78.5° zenith angles are considered, leading to AM under 5. In one hand, the equation used to calculate AM [14] is not accurate and, on the other hand, the solar irradiation is low and not relevant for PV applications.

Figure 1 shows monthly averaged AM , AOD at 500 nm and w values (for 2009) for the two considered sites, Palaiseau and Blida.

Those geographic and atmospheric data have a great influence on the solar spectral distribution.

3 Influence of atmospheric conditions on the solar spectrum simulated with SMARTS

The parameters that affect the most the solar spectrum are the path length through the atmosphere (AM), the amount of water vapor (w) and aerosols (AOD) [15]. To evaluate their impacts, we model with the SMARTS

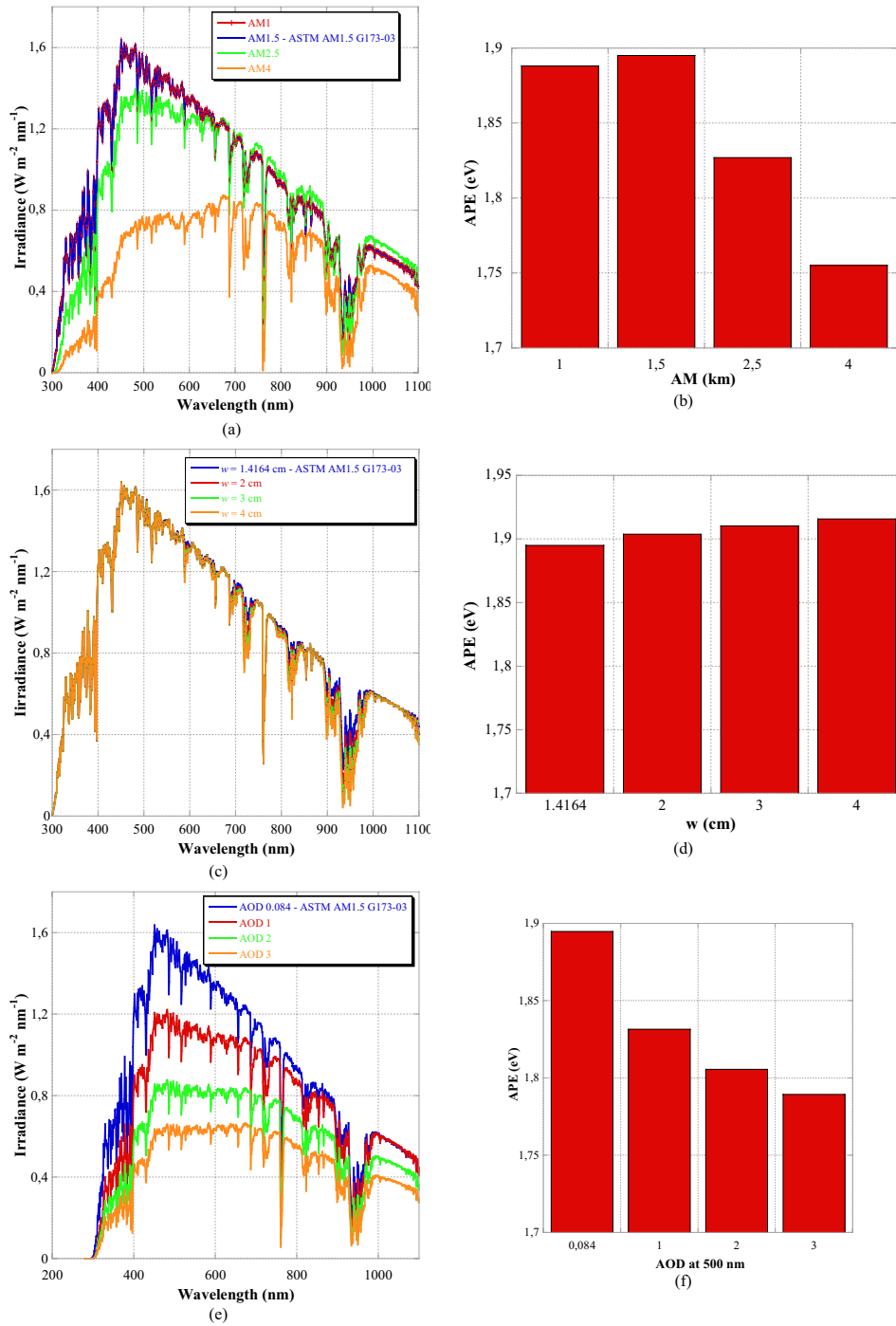


Fig. 2. Simulated spectra for different AM (a), different precipitable water vapor (c) and different AOD at 500 nm (e). Calculated APE associated with the spectra, for different AM (b), different precipitable water vapor (d) and different AOD at 500 nm (f).

program, the solar spectrum with the same inputs as the ASTM AM1.5 G173-03 hemispherical spectrum excepting one parameter, such as AM, water vapor or aerosols. Default values are $AM = 1.5$ km and $w = 1.4164$ cm and $AOD = 0.084$.

