Solar Energy 139 (2016) 599–607

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Degradation analysis of thin film photovoltaic modules under outdoor long term exposure in Spanish continental climate conditions

Santiago Silvestre [a,*], Sofiane Kichou [a], Letizia Guglielminotti [a], Gustavo Nofuentes [b,c], Miguel Alonso-Abella [d]

[a] MNT Group, Electronic Engineering Department, Universitat Politécnica de Catalunya (UPC) BarcelonaTech, C/Jordi Girona 1-3, Campus Nord UPC, 08034 Barcelona, Spain
[b] IDEA Research Group, University of Jaén, Campus de Las Lagunillas, 23071 Jaén, Spain
[c] Centre for Advanced Studies in Energy and Environment, University of Jaén, Campus Las Lagunillas, 23071 Jaén, Spain
[d] CIEMAT/DER, Avda. Complutense, 22, 28040 Madrid, Spain

ARTICLE INFO

Article history:
Received 11 July 2016
Received in revised form 3 October 2016
Accepted 18 October 2016

Keywords:
Thin-film
PV modules
Degradation rate (DR)
Performance ratio (PR)

ABSTRACT

The present study analyses the degradation of thin film photovoltaic modules corresponding to four technologies: a-Si:H, a-Si:H/μc-Si:H, CIS and CdTe, under 5 years of outdoor long term exposure in Leganés, Spain. The period of outdoor exposure ranges from January 2011 to December 2015. The degradation rate and the stabilization period are analysed by using two different techniques. Moreover, the evolution of the fill factor and performance ratio is assessed. The CdTe module was found to have the highest degradation rate: −4.45%/year, while the CIS module appears to be the most stable with a degradation rate of −1.04%/year. The a-Si:H and a-Si:H/μc-Si:H modules present stabilization periods of 24 and 6 months respectively. The CdTe module degrades significantly for a period of 32 months, while the CIS module is the least degraded PV specimen over the whole experimental campaign.

1. Introduction

Nowadays thin film photovoltaic (TFPV) modules cover a 10% of market share with an annual production of 2.4 GWp in 2014 (Institute for Solar Energy Systems, 2016). The most common PV materials used in the mass production of TFPV modules are cadmium telluride (CdTe), copper indium gallium selenide sulphide ($Cu(In,Ga)Se_2$, CIGS) and amorphous silicon (a-Si), presenting an annual production in 2014 of 1.9 GWp, 1.7 GWp and 0.8 GWp respectively (Institute for Solar Energy Systems, 2016).

The main advantages of TFPV modules are their lower production costs and lower temperature coefficients relative to the crystalline (c-Si) and polycrystalline silicon PV modules (Tossa et al., 2016; Virtuani et al., 2010). On the other hand, main problems of TFPV modules are the degradation phenomena after long term outdoor exposure (Jordan and Kurtz, 2013; Meyer and van Dyk, 2003; Mendoza-Pérez et al., 2009; Muñoz-García et al., 2012) and the lower efficiencies in the comparison to c-Si PV modules.

Hydrogenated amorphous silicon (a-Si:H) and hydrogenated amorphous silicon/hydrogenated microcrystalline silicon heterojunction (a-Si:H/μc-Si:H) TFPV modules have conversion efficiencies in the range of 8–13% and present low production costs and energy pay-back times. However, these TFPV modules are strongly affected by spectral and temperature effects when deployed outdoors (Virtuani and Fanni, 2014; Kichou et al., 2016a,b). The so called Staebler-Wronski effect (SWE) is the cause of light-induced degradation (LID) that strongly affects a_Si:H and also has effects on (a-Si:H/μc-Si:H) TFPV modules. It determines the amount of dangling bonds created depending on the operating temperature (Staebler and Wronski, 1977; Van Dyk et al., 2007; Yamawaki et al., 1997).

CdTe TFPV modules are well adapted to the spectrum of solar radiation due to their band gap of 1.45 eV. The theoretical efficiency limit for CdTe technology is 29% (Muñoz-García et al., 2012). However, the average commercial PV module efficiencies are around 10–11% and the highest efficiency to-date is 17.5% (Green et al., 2015). Main degradation mechanisms identified in these PV modules are related to Cu diffusion from the back contact of the cells (Romeo et al., 2000) and to the reduction of the fill factor as a result of shunting effects (Mendoza-Pérez et al., 2009).

Cu $(In,Ga)Se_2$ (CIGS) chalcopyrite semiconductors such as Cu $(In)Se_2$(CIS) are direct-gap polycrystalline semiconductors, having very high optical absorption coefficients (Shah et al., 1999). PV modules based on CIS and CIGS technologies are generally considered to be quite stable and TFPV module efficiencies up to 17.5%

* Corresponding author.
E-mail address: Santiago.silvestre@upc.edu (S. Silvestre).

http://dx.doi.org/10.1016/j.solener.2016.10.030
0038-092X/

have been recently reported (Institute for Solar Energy Systems, 2016). However, it is estimated that the initial power may decrease by up to 3% before stabilization (Muñoz-García et al., 2012).

Reliability and lifetime of PV modules are two crucial issues as they are the key for overall system performance and warranty to improve the energy generated. For the case of TFPV modules, the behavior under outdoor exposure is still not fully understood and is currently object of research. A better understanding on this topic would be important for selecting the best PV technology for each specific climatic condition and for improving the reliability and performance of TFPV modules.

