Solar Energy 171 (2018) 681–691

Contents lists available at ScienceDirect

Solar Energy

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

Analysis of the behaviour of cadmium telluride and crystalline silicon photovoltaic modules deployed outdoor under humid continental climate conditions

Sofiane Kichou[a,*], Petr Wolf[a], Santiago Silvestre[b], Aissa Chouder[c]

[a] University Centre for Energy Efficient Buildings, Czech Technical University in Prague Třinecká 1024, 273 43 Buštěhrad, Czech Republic
[b] MNT Group, Electronic Engineering Department, Universitat Politécnica de Catalunya (UPC) BarcelonaTech, C/Jordi Girona 1-3, Campus Nord UPC, 08034 Barcelona, Spain
[c] Electrical Engineering Laboratory (LGE), University Mohamed Boudiaf of M'sila, BP 166, 28000, Algeria

ARTICLE INFO

Keywords:
Degradation rate (DR)
CdTe
Crystalline silicon
ANN

ABSTRACT

Photovoltaic (PV) modules are the main element responsible for the harvesting of solar radiation in PV systems. Thus, their reliability and durability are two crucial factors to take in consideration for conceiving performant PV systems and improve the energy generation. The outdoor comportment analysis of different PV module technologies has gained an increased interest in last years in order to gain insight on the degradation of their performance.

The present work studies the behaviour of three different PV modules based on cadmium telluride (CdTe), monocrystalline (c-Si) and multicrystalline silicon (mc-Si) technologies deployed outdoor in a humid continental climate. The period under scrutiny ranges from August 2015 to September 2017. Moreover, a new approach based on artificial neural network (ANN) was developed for the prediction of missing weather data.

The obtained results showed that c-Si and mc-Si PV modules presented a slight performance degradation following the seasonal changes. The worst degradation rate of −5.55%/year was obtained for CdTe PV modules. Finally, the effects of the degradation on the I-V curve were proven by an indoor characterization of CdTe PV modules.

1. Introduction

The photovoltaic (PV) market experienced a rapid growth in the last decade, in which, the compound annual growth rate of PV installations from 2010 to 2016 was 40% (ISE, 2018). In 2016, solar PV was the world's leading source of additional power generating capacity. Its annual market increased nearly 50% to at least 75 GW_p raising the global total installed PV power to 303 GW_p (REN21, 2017). This important growth is driven by several factors –PV abundance and friendly nature, the reached grid parity, the expected depletion of most fossil fuels, increase of PV module efficiency and global warming which brought together the global community at Paris climate agreement– that all have a bearing on PV market.

Monocrystalline silicon (c-Si) and multicrystalline (mc-Si) PV modules accounted for about 94% of the total annual production in 2016 while the market share of thin film (TFPV) modules has decreased to 6% compared to previous years (ISE, 2018). The decrease of the TFPV modules market share is mainly related to their degradation and the fall of the c-Si cost. The most common materials used in the mass production of TFPV modules are cadmium telluride (CdTe), amorphous silicon (a-Si) and copper indium gallium selenide (CIGS), showing an annual production in 2016 of 3.1 GW_p, 0.5 GW_p and 1.3 GW_p respectively (ISE, 2018).

TFPV modules have plenty of advantages such as lower temperature coefficient relative to c-Si and mc-Si PV modules, low quantity silicon usage as raw material, low-cost manufacturing process and could be flexible. However, the decline of the TFPV modules market could be associated to their weaknesses such as low conversion efficiency and long term reliability and durability of the performance when deployed outdoor compared to crystalline technologies (Čampa et al., 2014; Hussin et al., 2015; Jordan and Kurtz, 2013; Kahoul et al., 2017; Kichou et al., 2016a; Polverini et al., 2013; Silvestre et al., 2016a).