The spectral range considered begins at 300 nm and ends at 1100 nm because of the spectral response of all PV cells.

Figures 2a and 2b represent the variations of the simulated solar spectrum and the calculated APE, for AM varying from 1 to 4. Figures 2c and 2d are the same but for w varying from 1 cm to 4 cm. At last, Figures 2e and 2f consider the variation of AOD at 500 nm between 0.084 to 3. The AOD variation is mainly due to the pollution as the pollution peak observed at Palaiseau during March 2014 which led to a 0.8 AOD value or during major

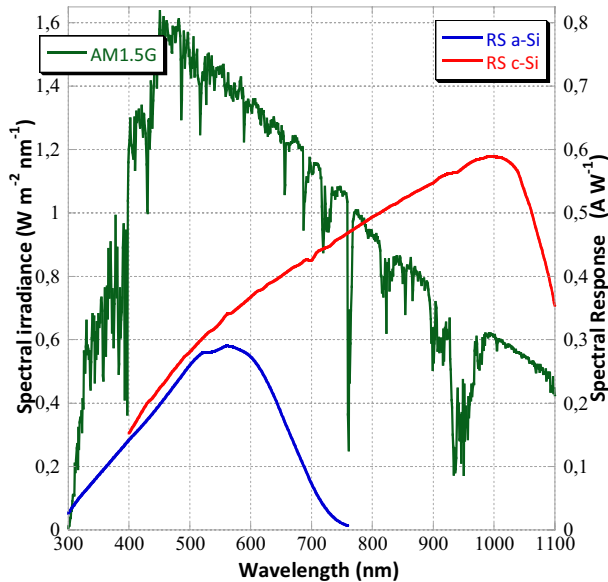


Fig. 3. Reference ASTM AM1.5G spectrum (left axis) and spectral response of a crystalline Silicon PV cell and of a thin film Silicon PV cell (right axis).

short-term pollution events as the wildfire during summer 2010 at Moscow which led to a 4.3 AOD value [16].

In Figure 2a, we observe that changing the path length modifies the solar spectrum intensity and distribution and in Figure 2b, we can notice that when AM increases, APE decreases. That means that the more the path length through the atmosphere is long (the sun is low in the sky, for example in early in the morning or late in the evening), the more the sunlight is red-rich. It is understandable because when the path length is thick, it is the short wavelengths that are scattered.

Water vapor absorption bands are centered at 724 nm, 824 nm and 938 nm, in the considered wavelength range as one can see in Figure 2c. Figure 2d shows that when the water vapor increases, the APE increases too.

To take into account the turbidity of the atmosphere, the spectral effects of changing AOD at 500 nm are plotted in Figures 2e and 2f. It can be studied as the main parameter to explain the radiative extinction by aerosols. However, the aerosols spectral effects depend also on the properties of the aerosols, such as the particle size and absorption properties. Increasing AOD have the impact of solar irradiance decreasing with larger impact for shorter wavelengths, so APE decreases. Choosing on other particle size or type also has an effect on the solar spectrum.

Taking into account the variation of the solar spectral distribution is of the most important in prediction of the photovoltaic yield because of the spectral response proper to each technology of PV cell like underscored in Figure 3.

Figure 3 shows that the spectral response for the amorphous cell is more selective than that of the crystalline cell. A change in the solar spectrum acts then differently respect to the cell technology because of its spectral response.

4 Calculating method for the spectral mismatch correction (M) during one year, for a given site

4.1 Modeling the solar spectrum

The SIRTAs Atmospheric Research Observatory (www.sirta.fr), located at Palaiseau (France: 48.8°N, 2°E, 156 m) has an AERONET station. The idea of this work is to calculate the spectral mismatch correction during one year for crystalline Silicon PV cells and thin film Silicon PV cells. We take monthly mean values of atmospheric conditions (AOD, w , size of the aerosols below and above 500 nm) and monthly mean values of AM . In other words, we model a typical spectrum for each month of the year, for the site of Polytechnique and we derive M as a function of the spectral response of the considered PV cell.

The results of this study are presented in Figure 4.

