Effect of moisture condensation on long-term reliability of crystalline silicon photovoltaic modules

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ABSTRACT

Moisture condensation (MC) can occur in photovoltaic (PV) modules in hot and humid climates, and the resulting water droplets can cause more areas of corrosion. Therefore, in this study, MC history of PV modules exposed to Miami climate (FL, USA) has been derived employing corresponding meteorological data. The duration of MC versus temperature of PV module (T_{module}) was calculated over 1 year. Furthermore, five types of accelerated tests were conducted to develop a MC-induced degradation prediction model. The thermal activation energy, 0.4524 eV, was calculated. The Brunauer–Emmett–Teller (BET) model was used to predict the degradation rate. The accumulated degradation rate of a PV module exposed to the accelerated condition of MC was 1.45 times greater than that of damp heat (DH). The effect of encapsulant materials on the frequency of MC and accumulated degradation rate over 1 year were calculated in the Miami climate.

1. Introduction

Moisture can diffuse into photovoltaic (PV) modules through their breathable back-sheets or their ethylene vinyl acetate (EVA) sheets [1]. When in service in hot and humid climates, the PV module will experience changes in moisture content, the overall history of which is correlated with degradation of the module's performance [1]. If moisture begins to penetrate through the polymer to the solar cell, it can weaken the interfacial adhesive bonds, resulting in delamination and increased numbers of ingress paths, loss of passivation, electrochemical corrosion, and, ultimately, device failure [2]. Moisture in a PV module can form small water droplets at the interface between the EVA sheet and the solar cell under specific conditions [1]. This water in the PV module will create more areas of corrosion. Water in PV module can accelerate the corrosion process. Corrosion affects the resistance in solder joints, cell metallization, and cell-interconnect bus bars, and resistances in junction-box terminations [3], and it indicates a reduction in the power generation produced by the cell, which ultimately depreciates the performance of the PV module. Therefore, under-standing moisture condensation (MC) is important for ensuring the long-term reliability of a PV module. The International Electro-technical Commission (IEC) 61215 test defines the damp-heat (DH) test, especially section 10.13, "Damp-heat test" (85 °C, 85% rh for 1000 h with less than 5% degradation). Therefore, Laronde et al. [4] studied the degradation of PV module subjected to corrosion due to damp heat testing. However, they did not consider the moisture condensation (MC) effects on the degradation. The other researchers [5–8] have also studied the reliability of PV modules based on IEC 61215. However, the research focused on the degradation mode and degradation of electrical characteristics in DH condition. Only a few of them focused on the lifetime under real-time field conditions. Few have focused on the MC-induced degradation rate in actual field conditions. Correctly predicting the degradation rate requires both accelerated testing and knowledge of the field degradation mechanisms.

This paper therefore documents a model for MC-induced degradation and the resultant module degradation. This allows prediction of real-world MC-induced degradation of PV modules and enables the computation of AF for the MC test.

In this research, thermal activation energy of degradation and condensation parameter was determined with five kinds of accelerated tests (ATs). MC-induced accumulated degradation rate was calculated with Miami (FL, USA) climate. Using the solubility of three sorts of encapsulant materials, the effects of the solubility on the MC of PV modules and accumulated degradation rate were determined. The AF of the MC test was determined.

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2. Degradation model and accumulated degradation rate

Degradation rate data can be postulated with an empirical kinetic model by assuming that the rate of degradation is proportional to the concentration of water in PV modules, and that the rate constant has Arrhenius temperature dependence. Klinger [9] showed that failure mechanisms associated with the effects of humidity on plastic packaged devices, and using the Brunauer–Emmett–Teller (BET) model, they derive a relation between surface concentration of water and relative humidity. This is expressed as

$$R_D = k_0 \exp\left(\frac{-E_a}{kT}\right)\left[\frac{\text{rh}}{1 - \text{rh} + \varepsilon}\right] \tag{1}$$

where R_D is the degradation rate, k_0 is a rate constant, E_a is the thermal activation energy of degradation, k is the Boltzmann constant, and rh is the relative humidity in a PV module. The $1 - \text{rh}$ term in the denominator makes this equation nonlinear in rh as rh approaches 1. To prevent numerical problems of infinite rate at rh = 1.0, we add the small constant ε to the denominator of the bracketed term.

