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Performance loss rate of twelve photovoltaic technologies under field conditions using statistical techniques

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Abstract

This paper presents a comparison of the annual performance loss rate (PLR) of twelve different grid-connected photovoltaic (PV) technologies based on outdoor field measurements. The annual DC performance loss rates of the installed PV technologies are obtained by using linear regression and classical series decomposition applied on the monthly DC performance ratio (PR) time series over five years (June 2006–June 2011). The PLR values obtained over the five-year period differ by up to 0.65% per year depending on the selection of the applied analysis method. The choice of the analysis technique affects the resulting PLR value but not the performance loss trend exhibited over the evaluation period for most technologies. Finally, there is evidence that the duration of the data used in the analysis affects the results as the PLR pattern exhibited by the crystalline-silicon (c-Si) and copper indium gallium diselenide (CIGS) technologies demonstrates a gradual convergence towards a steady state value over the five-year period, whereas more time is required to reach steady state for the thin-film technologies of amorphous silicon (a-Si) and cadmium telluride (CdTe).

Keywords: Classical series decomposition; Crystalline silicon; Linear regression; Performance loss rate

1. Introduction

As the penetration of photovoltaics increases and new technologies appear on the market, important questions regarding the lifetime power output and degradation of the different technologies arise. These factors are crucial for investment decisions, in an attempt to minimise the associated risk. Unfortunately, the prediction of degradation is a difficult task as it is required to wait until the end of the life of the modules to establish credible results. Degradation associated with photovoltaics is usually the result of packaging material degradation, loss of adhesion, cell/module interconnect and semiconductor degradation as well as degradation caused by moisture intrusion (Quintana et al., 2002).

Most manufacturers provide performance warranties of at least 20 years, with maximum loss of no more than 20% of the rated power. End customers or investors must be aware, however, that both the photovoltaic (PV) technology and the location of installation affect the degradation rates (Jordan et al., 2010). For this reason the performance warranties provided by manufacturers may not always be valid, especially for new PV technologies. Continuous outdoor degradation studies are necessary at various locations worldwide for gaining deeper insight and more credible results on long-term degradation of PV modules and systems. Moreover, an obvious but yet unsolved problem is

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how apparent degradation rates vary with the analysis technique used.

Degradation investigations using indoor methodologies were based on the acquisition of current–voltage (*I–V*) characteristics and power at Standard Test Conditions (STC) of 25 °C cell temperature, 1000 W m^{-2} plane of module irradiance and AM 1.5G spectrum (61215:2005, 2005), or on the standardised re-normalisation of the *I–V* data to STC for comparisons over long time periods and between different locations of test sites. The electrical characteristics of PV modules are initially measured at STC, with the modules then exposed either indoors through accelerated procedures (Osterwald et al., 2002; Carr and Pryor, 2004; Ikisawa et al., 1998), or outdoors (Osterwald et al., 2002; Carr and Pryor, 2004; Ikisawa et al., 1998; Jahn et al., 2012; Schweiger et al., 2011; Akhmad et al., 1997). For each investigated PV cell or module, the *I–V* characteristics are regularly acquired using solar simulators, while the current, voltage or power differences from the initial value provide indications of the degradation rates at successive time periods.

Monitoring the long-term performance of PV in outdoor setups was performed in two fundamentally different ways: On the one hand, dedicated module test sites or small PV systems were operated outdoors and carefully characterised over time periods of months to years. For quantitatively evaluating long-term performance, these test sites usually operate the PV modules at their maximum power point (MPP) and perform *I–V* scans at regular time intervals (Jordan et al., 2010; Osterwald et al., 2002; Carr and Pryor, 2004; Ikisawa et al., 1998; Jahn et al., 2012; Schweiger et al., 2011; Akhmad et al., 1997), e.g. every 10 min (Jahn et al., 2012), while normal MPP operation is briefly interrupted. On the other hand, continuously recorded environmental and electrical data of regular grid-connected PV systems serve as a basis to quantify long-term performance degradation (Jordan et al., 2010; Schweiger et al., 2011; Pulver et al., 2010; Konishi et al., 2012). Both approaches return complementary information according to their specific strengths and weaknesses (Ueda et al., 2010).

Recording of *I–V* characteristics and translating or normalizing those to standard conditions is generally limited to single module investigations, whereas continuous energy yield, power or performance ratio (PR) data are available for regular PV systems at comparatively low effort, though often with limited precision. In addition to recording the *I–V* data of the modules, precise and long-term stable monitoring of module temperature, irradiation and spectrum are mandatory to re-normalize *I–V* data from indoor flashing or outdoor *I-V* scans to STC. Moreover, long-term stable reference modules are needed, which may be difficult to assure for assessments over several decades (Dunlop et al., 2005).

The European Framework-6 Integrated Project PERFORMANCE (Herrmann et al., 2010; Stellbogen et al., 2010; Domine et al., 2010; Mohring et al., 2010), the NREL outdoor test facility (Jordan et al., 2010; Osterwald et al., 2002; Jordan and Kurtz, 2010; Osterwald et al., 2006; Osterwald, 1986), and the joint International Energy Agency (IEA) Photovoltaic Power Systems Programme (PVPS) task 13 (Jahn et al., 2012; International Energy Agency, 2013) made substantial efforts to develop and harmonize procedures to measure and track PV performance, as well as ensuring their usefulness and reliability for standard and innovative types of PV modules. Recent issues discussed include sweep time (Virtuani et al., 2011), temperature (Mohring et al., 2010; Kurtz et al., 2011), irradiance and spectral dependencies (Schweiger et al., 2011; Gottschalg et al., 2005a; Bliss et al., 2010), as well as error propagation through the necessary normalisation steps (Domine et al., 2010; Whitfield and Osterwald, 2001).

In contrast to single module degradation studies, quantitative evaluation of the degradation of grid-connected outdoor PV systems must take into account additional factors which affect the power output of a PV system, such as seasonal performance variations (Pulver et al., 2010; Jordan and Kurtz, 2010; Makrides et al., 2013a; Gottschalg et al., 2005b), soiling (Qasem et al., 2012), shading, increasing electrical mismatch, faults and failures of modules or other system components. At a system level, it is therefore appropriate to more generally refer to ‘performance loss’ which implies the overall gradual loss in PR of the PV system, rather than just to degradation of the PV modules.

Moreover, other factors affect the experimentally deduced long-term performance loss rate (PLR) such as the analysis technique employed and assumptions made about the PLR behaviour which is commonly considered linear in time. The duration of the data used in the analysis is another important factor that affects the results, and it is expected that the longer the monitoring period the more credible the predictions will be, as the results will converge to their long-term values.

Common selections of data-sets for comparing the degradation of different PV technologies installed outdoors are either (a) the performance ratio which is a system performance index that indicates the overall effect of losses on the array’s rated output due to array temperature, incomplete utilisation of the irradiation and system component inefficiencies or failures (61724:1998(E), 1998), or (b) the maximum power normalised to Photovoltaics for Utility Scale Applications (PVUSA) Test Conditions (PTC) of solar irradiance of 1000 W/m^2, air temperature of 20 °C and wind speed of 1 m/s. Statistical techniques are then applied to time series of these data-sets to obtain the trend and hence the degradation rate (Osterwald et al., 2002; Jordan and Kurtz, 2010; Osterwald et al., 2006; Adelstein and Sekulic, 2005).

This paper investigates the performance loss rates of twelve grid-connected PV systems of different technologies operated in Nicosia, Cyprus, since June 2006. Keeping the above mentioned challenges and limitations of the different approaches for determining PLR in mind, we follow the methodology proposed by Jordan and Kurtz (2010). More