# MODELING THE SOLAR SPECTRUM INCLUDING CLEARNESS INDEX AND AVERAGE PHOTON INDEX TO CALCULATE A-SI THIN FILM MODULES PERFORMANCE

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ABSTRACT: Accurate prediction of the energy produced by photovoltaic modules is a key issue to make a proper integration into the energy grid. Even though crystalline silicon based modules have a bigger presence on photovoltaic installations, thin film technologies are getting more market share. The effect of varying spectrum is not always taken into account but several studies indicates that spectrum effect should not be obviated in thin film technologies, especially those with narrower spectral response, as happens for amorphous silicon technologies. A new method to show the performance ratio of thin film modules having into account the spectrum is developed in this work by clustering all the spectra into a few groups. For this characterization, both, statistical and data mining techniques have been used to cluster all spectra in groups by means of its APE value. Afterwards a depiction using contour graphs of modules PR indexed by clearness index and module temperature has been carried out in every one of the APE clusters. The data used have been registered in the Photovoltaic Laboratory of the University of Malaga for more than one year in order to take into account seasonal effects that could occur.

Keywords: a-Si, Clustering, Performance Ratio, APE, Clearness Index.

## 1 INTRODUCTION

Thin film photovoltaic modules are getting more market share in the photovoltaic industry, because of the lowest fabrication costs, but the behavior of thin film technologies is not completely understood since linearity is not as confirmed as happens for crystalline Silicon technologies [1]. One of the reasons of this behavior is due to the module spectral response which is lower; especially in a-Si [2] so changes in the solar spectral distribution affects the energy output of these modules. To get a proper integration in the energy grid it is important to make accurate predictions of the electricity that modules generate. Some studies show the importance of the spectral response and the spectrum effect on a-Si photovoltaic modules concluding that power output of a-Si PV module has a great dependence on spectrum distribution [3, 4]. Previous works, for instance Minemoto et al. [5], include spectrum influence to calculate crystalline silicon modules performance where it is demonstrated a linear variation with irradiance. In cited work, contour graphs of PR as a function of APE (Average Photon Energy) and $T_{MOD}$ (module temperature) are calculated. But this presentation is not valid for thin film modules since module degradation and irradiance linearity is not deeply understood and confirmed. According to this premises, a different representation is proposed. First of all, all spectra are clustered in three groups and for each group, contour graph of PR are calculated as a function of $T_{MOD}$ and $k_t$ (clearness index). The proposed representation can be used to forecast the performance of thin film modules allowing a better prediction of energy produced. It helps to understand better the behavior of a-Si modules technologies.

## 2 MEASUREMENT SYSTEM

### 2.1 Apparatus

All devices used for this study have been set on a fixed 21° slope structure according to the standard IEC 60904-7 [6] at the Solar Photovoltaic Systems Laboratory of the University of Malaga with geographical coordinates: latitude 36.7° N and longitude 4.5° W, height 50 m. An a-Si photovoltaic module (Table I), a piranometer, a four-wire RTD Pt100 coupled to the back of the panel and a grating spectroradiometer prepared for continuous outdoor exposure that has been used to record the solar spectral irradiance in the range of 350 to 1050 nm (spectral range involving visual and near-infrared) with a spectral resolution of below 8 nm at a wavelength interval of 0.75 nm. This spectral range is wider than the module spectral response as can be seen in Fig. 1 and Table I.

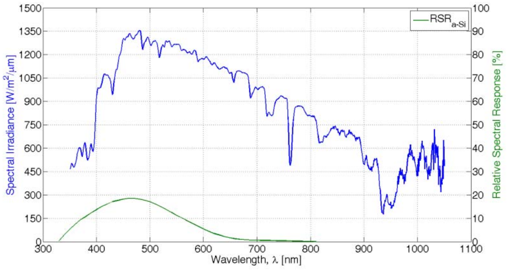

**Figure 1:** a-Si Spectral Response VS Solar Spectrum

In fact, spectral response for a-Si technologies is usually narrow. Most part of irradiance captured by these devices comes from the visible part of the spectrum, the one affected mostly by Rayleigh scattering.

**Table I:** Module characteristics

| Technology | $\eta_{STC}$(%) | Area[$m^2$] | P[$W_p$] | SR [nm] |
|---|---|---|---|---|
| a-Si | 6,3 | 0,95 | 60 | 350-750 |

### 2.2 Data acquisition

A custom-built system for measuring I-V curves developed by Piliougine et al. [7] in the PV systems group at University of Malaga was used to collect the meteorological data and the electrical module parameters.