From Figure 4a, we can notice that for the thin film Silicon PV cell, there may be a difference of 9.7% between I_{sc} predicted during the winter and during the summer months. I_{sc} is close to its rated value during summer months and lower for winter months. In summer, AM decreases and w increases, as shown in Figure 3 where we can see that w is four times higher in summer than in winter. This leads, in summer, to a more blue-rich solar spectrum ($APE > 1.895$ as shown in Fig. 4c), which is better suitable to the thin film PV cell spectral response (maximum absorbance around 550 nm). Whereas in winter the sun is lower in the sky and AM increases, which leads to a more red-rich sky ($APE < 1.895$ as shown in Fig. 4c).

The opposite effect occurs for crystalline Silicon PV cells that absorb also in the near infrared. Moreover, we can see in Figure 3 that there are two important water bands of absorption close to crystalline Silicon PV cells maximum of absorption (900–1000 nm). This means that increasing w in summer has a strong effect on crystalline Silicon PV cells yield. In Figure 4b, we observe a difference due to the season of 6.6% for crystalline Silicon PV cells. They are less sensitive to the solar spectrum distribution than the thin film PV cells because of their wide spectral response [17].

On the 3 studied years in Palaiseau, the reference solar distribution spectrum overestimated I_{sc} of a thin film Silicon PV cell of about 3.5% and underestimated that of a crystalline Silicon PV cell of about 2.4%.

In Figure 5, the equivalent exercise is presented, for the site of Blida (Algeria: 36°N, 2°E, 230 m) in 2009.

For the Blida site, the average APE is 1.876 eV, the average M for thin film Silicon PV cells is 0.985 and the average M for crystalline Silicon PV cells is 1.011 during 2009. Compared to the first studied site Palaiseau, w is higher and AM is lower as resumed in Table 1. This leads to a more blue-rich sky for Blida than Palaiseau. We can say that, with respect to the spectral response point of view, crystalline Silicon PV cells are more efficient for high latitude site compared to thin film PV cells.

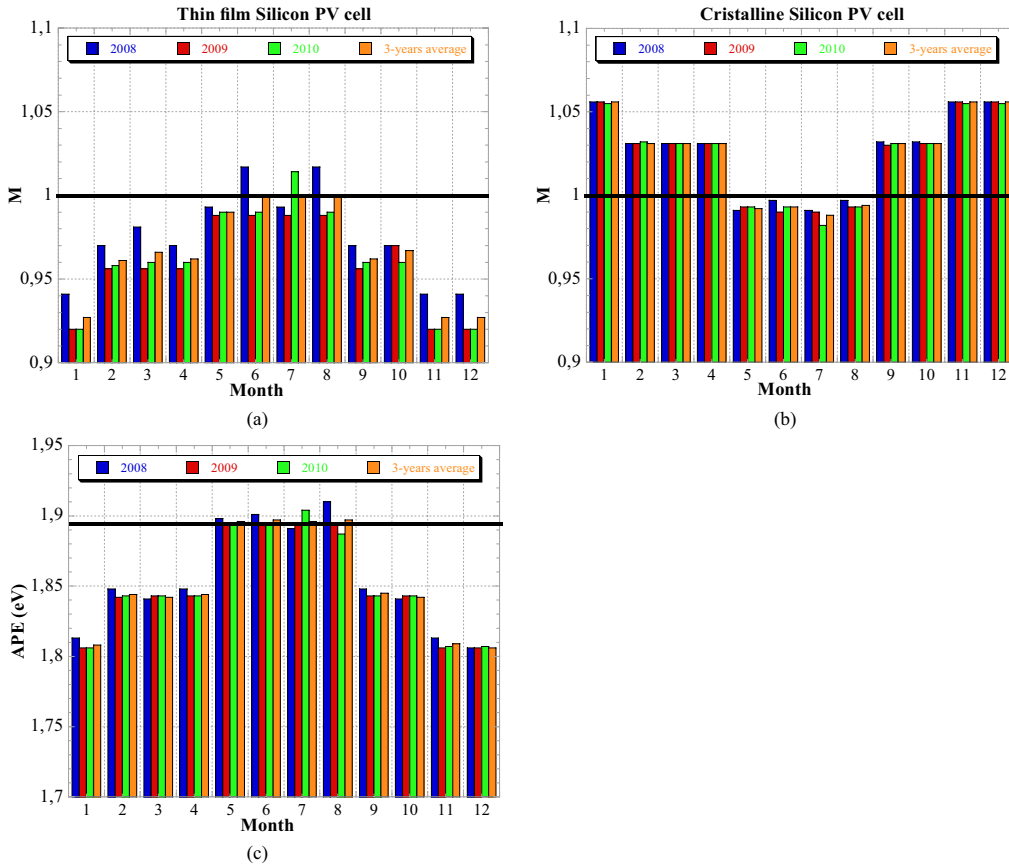


Fig. 4. M calculated for thin film Silicon PV cell (a) and crystalline Silicon PV cell (b) and APE (c) corresponding to the modeled solar spectrum. All the calculated values used monthly mean atmospheric data for years between 2008 and 2010, at Polytechnique (Palaiseau, France: 48.8°N, 2°E, 156 m).

