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Seasonal performance comparison of three grid connected photovoltaic systems based on different technologies operating under the same conditions

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ABSTRACT

Three grid connected photovoltaic systems based on different PV technologies (poly-Si, a-Si and CdTe), operating under the same conditions were analysed to determine their degradation and the variation in seasonal performance. In addition to the intrinsically different degradation of each technology through indoor tests at standard test condition (STC), a deeper analysis of the variables affecting the fluctuations of the performance was performed. The performance seasonal fluctuations resulting from the solar spectrum and module temperature was studied during a single year (December 2014 to December 2015). A notable solar air mass spectrum dependence (−11.22%/AM) of the generated power but scarcely detectable instantaneous temperature dependence was observed in the a-Si array. In contrast, the poly-Si array suffered the highest power decline with an elevating temperature (−0.56%/°C). The CdTe array exhibited a tempered interaction with the solar spectrum (−4%/AM) and temperature (−0.25%/°C). Finally, the significant maximum power difference between two months (April and September) due to the thermal annealing and light soaking effects in the a-Si array is confirmed, where the quantified variation of these two effects were 5.9% and −5.7%, respectively.

1. Introduction

Photovoltaic (PV) energy generation has steadily grown parallel to the increasing world energy demand and decreasing cost of PV modules. Worldwide installed PV capacity grew by 45–50 GW in 2015, while the cost was reduced by two-thirds from 2010 to 2015 (IEA, 2016). Although PV is generally applicable to most locations, it is highly site-specific (Marion et al., 2014) and susceptible to meteorological factors (Ueda et al., 2009).

Previous studies have portrayed the PV performance maps of how different PV technologies perform under site-specific climate conditions, emphasizing the importance of the performance evaluation under actual field operation. Akhmad et al. (1997), through the investigation of the output performance comparison of amorphous silicon (a-Si) and polycrystalline silicon (poly-Si) modules for a 2-year period, suggested that a-Si is well suited for tropical climates based on its thermal–recovery effect. Carr and Pryor (2004) reported that after conditioning and proper ratings, the analysed thin film a-Si and copper indium diselenide (CIS) modules outperformed the crystalline silicon (c-Si)based technologies in Perth, Western Australia, especially in the summer because of low temperature losses. Cañete et al. (2014) compared three thin film technologies, including a-Si, tandem structures of amorphous silicon and microcrystalline silicon (a-Si/μc-Si), cadmium telluride (CdTe) and poly-Si in Southern Spain, reporting a higher seasonal variation in these thin film modules, especially in the a-Si module. They concluded that low temperature losses made a-Si modules suitable for high irradiation conditions.

However, with the expansion of the PV industry, new studies have emerged to assess the performance differences on grid-connected PV (GCPV) systems and their overall energy output profile. Sasitharanuwat et al. (2007) evaluated the first six months of operational performance of a 10 kWp PV system based on three PV technologies including a-Si, poly-Si and heterojunction with intrinsic thin-layer (HIT), illustrating the highest energy output from the a-Si PV system. Minemoto et al. (2007a) characterized the effects of the solar spectrum distribution and module temperature on the performance of two GCPVs based on a-Si and poly-Si. The study revealed a stronger spectral dependence but weaker temperature dependence of the a-Si output energy, while the poly-Si GCPV had the opposite behaviour. Makrides et al. (2010) highlighted the

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influences of the meteorological conditions and geographic locations on the energy performance of 13 GCPVs located in two high irradiation cities (Nicosia, Cyprus and Stuttgart, Germany). These researchers outlined that thin films with lower temperature coefficients generated more energy than c-Si technologies in high irradiation locations. Ferrada et al. (2015) conducted a comparison concerning two GCPVs consisting of monocrystalline silicon (mono-Si) and a-Si/μc-Si technologies, for 16 months under a coastal desert climate in Chile. They concluded that the dust accumulation affected a-Si/μc-Si more severely than mono-Si.

These studies concluded that irradiance and temperature are the two main meteorological variables that affect the performance of GCPV system. Seasonal variation in the solar spectrum contributes to the seasonally changed irradiance. Therefore, the seasonal variation in the PV module output is influenced by the overlap of the thermal effects and the solar spectrum changes (Aste et al., 2014; Katsumata et al., 2011; Makrides et al., 2012; Minemoto et al., 2007b; Phinikarides et al., 2015).

