COMPARATIVE ANALYSIS OF THE EFFECTS OF SPECTRUM AND MODULE TEMPERATURE ON THE PERFORMANCE OF THIN FILM MODULES ON DIFFERENT SITES

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ABSTRACT: The electric behavior under natural sunlight of thin film PV modules is more difficult to predict than that of crystalline silicon ones owing to the higher sensitivity to the spectral distribution of the former when compared with the latter, among some other factors. The purpose of this work is aimed at looking into the influence of the spectral irradiance and the module temperature on the outdoor performance of recent commercially available a-Si, CdTe and a-Si/μc-Si modules in sites with different climates in Spain. This paper is addressed to present the results of a 12-month experimental campaign experienced by modules of these thin film technologies carried out in the utilities of the CIEMAT/DER (Madrid, continental climate) and those of the University of Málaga (Málaga, Mediterranean climate). For each one of the tested specimens, contour graphs of their performance ratio (*PR*) as a function of module temperature and average photon energy (*APE*) are shown. A strong dependence of *PR* on *APE* is noticeable at module temperatures below some 45º C so that as a general trend, the module performance improves as *APE* increases. However, the tested a-Si and a-Si/uc-Si modules show little sensitivity to module temperature within some specific ranges of values of *APE* which lie in the vicinity of the *APE* value for the AM1.5G spectrum. Last, spectral gains achieved at high values of *APE* together with cold temperatures yield figures of *PR* above 1 in some cases.
Keywords: PV module, Thin Film, Test & Measurement

1 INTRODUCTION

The electricity yield estimation derived from both the climate conditions of a specific site and the most characteristic electric parameters of PV module measured at standard test conditions (STC) is far from being so successfully solved for thin film technologies as it is for crystalline silicon. Noticeable errors can be made when using irradiance data collected only by pyranometers –flat response sensors- since thin film PV modules are specially sensitive to the spectral distribution of the irradiance. However, the data recorded by means of a spectro-radiometer does not lend itself well to be used in engineering approaches as it consists of a more or less dense ensemble of points- depending on the spectral range and the instrument resolution. In this sense, the average photon energy (*APE*, commonly expressed in eV) is a single number that characterises the shape of the incident irradiance spectrum [1][2], so that the higher the *APE*, the higher the blue content of light. This index is calculated by dividing the incident irradiance by the total photon flux density:

$$APE = \frac{\int_a^b G_\lambda(\lambda)\,d\lambda}{\int_a^b \Phi(\lambda)\,d\lambda} \qquad (1)$$

where G_λ ($W\cdot m^{-2}\cdot nm^{-1}$) is the spectral irradiance, Φ ($m^{-2}\cdot nm^{-1}\cdot s^{-1}$) is the spectral photon flux density, *a* and *b* are the lower and upper limits, respectively, of the considered interval of the spectrum. The figures for *a* and *b* are usually determined by the measurement range of the spectro-radiometer.

An interesting and useful method to estimate the energy yield per watt peak has been presented for PV grid-connected systems which use sc-Si, mc-Si, a-Si, a-Si/μc-Si and a-Si/a-SiGe/a-SiGe technologies [3][4]. This method is based on obtaining a contour graph for each technology in which the module performance ratio (*PR*) is depicted vs. *APE* and module temperature (T_{mod}). This approach is convenient as *PR* indicates PV module efficiency without the effect of irradiance intensity; in fact *PR* is defined as the actual output energy divided by the nominal output energy calculated from the PV module performance at STC.

The purpose of this work is aimed at ascertaining the impact of the spectral distribution of the irradiance and the module temperature on the electricity yield of recent commercially available a-Si, CdTe and a-Si/μc-Si modules in sites with different climates in Spain. This paper is addressed to present the results of a 12-month experimental campaign carried out in the utilities of the CIEMAT/DER (Madrid, Spain, lat. 40.2 N, long. 3.4W, with a continental climate) and those of the University of Málaga (Málaga, Spain, lat. 36.4 N, long. 4.5W, with a Mediterranean climate). The above method [3][4] will be followed, bearing in mind that, as far as we know, this method has not been applied to CdTe technologies yet. The methodology is based on carrying out an outdoor experimental campaign in both Madrid and Málaga basically intended to scan through five-minute intervals thin film module voltage-current curves, ambient temperature, module temperatures (T_{mod}), wind speed, relative humidity, barometric pressure, on-plane incident irradiance (*G*) and its spectral distribution.

2 APPROACH

2.1 Experimental setup

One specimen of each considered technology was deployed outdoors in Madrid in December 2010. The same number of specimens of each considered technology were also deployed in Málaga in September 2010.