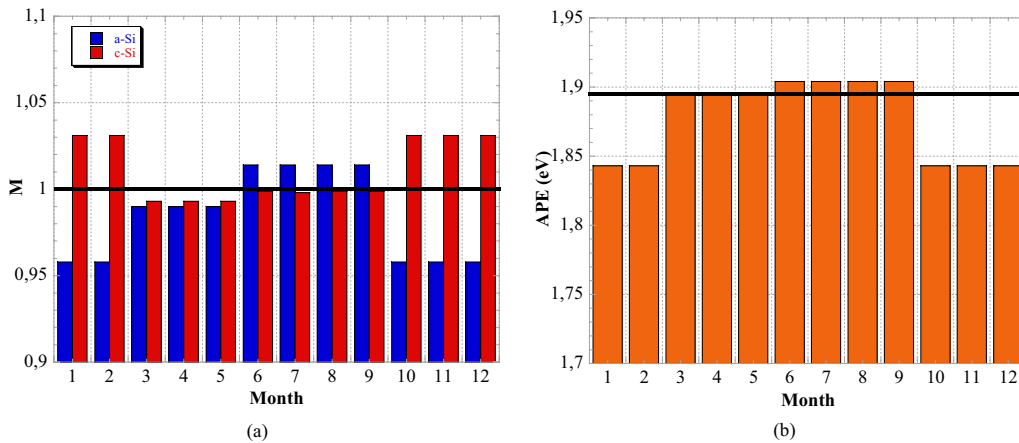


Fig. 5. M calculated for thin film and crystalline Silicon PVs cell (a) and APE (b) corresponding to the modeled solar spectrum. All the calculated values used monthly mean atmospheric data 2009, at Blida (Algeria: 48.8°N, 2°E, 230 m).

Table 1. Average AM , w and APE for Palaiseau, Blida and ASTM AM1.5 G173-03 in 2009.

Site	AM (km)	w (cm)	APE (eV)	M (thin film)			M (crystalline)		
	Moy.	Moy.	Moy.	Min.	Max.	Moy.	Min.	Max.	Moy.
Palaiseau	2.478	1.246	1.852	0.920	0.988	0.959	0.990	1.056	1.024
Blida	2.024	1.712	1.876	0.958	1.014	0.985	0.993	1.031	1.011
ASTM AM1.5	1.5	1.416	1.895			1			1

