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Analysis and characterization of photovoltaic modules of three different thin-film technologies in outdoor conditions

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HIGHLIGHTS

- The instantaneous PR of thin-film modules of 3 different technologies is characterized.
- Module temperature, clearness index and APE were used as explanatory variables.
- Clearness index is the variable that better explains the PR variability for a-Si.
- For a-Si/μc-Si technology the most significant variable is temperature.
- Clearness index and module temperature have a similar influence on PR for CdTe.

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ABSTRACT

The instantaneous performance ratio of thin-film photovoltaic modules of three different technologies is analyzed and characterized using contour graphs for different outdoor conditions. This parameter changes when modules are working in outdoor conditions depending on several variables. The most explanatory parameters we have found are the module temperature, the atmospheric clearness index and the solar spectral irradiance distribution; this latter has been included in the characterization using the average photon energy index as it has been identified as a good indicator of the solar spectral irradiance distribution. Moreover, the variance of instantaneous performance ratio for each studied technology has been analyzed. We can conclude that the joint use of all these parameters in contour graphs allows us to better characterize the performance of modules and to reduce the uncertainty observed in previous proposals that only use two of these parameters.

1. Introduction

Predicting the energy that photovoltaic systems will generate is essential for such installations to be integrated in the power grid. This involves knowing the behavior of the photovoltaic modules in the different climatic conditions to which they will be exposed. One way of characterizing this behavior is to estimate the performance ratio (PR) that describes the relationship between the actual and theoretical energy outputs of a PV plant. This is independent of location and can be used to compare different PV plants. It measures the deviation from standard operating conditions as it depends on the meteorological conditions.

The performance of photovoltaic modules is primarily influenced by the intensity of radiation received and the module temperature, T_{MOD}, but also by the spectral distribution of solar radiation. This is especially important when dealing with thin film modules, mainly due to their spectral response, [1–3], which means that they only use a portion of the whole solar spectral irradiance received on their surface. Furthermore, this type of modules has a more remarkable nonlinear behavior with respect to the irradiance received regarding modules mono and polycrystalline [4].

Establishing the behavior of thin film modules is important as they are attractive to be integrated in building [5]. For instance, the performance of triple and simple junction amorphous silicon PV modules integrated in West and East facade in Mugla (Turkey) is evaluated in [6]. It is likewise important for systems using both the electricity produced and the heat rejected by the PV modules [7].

Therefore, many studies including some parameter related to the solar spectrum in the modelling of thin-film modules, such as the spectral factor, SF, in [8]. One of the most used is the average photon energy (APE) as it has been identified as a good indicator of the distribution of solar spectral irradiance. According to

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Nomenclature

λ	wavelength	G_t	global irradiance
μc-Si	microCrystalline Silicon	IEC	International Electrotechnical Commission
$\overline{\text{PR}}$	mean PR	k_t	Instantaneous Clearness Index
PR	performance ratio	NIR	Near Infra-Red
PR_t	instantaneous PR	P	power
T_{MOD}	module temperature	PV	photovoltaic
a-Si	amorphous silicon	SF	spectral factor
APE	average photon energy	STC	Standard Test Conditions
CdTe	Cadmium Telluride	STD	standard deviation
E	solar spectral irradiance	T	temperature
G_0	Extraterrestrial Irradiance	VIS	visual

Moreno-Sáez and Mora-López [9], there is a two-way relationship between solar spectral irradiance distribution and the value of average photon energy (APE).

Minemoto et al. [10] propose a methodology to link the solar spectrum with the energy produced by a photovoltaic module. The authors use the data obtained in experiments with silicon modules, both amorphous and crystalline, in Japan. Contour graphs are then used to represent the PR values obtained. The same type of representation is used by Yoshida et al. [11]. Four modules of different technologies were characterized in this last paper: multicrystalline Si (mc-Si), a-Si/microcrystalline-Si (tandem), amorphous Si (a-Si) and a-Si/a-SiGe/a-SiGe triple junction (3-stack); they combine the contour graph of PR proposed by Minemoto et al. [12], with estimated irradiance contour graph to obtain energy values.

In Minemoto et al. [13], contour plots of the average PR value and standard deviation were built for c-Si (crystalline silicon), a-Si and tandem a-Si/μc-Si. Contour plots of data points of irradiance were also built with an irradiance range from 0.2 to 1 kW/m^2 as a function of T_{MOD} and APE for a-Si PV module. They conclude that the PR of a c-Si module is determined by the module temperature while for a-Si and tandem a-Si/μc-Si modules is determined by the APE value.

Takei et al. [14] use modules of the four different technologies used in [11]. The influence on the outdoor performance of modules is analyzed in two different ways: using APE and module temperature and using clearness index and air mass. Radiation information is then used to estimate the output energy obtained. They conclude that the estimated output energy obtained using either of these two procedures is similar.

In all the above mentioned research filter data is performed, so that only data with irradiance values higher than 0.2 kW/m^2 were used in order to remove the uncertainty.

In all these cases, the calculated PR value refers to the energy produced by the module compared to that produced in standard conditions. In this paper, the definition of an instantaneous value of the performance ratio, PR_t, is proposed as an extension to the well-known performance ratio that is used for long time periods, typically one year. An extension is therefore proposed of the classic PR concept, which is used for the energy evaluation of the whole system. This PR instantaneous value compares the power value of the module with respect to the power module in standard conditions at a particular moment. Several meteorological and installation parameters have been used to analyze and characterize the PR_t. We propose to use jointly module temperature, APE and clearness index to obtain a contour graphs of PR_t that integrate all three as we have checked that all these variables are significant. Once analyzed and characterized, this new parameter can be used to establish the real time operation of an installation under certain meteorological conditions.

The rest of the paper is organized as follows. Materials and methods, including data used, are described in Section 2. The proposed methodology to estimate the PR_t of modules is presented in third section. The data used for the experimentation are described in the fourth section. The results obtained are presented and discussed in the fifth section. Finally, the conclusions are summarized in the last section.

2. Materials and methods

2.1. Performance ratio

The performance ratio (PR) is one of the indices that has been used to evaluate the performance of photovoltaic modules for long periods, typically one year. The PR is defined in IEC61724, [15], in terms of energy yield in a given period of time, and considering the whole system. This parameter gives the overall losses of the PV system related to the expected energy delivered in standard conditions. As an extension of this index, the instantaneous PR is defined as the ratio of the output power of the PV module power normalized to its peak and global solar irradiance received at the module normalized by the global solar irradiance at standard conditions according to Eq. (1):

$$PR_t = \frac{P_{OUT}/P_{STC}}{G/G_{STC}} \qquad (1)$$

where:

P_{OUT}, is the maximum power point (W) of the module,
P_{STC}, is the peak power of the module measured at standard conditions (W) and
G, is the global solar irradiance received in the surface of the module (W/m^2),
G_{STC}, is the value of global solar irradiance at standard conditions (1000 W/m^2).

The PR_t is dimensionless. Different values of PR_t represent the different working conditions of the module produced by changes in irradiance, air mass, module temperature and spectral distribution of the incident radiation. The PR_t thus indicate the losses or gains relative to their instantaneous power in standard conditions.

2.2. Clearness index

The atmospheric clearness index is defined as the ratio of the solar global irradiance received in a surface and the extraterrestrial radiation, according to the Eq. (2):

$$k_t = \frac{G_t}{G_0} \qquad (2)$$