Various researches have been conducted to analyse the behaviour and assess the degradation rates of PV modules of different technologies deployed outdoor for long-term exposure in order to ensure a reliable and durable PV system by selecting the best technology for the

* Corresponding author.
E-mail addresses: sofiane.kichou@cvut.cz (S. Kichou), petr.wolf@cvut.cz (P. Wolf), santiago.silvestre@upc.edu (S. Silvestre).

https://doi.org/10.1016/j.solener.2018.07.028
Received 3 April 2018; Received in revised form 18 June 2018; Accepted 9 July 2018

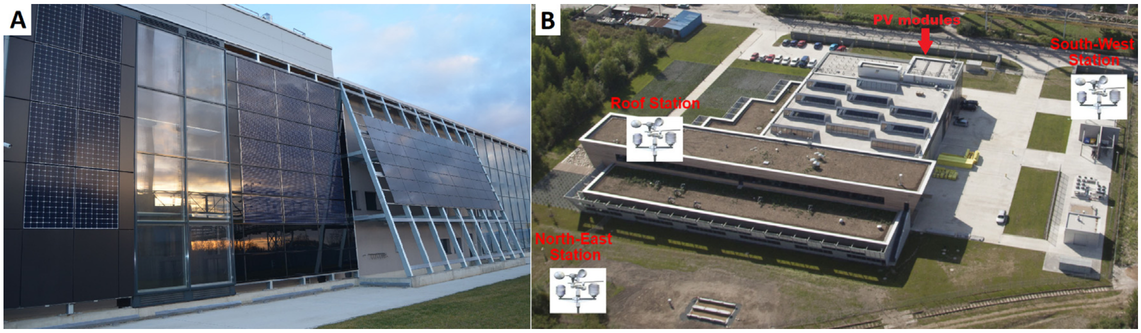

Fig. 1. (A) Analysed PV modules (c-Si: left side, mc-Si: middle and CdTe: right side), (B) UCEEB meteorological stations.

appropriate climate conditions. Performance analysis of c-Si and mc-Si PV modules which have provided electric power as PV systems for more than 20 years showed that both PV technologies exhibit stable power generation, especially in the first years of outdoor exposure (Jordan et al., 2017; Polverini et al., 2013). Various studies carried out in various locations suggested slight degradation rates around 0.7%/year and 1%/year for c-Si and mc-Si PV modules respectively (Jordan and Kurtz, 2013). It is also found that, the decrease of performances of crystalline silicon PV modules could be related to other degradation modes such as hot spots, cracked cells or solder bond failures, corrosion and encapsulant discoloration (Jordan et al., 2017; Kahoul et al., 2017; Polverini et al., 2013).

Several works carried out for the study of the behaviour of Hydrogenated amorphous silicon (a-Si:H) and micromorph (a-Si:H/µc-Si:H) TFPV modules reported that these technologies present light-induced degradation (LID) due to the Staebler-Wronski effect (SWE) (Hussin et al., 2015; Meyer and E.d, 2004; Staebler and Wronski, 1977; Yamawaki et al., 1997). The LID is found to be very important during the first months of exposure to outdoor light due to changes in photoconductivity and dark conductivity. This effect gradually tends to stabilize after certain period of exposure resulting in power loss rates ranging from 10% to 30% of the nominal power of the PV module (Hussin et al., 2015; Kichou et al., 2016a, 2016b; Silvestre et al., 2016a). In addition, thermal annealing effect which allows partially recovering the initial performance with the increase of temperature was also observed in the behaviour of amorphous and micromorph TFPV modules when deployed in hot climate conditions (Kichou et al., 2016a; Silvestre et al., 2016a; Yamawaki et al., 1997).

Cu (In,Ga)Se_2 (CIGS) chalcopyrite semiconductors such as Cu(In) Se_2(CIS) are direct bandgap polycrystalline semiconductors, and their optical absorption coefficients are considered high (Shah et al., 1999). CIGS PV module efficiency value up to 19.2% has been reported in (Green et al., 2017). In recent work published in (Silvestre et al., 2016a) it was found that the CIS PV module presented a stable comportment under long term outdoor exposure in a dry and sunny inland site. The generated initial power of CIGS PV modules has been estimated to decrease by up to 3% before stabilization (Muñoz-García et al., 2012; Silvestre et al., 2016a).