Prior to their outdoor deployment, the calibration in STC of all the significant electrical parameters of the three thin film PV modules to be deployed in Madrid –a sample for each one of the three considered technologies (a-Si, CdTe and a-Si/μc-Si) - was entrusted to CIEMAT / DER (Madrid) at the beginning of our work. For the sake of simplicity, only the most meaningful parameter for our purpose -the peak power of these PV modules- is shown in Table I. It is noticeable that the nominal values –as provided by the manufacturer- of this parameter are somewhat under-rated when compared to outdoor calibration figures, save CdTe. However, the three specimens that were to be tested in Málaga did not undergo any measurement by any accredited independent laboratory. In this work, the calibration figures will be considered as the peak power of each one of the three PV modules tested in Madrid, while the nominal power will be considered as the peak power for those specimens tested in Málaga.

Table I: Figures of the module maximum power in STC (W) considered for the three thin film PV modules under test in Málaga -as provided by the manufacturer- and for the three modules under test in Madid –according to a certificate of calibration dated July 2010 issued by the CIEMAT/DER.

Module technology	Manufacturer data sheet (Málaga)	CIEMAT/DER calibration (Madrid)
a-Si	60 -5/+10%	78.7 ± 2.2%
CdTe	70 ± 5%	65.3 ± 2.2%
a-Si/μc-Si	121 -5/+10%	141.9 ± .2%

The used outdoor measurement systems were installed in Madrid and Málaga in the laboratories of the High Technical School buildings of the University Carlos III of Madrid and the University of Málaga, respectively. The basic features of the test and measurement facilities have been described in some previous works [5][6].

2.2. Methodology

The output DC energy for each module is calculated by means of the integration of the maximum power obtained from each *V-I* curve over 5-minute time intervals. The same method applied to stored values of *G* has been used to calculate the on-plane collected irradiation (*H*).

The lower and upper limits of the considered interval of the spectrum -*a* and *b*, in eqn. (1)- are set to 350 and 1050 nm, respectively. The *APE* value for the AM 1.5G standard solar spectrum calculated within this range equals 1.88 eV [2].

As commented above, the three thin film PV modules to be tested in Madrid were deployed outdoors in December 2010 while the remaining three to be tested in Málaga were deployed outdoors in September 2010. All of them were in their undegraded state. Data collected from April 2011 to March 2012 have been used to produce the contour graphs to be shown hereafter. These countour graphs depict, according to a colour code, matrices of *PR* that have *APE* and T_{mod} for row and column, respectively, with a grid mesh size of 1ºC X 0.005 eV.

The procedure to create the above contour graphs may be summarized as follows:

1. The *APE* of *G* is determined by the spectrum shape.
2. The rows of both *H* and the output DC energy are indexed by *APE*.
3. The columns of both *H* and the output DC energy are indexed by T_{mod}.
4. The figures of *H* and the output DC energy are added to the corresponding grid mesh.

PR is calculated in each grid mesh as the total DC output energy obtained in step 4 divided by the nominal output energy, calculated from the PV module performance at STC during the considered time period.

3 RESULTS

3.1. On-plane collected irradiation

Figs. 1 and 2 show the percentage contribution of *APE* classes to the on-plane collected irradiation over the considered period in Madrid and Málaga, respectively. In Madrid, some 55% of *H* has been generated with values of *APE* below 1.88 eV (AM 1.5G). However, in Málaga this fraction of *H* generated with values of *APE* below 1.88 eV lowers down to some 30%. This clearly indicates a prevailing higher blue-rich content of *G* in Málaga than that of Madrid. This is due to the inland location of Madrid and the coastal one of Málaga. The lower humidity of Madrid leads to a smaller absorption by water vapor, so that the proportion of spectral irradiance at longer wavelengths is enhanced. This causes a 'red-rich' spectrum.

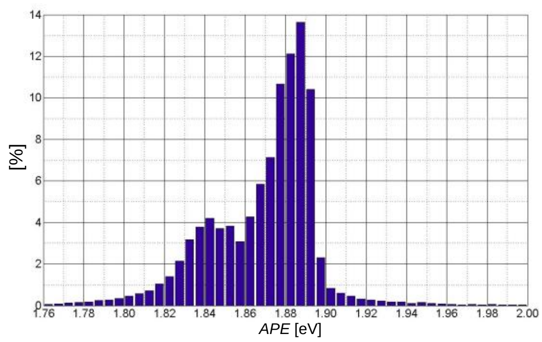

Figure 1: Percentage distribution of the on-plane collected irradiation as a function of *APE* in Madrid (class width = 0.005 eV).