The objective of this work is the analysis of behavior of TFPV modules of four technologies under outdoor long term exposure in a relatively dry and sunny inland site. The period under scrutiny ranges from January 2011 to December 2015.

This paper is organized as follows. Section 2 describes the PV modules used in the study and details the monitoring system. An overview of the degradation analysis methodologies followed in the study is given in Section 3. The results and discussion are presented in Section 4. The conclusions of the study are given in Section 5.

2. PV modules and experimental setup

The four PV modules considered in this work correspond to the following thin film technologies: a-Si:H, a-Si:H/μc-Si:H, CIS and CdTe. The modules were deployed in Leganés, a city 16 km south east of Madrid (Spain, Latitude: 40°19′42″N, Longitude: 3°45′55″W, Altitude: 666 m) which lies within the metropolitan area of the latter. Leganés has a Mediterranean climate with strong continental influences and experiences pollution episodes and occasional Saharan dust intrusions as in the case of Madrid. The PV modules were mounted on an equator-facing open rack with a tilt angle of 30°. The tilt angle selected for the open rack was meant to maximize the collection of annual on-plane irradiation. The main parameters of the TMPV modules at standard test conditions (STC): G = 1000 W/m^2 AM1.5G, Tc = 25 °C, used in this study are given in Table 1.

An automatic test and measurement system was used to scan both the electrical and environmental parameters every five minutes over the whole experimental campaign. The experimental setup was intended to scan the current-voltage (*I-V*) curves of each of the four TFPV modules under study together with some environmental parameters that influence their outdoor performance. A PC-based system controlled by LabVIEW™ managed the acquisition and storage of data for their subsequent processing. Thus, *I-V* curves were traced using a PVE PVPM 2540C capacitive load so that 128 current-voltage data points were retrieved from this device in each scan. Additionally, the four PV modules could be tested sequentially using this setup, by means of a switchgear box of solid state relays driven by a multipurpose Agilent 34970A data acquisition/data logger switch unit.

Some external environmental parameters such as the horizontal and on-plane incident irradiance together with its spectral distribution, module temperature, relative humidity, ambient temperature, wind speed and barometric pressure were registered with the above data acquisition/data logger switch unit, so that these parameters were recorded simultaneously with the *I-V* curve tracing. The in-plane irradiance came from a Kipp & Zonnen CMP 21 pyranometer with directional response (up to 80° with 1000 W/m^2 beam) < 10 W^2 while the spectral irradiance distribution was measured by means of a weatherproof EKO MS-700 grating spectroradiometer whose specifications include a 10-nm spectral resolution. T thermocouples pasted to the rear side of each PV module were used to measure the module temperature, while the relative humidity and ambient temperature were measured by a Young 41382VC relative humidity/temperature probe with an accuracy at 23 °C of ±1% for relative humidity and ±0.3 °C for temperature. Finally, a Young 05305VM anemometer with an accuracy of ±0.2 m/s of wind speed and ±3 degrees of wind direction and a Vaisala barometric pressure sensor with an accuracy at +20 °C of ±0.10 hPa completed the experimental setup.

Table 3 summarizes a brief statistic of the meteorological parameters recorded for the period of measurements.

3. Methodology

The two techniques applied in this study to all modules under test, based on the analysis of the output power of the PV modules, are described in this section. The combination of these two techniques allows a good approach to understand the degradation effects and helps to identify better the degradation rates, stabilization periods and seasonal variations.

3.1. Effective peak power of the PV modules

The effective peak power of a PV module, P^*_M, at STC is given by the following equation (Martínez-Moreno et al., 2012; Nofuentes et al., 2006):

$$P^*_M = \frac{G^* P_{DC}}{G} TF \tag{1}$$

where P_{DC}, G and G^* are the DC output power of the PV module, the irradiance, and irradiance at STC respectively. *TF* is the thermal factor defined as follows:

$$TF = \frac{1}{\left[1 + \delta(T_m - T^*_m)\right]} \tag{2}$$

where T_m is the PV module temperature, $T_m{}^*$ is the module temperature under STC (25 °C), and δ is the power temperature coefficient of the PV modules.

The evaluation of P^*_M from the monitoring data set was performed after disregarding data recorded at low irradiance values. Specifically, only measurements taken at G > 700 W/m^2 were used. Thus, the shape of varying solar spectra recorded in Leganés above this irradiance threshold closely resembles that of the spectral AM1.5G reference spectrum and consequently no spectral effects are taken into account in Eq. (1). This agreement between recorded

Table 1
Main parameters of PV modules derived from the PV module manufacturers' data sheet.

Technology	PV module			
	Sharp NA-121 a-Si:H/μc-Si:H	Shell Powermax™ Ultra 80C CIS	First Solar FS-270 CdTe	Kaneka GEA 60 a-Si:H
Peak power (W)	121	80	72.5	60
Isc (A)	3.34	2.68	1.19	1.19
Voc (V)	59.2	46.6	90	92
Temperature coefficient- power δ (%/°C)	−0.24	−0.43	−0.25	−0.23
η (%)	8.5	12.7	10	6.3