To avoid dust and other substances being deposited on the spectroradiometer and the PV devices, daily cleaning and maintenance has been carried out in order to get data as more accurate as possible. Measurements have been collected from November 2010 to May 2012. The total amount of solar spectral irradiances that were measured is up to 400.000.

### 2.3 Data preparation

Afterwards, to avoid reflection produced by angle of incidence and other effects a filtering was addressed by removing spectra taken with an elevation angle under $15^o$ [8]. Finally an amount of over 250.000 spectra remained. On the other hand, data recovered for the module were obtained with a time interval of five minutes, where module electrical parameters $I_{SC}$, $V_{OC}$, $P_M$, $T_{MOD}$ and I–V curve plus meteorological data G, H, T, HR are captured simultaneously. Records of 60.000 of these data were recovered. Spectrum is added to the PV module data by matching daytime.

## 3 PROPOSED METHODOLOGY

### 3.1 Average Photon Energy

Spectrum captured is a detailed signal of radiation all along the spectral wavelength of 920 points. To handle this amount of information a simplification has been done. For this scope, a good indicator is the APE index. APE (Average Photon Energy) is an indicator of the kind of light that reaches the earth surface [4]. The expression to calculate APE is as follows, Eq.1:

$$APE = \frac{\int_a^b E(\lambda)\cdot d\lambda}{q\int_a^b \phi(\lambda)\cdot d\lambda} \quad [eV] \qquad (1)$$

where:
E.- is the irradiance distribution per wavelength,
ϕ.- is the photon flux density per wavelength,
q.- is the electron charge.

In an initial classification all spectra are indexed by APE value, the result can be seen in Fig. 2:

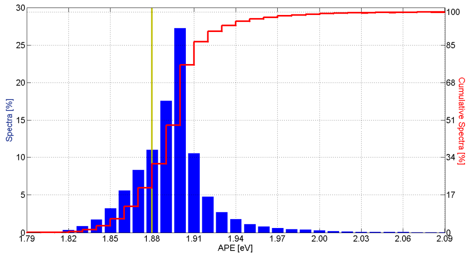

**Figure 2:** Spectra distribution indexed by APE value

### 3.2 Spectral clustering

Using the procedure described in Moreno-Sáez and Mora-López [9], all spectra can be clustered in a few groups. To address this clustering it is necessary to normalize spectra. This normalization can be done by calculating the cumulative probability distribution function (c.p.d.f.), see Eq. 2:

$$c.p.d.f.(\lambda) = P(\Lambda \leq \lambda) = \int_{\lambda_o}^{\lambda_f} f(\lambda)\cdot d\lambda \qquad (2)$$

Resulting in the following curve, see Fig. 3:

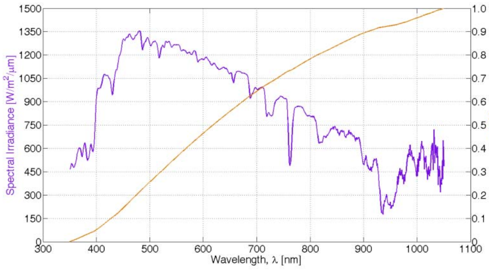

**Figure 3:** Spectral curve and its c.p.d.f.

After calculating c.p.d.f. for each spectrum a classification is done. Using the k-means clustering method, all 250.000 spectra are grouped into three clusters. Every one of these clusters has an element called centroid that is the most similar to the rest of the elements of the cluster. The spectra distribution in clusters is as follows (spectra are indexed by APE value), Fig. 4:

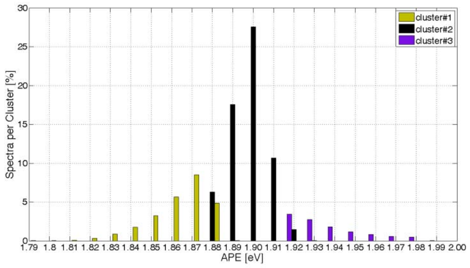

**Figure 4:** Spectra classified per clusters

### 3.3 Clustering outcome

A proper distribution happens, with low overlapping at the histograms clusters tails. This clustering lets all spectra recovered to be reduced to three spectra, what means that with only three spectral irradiance distributions all spectra in this location get characterized. From now on, all measurements are grouped by means of APE value.

APE value is a good indicator of the water vapor suspended in the atmosphere [10]. A low value of APE indicates a clear day meanwhile a high value of APE stands for a cloudy day [11]. With the addressed clustering we get all three situations, sunny and clear days, very cloudy days and days with some humidity suspended (the most) according to the climatology of Málaga, a seaside city with a high rate of relative humidity.