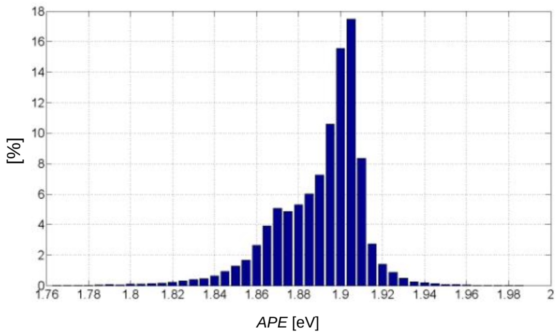

Figure 2: Percentage distribution of the on-plane collected irradiation as a function of *APE* in Málaga (class width = 0.005 eV).

3.2. Performance ratio

Figs. 3-8 show the contour graphs of *PR* for the a-Si, CdTe and a-Si/μc-Si PV modules tested in each considered site as a function of T_{mod} and *APE*. Depending on the technology, *PR* decreases more or less noticeably as T_{mod} increases, but a strong dependence of *PR* on *APE* is detected, specially noticeable at module temperatures below some 45º C. This becomes evident by scanning each contour graph in the vertical direction, at a fixed value of T_{mod}: in general, the higher the *APE*, the higher the *PR*. Thus, the dependence of *PR* on *APE* has already been raised in some previous works [3][4]. Figures 3 and 4 also show some lenghthy horizontal 'strips' in which the figures of *PR* of the tested a-Si modules show little sensitivity to variations of T_{mod}. The same happens in Figures 7 and 8 for the tested a-Si/μc-Si tested specimens. This should be investigated further in future works.

In general, given the same operation conditions -as specified by *APE* and T_{mod} - lower values of *PR* are obtained for the a-Si and a-Si/μc-Si modules in the site of Madrid than those obtained in the site of Málaga. This is mainly due to the higher figures for the maximum power at STC that have been considered for Madrid (calibrated values). However, this is not the case for CdTe modules. Consequently, a compelling explanation for this fact is to be delivered in future works.

The tiny areas of Figs. 3-8 that show values of *PR* above 1 broadly appear at temperatures below 35ºC and high values of *APE*. The spectral gains experienced by the tested materials under a rich blue spectrum together with cold or moderate temperatures help explain this behavior.

3 CONCLUSIONS

Some results of the research on the influence of the solar spectrum distribution and module temperature on the outdoor behavior of some thin film technologies in the city of Madrid and Málaga (Spain) have been presented. The prevailing environmental conditions under which these modules have performed are characterized by a higher blueness of sunlight in Málaga than in Madrid. Additionally, the former site is affected by higher temperatures than those that affect the latter.

A strong dependence of *PR* on *APE* is noticeable at module temperatures below some 45º C so that as a general trend, the higher the *APE*, the better the module performance. On the other hand, the tested a-Si and a-Si/uc-Si modules also show little sensitivity to T_{mod} within some specific ranges of values of APE which lie in the vicinity of 1.88 eV, which correspond to the *APE* value of the AM1.5G spectrum. Last, some values of *PR* exceeding the ideal figure of 'one' appear under temperatures below 35ºC and high figures of *APE*.

4 ACKNOWLEDGEMENTS

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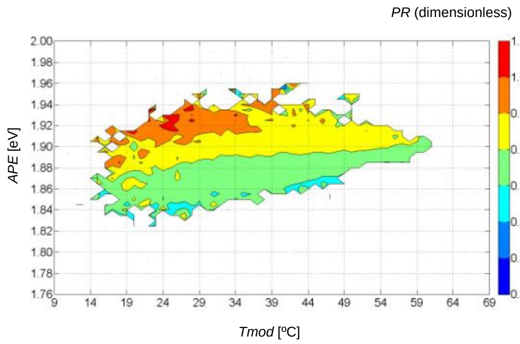

Figure 3: Contour graph of *PR* of the a-Si module in the site of Málaga as a function of T_{mod} and *APE*, Blank areas indicate no data points.

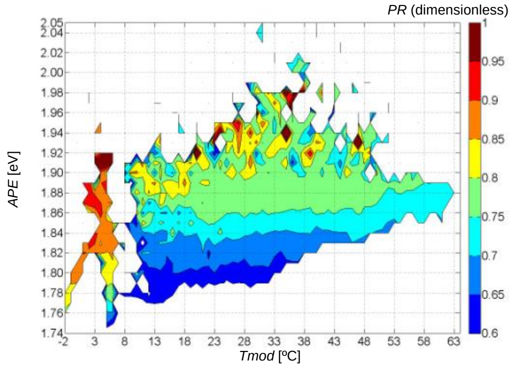

Figure 4: Contour graph of *PR* of the a-Si module in the site of Madrid as a function of T_{mod} and *APE*, Blank areas indicate no data points. Some data filtering is required for values of APE above 1.96 eV.