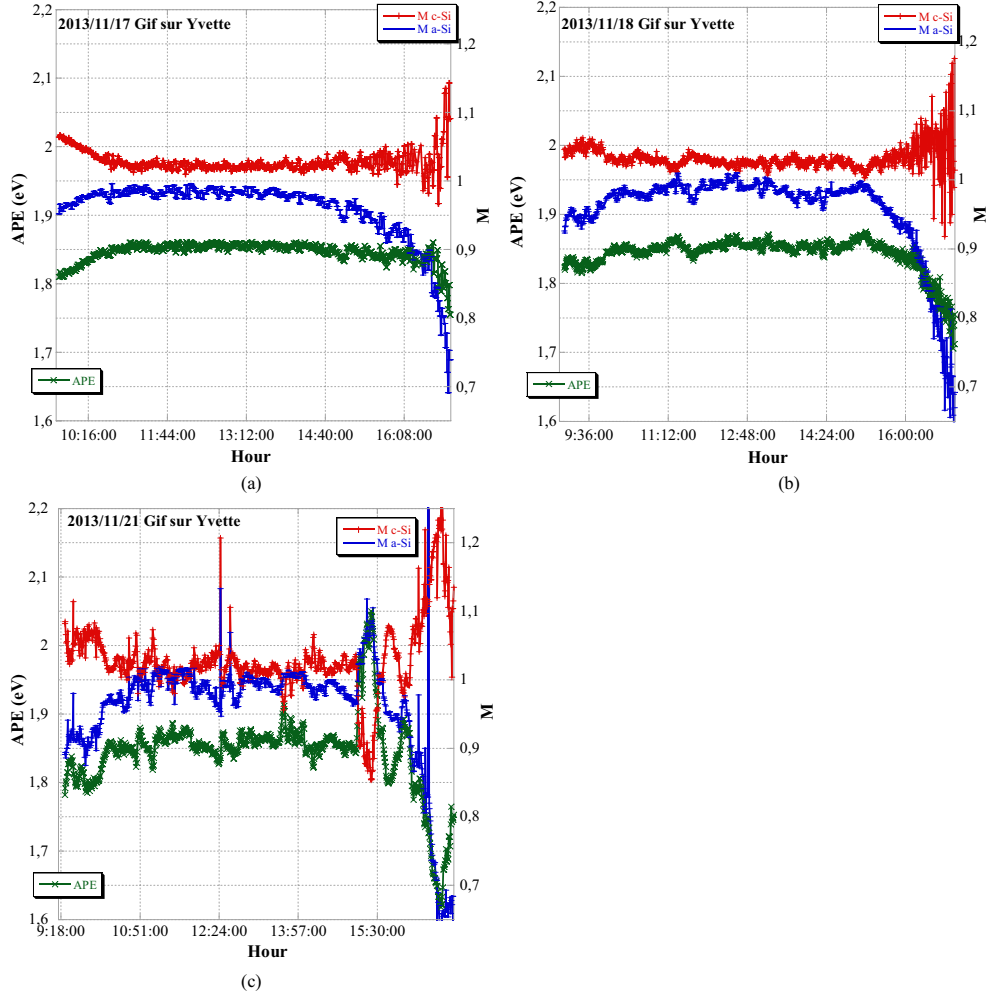


Fig. 6. Calculated APE and M during three days at LGEP, Gif-sur-Yvette (near Palaiseau), 2013/11/17 (a), 2013/11/18 (b) and 2013/11/21 (c).

4.2 Measuring the solar spectrum

Another way, more accurate, to estimate the spectral mismatch correction is to measure the solar spectrum with a USB2000+ Spectrometer with Enhanced Sensitivity (from 210 to 1035 nm) produced by Ocean Optic. Measures of the solar spectrum are taken every 30 s from the sunrise to the sunset and we derived, in Figure 6, the values of APE and M for crystalline Silicon PV cells and thin film Silicon PV cells. We can observe that at the beginning and the end of the day, thin film Silicon PV cell has a lower M contrary to the crystalline Silicon PV cell. This can be mainly explained by the fact that the AM is higher during these periods and then the spectrum is less blue-rich. This is confirmed by looking at the APE which is higher around noon than at the beginning or at the end of the day.

One goal of that kind of study would be to make more accurate models used for PV plant production. For instance, the very used PVsyst software or the Sandia model, utilize an empirical function $f_1(AM_a)$ to quantify the influence of variation in the solar spectrum, on the

short-circuit current of the PV module [18]:

$$I_{sc} = I_{sc0} \times f_1(AM_a) \times f_E(AOI) \times f_T(T) \quad (5)$$

$$f_1(AM_a) = a_0 + a_1 AM_a + a_2 (AM_a)^2 + a_3 (AM_a)^3 + a_4 (AM_a)^4. \quad (6)$$

f_1 is a 4th order polynomial function of absolute air mass AM_a , and is called the air mass modifier, where a is a vector of coefficients that are determined from module testing.

If we model or measure M during one year in one site, then substitute $f_1(AM_a)$ by the measured M in these programs should reduce uncertainty respect to the solar spectrum.

5 Conclusion

The solar spectrum variations differently impact the short-circuit current of solar cells, according to their technology. A spectral mismatch correction (M) must be applied to I_{sc} estimated under reference spectral conditions

(ASTM G 173-03) to evaluate precisely the yield of a PV module, for a given site.

This paper gives a method to calculate the spectral mismatch correction according to a PV cell, in a given site. The needed information to take into account is the AERONET monthly data or the solar spectrum measured by a spectrometer. Thus, we can derive the APE and M , and the associated I_{sc} . This can be particularly useful for decrease the uncertainty in PV plant prediction models like PVsyst or the Sandia model.

Application for the site of Polytechnique (Palaiseau) in France, is realized using data issued from the SIRTAs during 3 years (2008–2010). We found a difference of 9.7% for I_{sc} , throughout one year for thin film Silicon PV cells and 6.6% for crystalline Silicon PV cells. That highlights the importance to consider the spectral mismatch correction. For comparison, we made the same study in the site of Blida in Algeria.

We also emphasize that the reference AM1.5 solar spectrum is blue-rich respect to the mostly real solar spectrum for high latitudes.

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