CdTe/CdS PV modules are considered as promising TFPV technology because of their lower production cost and higher cell efficiency. Their band gap value of 1.45 eV makes them well adapted to the solar radiation spectrum (Kumar and Kumar, 2017). The theoretical efficiency limit for CdTe technology is 29% (Muñoz-García et al., 2012; Shockley and Queisser, 1961), however, the reported conversion efficiencies of CdTe/CdS solar cells up to date are around 22% (Green et al., 2017; Kumar and Kumar, 2017). Outdoor long-term exposure of CdTe/CdS PV modules exhibit performance degradation due to detrimental changes in the device material. Degradation mechanisms identified in CdTe/CdS PV modules are related to light soaking effects (Gostein and Dunn, 2011), Cu diffusion from the back contact of the cells (Romeo et al., 2000) and the fill factor reduction due to shunting effects (Mendoza-Pérez et al., 2009).

Understanding the outdoor behaviour of different PV module technologies is the main aim of the present work. The behaviour of three different PV modules based on CdTe, c-Si and mc-Si technologies deployed outdoor under humid continental climate conditions for more than three years is analysed in this paper. The period under scrutiny ranges from August 2015 to September 2017. Moreover, a new approach based on artificial neural network (ANN) has been developed in order to predict missing weather data which are crucial for performing an accurate assessment of the degradation rate and the stabilization period. Finally, an indoor characterization of the CdTe PV module was carried out in order to show the effects of the degradation on the I-V curve.

The remainder of the paper is structured as follows: The description of the monitoring system as well as the PV module technologies included in the study are given in Section 2. Section 3 summarizes the methods used for the prediction of missing data, study of degradation and the evaluation of the performance of the different PV module technologies. Results obtained are shown and discussed in Section 4. Finally, general conclusions are provided in Section 5.

2. Description of the monitoring system and PV modules

The three PV module technologies analysed in this work correspond to c-Si, mc-Si and CdTe. The PV modules are installed at the University Centre for Energy Efficient Buildings (UCEEB) situated in Buštěhrad, small city 20 km northwest of Prague (Czech Republic, Latitude: 50°09′24.2″N, Longitude 14°10′10.5″E). The city of Prague has a humid continental climate, which is typified by large seasonal temperature differences, with warm to hot (and often humid) summers and cold (sometimes severely cold) winters (Chen and Chen, 2013).

PV modules under study are mounted in the South-southeast façade of the UCEEB building with an azimuth angle of 158°. The crystalline (c-Si and mc-Si) PV modules were directly integrated to the façade wall (tilt angle = 90°). However, CdTe PV modules were installed on an open rack with a tilt angle of 75° as it shown in Fig. 1.

The nameplate parameters of the PV modules under standard test conditions (STC): $G^* = 1000\ \mathrm{W/m^2}$, $T_c^* = 25\ ^\circ\mathrm{C}$, used in this study are given in Table 1. Each PV module from the c-Si or mc-Si PV arrays has its own optimizer, however, in the case of the CdTe PV array each string composed of three PV modules is connected to one optimizer. Thus, the analysis has been carried out on one c-Si PV module, one mc-Si PV module, and one string composed of three CdTe PV modules.

The measured coordinates of the maximum power point of the PV modules/string are provided by the optimizers every five minutes in the monitoring system based on SolarEdge web monitoring portal. The external environmental data such as solar irradiance on different angles of incidence, relative humidity, rainfall, wind speed and ambient temperature are given by the three meteorological stations of UCEEB. The module temperature as well as the in-plane irradiance related to each PV module technology are measured every second.