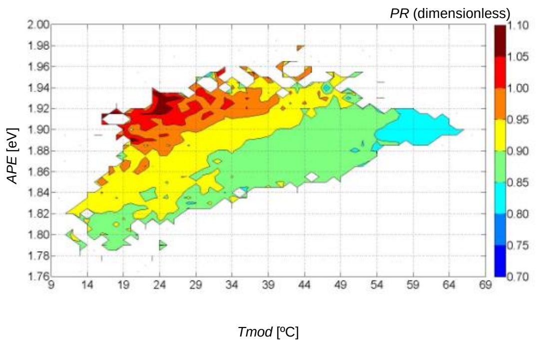

Figure 5: Contour graph of *PR* of the CdTe module in the site of Málaga as a function of T_{mod} and *APE*, Blank areas indicate no data points.

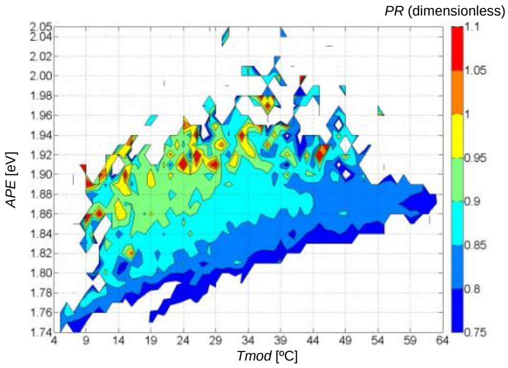

Figure 6: Contour graph of *PR* of the CdTe module in the site of Madrid as a function of T_{mod} and *APE*, Blank areas indicate no data points. Some data filtering is required for values of APE above 1.96 eV.

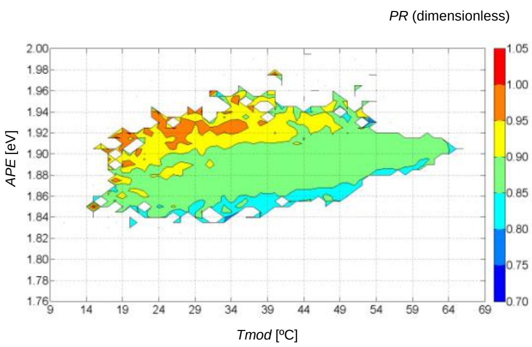

Figure 7: Contour graph of *PR* of the a-Si/µc-Si module in the site of Málaga as a function of T_{mod} and *APE*, Blank areas indicate no data points.

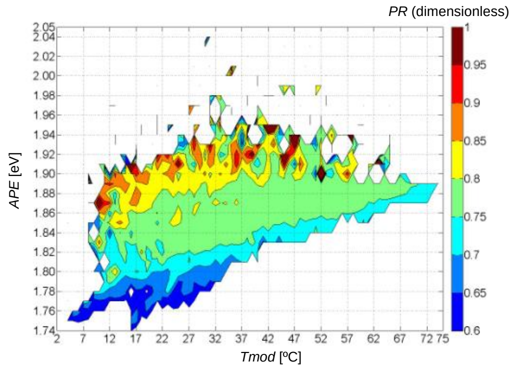

Figure 8: Contour graph of *PR* of the a-Si/µc-Si module in the site of Madrid as a function of T_{mod} and *APE*, Blank areas indicate no data points. Some data filtering is required for values of APE above 1.96 eV.

5 REFERENCES

[1] Williams S. R., Betts R., Helf T., Gottschalg R., Beyer H. G., Infield D. G. Modelling long-term module performance based on realistic reporting conditions with consideration to spectral effects. In: Proceedings of the III World Congress on PV Solar Energy Conversion 2003, Osaka (Japan)

[2] Minemoto T., Nakada, Y., Takahashi H., Takakura H., Uniqueness verification of solar spectrum index of average photon energy for evaluating outdoor performance of photovoltaic modules, Solar Energy 2009; 93, 720-727

[3] Minemoto T., Nagae S., Takakura H., Impact of spectral irradiance distribution and temperature on the outdoor performance of amorphous Si PV modules, Solar Energy Materials and Solar Cells 2007; 91, 919-923

[4] Minemoto T., Fukushige, S.., Takakura H., Difference in the outdoor performance of bulk and thin-film silicon-based photovoltaic modules, Solar Energy Materials and Solar Cells 2009; 93, 1062-1065

[5] Nofuentes, G., Alonso-Abella, M., Muñoz, JV., García-Domingo, B., Fuentes, M., De la Casa, J., Chenlo, F.,Influence of Spectral Irradiance Distribution and Module Temperature on The Outdoor Performance of Some Thin Film PV Module Technologies. In Proceedings of the 26th European Photovoltaic Solar Energy Conference, 2011, Hamburg (Germany)

[6] M. Piliougine, J. Carretero, L. Mora-López and M. Sidrach-de-Cardona. Experimental system for current–voltage curve measurement of photovoltaic modules under outdoor conditions, Progress in Photovoltaics: Research and Applications; 2011, 19 (5), 591-602