Since different semi-conductor materials have different band gaps, they vary in their responses to changes in the wavelength-dependent radiation, which also has a relationship with the seasons because the solar spectrum undergoes a seasonal variation. The solar spectrum has a larger blue (shorter wavelength) content during the summer and higher red (longer wavelength) content during the winter (Virtuani and Fanni, 2014).

Commonly, the solar spectral irradiance distribution is characterized by three approaches: Average photon energy (Katsumata et al., 2011), useful fraction (Gottschalg et al., 2003), and air mass (AM), which is the sunlight's path-length through the atmosphere and is the approach used in this study (King et al., 1997).

The operating temperature has varied influences on different PV technologies. The performance of c-Si decreases with an increased operating temperature due to a higher negative temperature coefficient (Radziemska, 2003), whereas the performance reduction in CdTe is relatively less due to a lower negative temperature coefficient (Cueto, 2002). In contrast, modules based on a-Si technology increase their output power under higher-temperature conditions and yield a decreased performance under low-temperature conditions. This phenomenon combines the two processes, the *light-soaking effect* (LSE) and the *thermal annealing effect* (TAE) (Nikolaeva-Dimitrova et al., 2010).

The objective of the work presented in this paper is to compare the performance of three GCPVs operating in Madrid, Spain. These GCPVs are poly-Si, CdTe and a-Si modules, which allows inferring conclusions of the behaviour of each technology operating under the same conditions. These conditions are different from previous studies, with high variation in the temperature, irradiance and AM. The paper is organized as follows. Section 2 provides a description of the experimental setup, as well as the indoor test process, performance evaluation metrics, AM calculation and data filter and processing. The results and discussion are presented in Section 3 where the module performance variation at STC during a three year interval is described. Then, the results of the energy conversion chain are presented, where the analysis of the energy yields and losses for each GCPV is performed. Finally, different GCPV performances with respect to seasonal variations causing variability in the solar spectrum and thermal effects is presented and discussed. The primary conclusions are presented in Section 4.

2. Materials and methods

2.1. Experimental setup

This research was conducted by analysing the data obtained from a grid-connected, roof-standing solar PV plant that has been in operation since December 2012, in ETSIAAB (Madrid, Spain, 40.4426°N, 3.7295°W). The nominal power of the entire plant is 21.77 kWp, divided into two main areas with several sub fields. The larger area consists of a poly-Si 16.83 kWp array connected to a 15.34 kW inverter. The plant counts on an experimental area (Fig. 1) formed by three independent systems based on poly-Si (1.61 kWp), a-Si (1.68 kWp) and CdTe (1.65 kWp) with similar total voltages and currents, each connected to an independent 1.2 kW inverter with maximum power point (MPP) tracking. All of the modules are mounted in open-air aluminium support structures with a 30° tilt angle and oriented with an azimuth angle of 3°. This study is focused on the experimental area, and more detailed information regarding the above mentioned three systems is presented in Appendix A.

The output of each inverter, the voltage and current at the DC side, and the meteorological information (solar irradiance, back-of-module temperature, ambient temperature, and wind speed), are measured and stored every 15 min. The main features of the inverter are shown in Appendix B.

At the end of 2014, an *HD32 MT.1* data logger (*Delta OHM®*) with eight differential channels was installed to obtain measurements at a higher sampling rate (1-min). One module of each technology was randomly selected to attach two thermocouples in the centre of its rear side to record the operating temperature of randomly selected modules for each GCPV. Additional irradiance data were monitored by an extra reference solar sensor based on a c-Si solar cell. The main features of this equipment are listed in Appendix C.

The site where the solar field is located has a transitional climate between the typical Mediterranean climate and the cold semi-arid climate with high irradiation. The site measured annual meteorological profile in the daytime of 2015 showed the monthly irradiation on panel varied from 2.92 kW h/(m^2 day) in December to 6.83 kW h/(m^2 day) in June. The monthly average ambient temperature varied from 9.7 °C in January to 32.7 °C in July, the wind speeds in this site were weak with an annual average of 0.75 m/s, and the average relative humidity varied from 40.28% in August to 54.84% in January.

2.2. Experimental methodology

2.2.1. Indoor test

The study includes both indoor and outdoor tests. First, the indoor test was completed in June 2012, six months before the beginning of the operation of the plant to provide original electrical information about each PV technology to be installed. Thereafter, the tested modules were operating under the same conditions as part of the entailed GCPVs. A second test of the same modules was conducted in January (poly-Si) and June (CdTe) 2015 after an approximate operating period of three years.

Fig. 1. Experimental portion of the grid-connected roof-standing solar plant in ETSIAAB (Madrid, Spain).