### 3.4 Performance ratio

A methodology to measure the performance of solar photovoltaic modules has been developed following the procedure used by Minemoto et al. [5] where contour graphs of PR are calculated.

Usually this performance is calculated using STC conditions without taking into account the spectral distribution effect, but, it is documented that solar spectral distribution affects in an important manner to thin film photovoltaic modules, especially those with a narrow spectral response as happens for amorphous silicon modules [12].

PR indicates PV module efficiency without the effect of the irradiance intensity. The proposed method is to calculate PR contour graphs of the a-Si module indexed by $T_{MOD}$ (module temperature) and $k_t$ (clearness index), which is defined as global irradiance divided by extraterrestrial irradiance ($G/G_0$).

To take into account the spectral effect, measurement will be held in each one of the clusters of Fig. 4.

The result of the PR calculated at each cluster is as can be seen in Figures 5, 6 and 7:

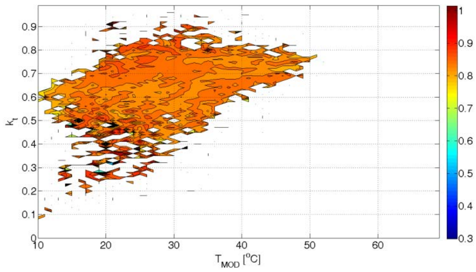

**Figure 5:** Module PR in cluster #1

Figure 5 is calculated with data grouped in cluster#1, with low water vapor conditions in the atmosphere. PR value obtained is close to 80%, which could be considered as a low value. This means that in clear days, module performance ratio is not as high as could be.

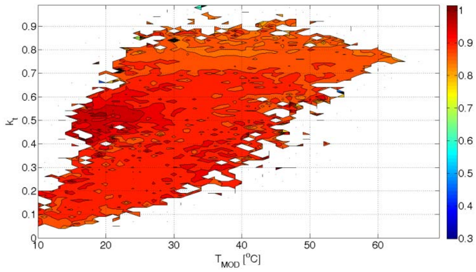

**Figure 6:** Module PR in cluster#2

Figure 6 is depicted with measurement grouped in cluster#2 with normal relative humidity. In this conditions PR value increases as $k_t$ decreases, what means that as long as the atmosphere turns overcast module performance ratio gets higher. Some temperature effect can be seen. The lower the module temperature the higher the PR is obtained, as expected.

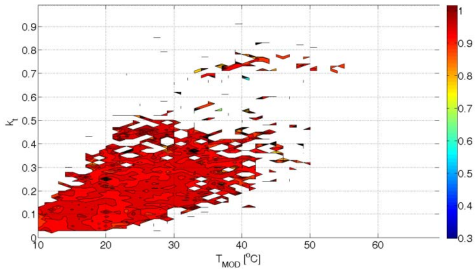

**Figure 7:** Module PR in cluster#3

Figure 7 is done for elements in cluster#6 with high APE value, what stands for very cloudy days. Here, PR obtained is very high, over 100% in some cases what means that with very cloudy days the module is getting a really good behavior.

### 3.5 Results

According to PR contour graphs, module performance is worst for clear than for cloudy atmosphere, with very high rates of water vapor suspended. This result has to be explained as PR is not a measure of the absolute module performance but an indicator of the module behavior under specific climatic conditions [13].

To understand these three figures it is necessary to take into account Fig. 1.

When module is working in cluster#1 APE value is low what means there is irradiance contribution from the NIR (near infrared) and VIS (visual) range of the spectrum, but a-Si technology spectral response cannot capture NIR wavelengths.

When module is working in cluster#3, clouds filter NIR solar irradiances and all the spectral contribution comes from VIS spectrum which matches module SR.

This explains a higher PR when module is working in overcast conditions. The lower the APE value, the clearer the atmosphere, in this situation spectral irradiance does not match module spectral response. On the other hand, high APE values stands for water vapor suspended in atmosphere which filters NIR spectral contribution, in this situation spectral irradiance fits module spectral response.

## 4 CONCLUSIONS

A new methodology for estimating the performance ratio of a-Si photovoltaic modules is proposed based on the use of PR contour graphs estimated using module temperature and clearness index.

The obtained results agree with previously reported. As known a-Si photovoltaic modules have the lowest efficiency among technologies but this contour graphs show that could be a good solution in areas with high rates of cloudy days. These modules are usually cheaper than other technologies and its installation in places with few sunny days would be advantageous since no spectral response would be wasted and module would work properly as indicates high PR values shown.

## 5 ACKNOWLEDGEMENT

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