The BET equation can be represented on a logarithmic scale by a straight line, using the following equation:

$$Ln(R_D) - Ln\left(\frac{\text{rh}}{1 - \text{rh} + \varepsilon}\right) = Ln(K_0) - \frac{E_a}{kT} \tag{2}$$

A plot of the left-hand-side of Eq. (2) versus $1/T$ (K) gives an Arrhenius plot with slope E_a/k and intercept $Ln(k_0)$. The BET equation indicates that the cell degradation is dependent on the thermal activation energy and relative humidity significantly.

The relative humidity in PV modules can be evaluated as using the following equation [10]:

$$\text{rh} = \frac{C_E}{S_E}$$
$$= \text{rh}_{ambient}\left[1 - \gamma \exp\left(\frac{-t}{t_c}\right)\right]\left[\gamma = 1 - \frac{C_E(0)}{S_E \cdot \text{rh}_{ambient}}, t_c = \frac{S_E L_E}{\text{WVTR}_{max}}\right] \tag{3}$$

Here, C_E is the concentration (g/cm^3) of water in the encapsulant, S_E is the solubility of water in the encapsulant (g/cm^3) at a given temperature, $\text{rh}_{ambient}$ is the relative humidity of the air, L_E is the encapsulant thickness, WVTR_{max} is the water vapor transmission rate $(g/m^2$ per day) of the back-sheet at the current temperature and a 100% rh differential, and γ is the measure of how close the initial condition is to equilibrium ($\gamma = 1$ if initially dry). Firstly, S_E can be measured in simple water-uptake experiments. Secondly, the WVTR_{max} through the film can be measured using a WVTR instrument (Permatran-W®3/33, Mocon, Minneapolis, MN, USA).

The accumulated degradation rate based on the temperature and rh can be calculated by summing the hourly degradation amounts over the time history, as given in the following equation:

$$\sum R_D(t) = \sum \left\{ k_0 \exp\left(\frac{-E_a}{kT}\right)\left[\frac{\text{rh}}{1 - \text{rh} + \varepsilon}\right]\right\} \cdot t \tag{4}$$

3. Experiments

3.1. Solubility of water in the encapsulant and water vapor transmission rate of the back-sheet

EVA consisting of 67 wt% ethylene and 33 wt% vinyl acetate was used in this study. This EVA was cured according to the manufacturer's specifications. Five samples of 5 cm in length, 3 cm in width, and 0.045 cm in thickness were made for the measurements of the saturated moisture concentrations under various conditions. The samples were baked at 85 °C for 24 h to remove any initial mois-

ture, and dry samples were placed in a temperature and humidity (T/H) chamber (Hygros340C, ACS Co., Massa Martaba, Italy). The T/H chamber was programmed to three sets of conditions for testing: 85 °C–85% rh, 65 °C–85% rh, and 45 °C–85% rh. The weight gain was periodically monitored with a high-resolution analytical balance until saturation was reached.

The solubility can be fit to the following equation [11]:

$$S = S_0 \exp\left(\frac{E_s}{kT}\right) \tag{5}$$

where S_0 is the pre-exponential factor (g/cm^3), E_s is the activation energy (eV), T is the temperature (°K).

The WVTR_{max} through the film was measured by first drying the back-sheet in a Mocon test cell by blowing dry nitrogen separately over the top and bottom of the film until moisture was no longer detected. Then, liquid water was injected into the bottom chamber so that the WVTR_{max} could be measured with one side of the back-sheet exposed to saturated nitrogen and the other to a dry nitrogen purge. WVTR_{max} was measured at 25 °C, 37.8 °C, and 50 °C. Assuming the Arrhenius equation between WVTR_{max} and temperature, WVTR_{max} can be described by the following equation:

$$\text{WVTR}_{max} = A \exp\left(\frac{E_w}{kT}\right) \tag{6}$$

where E_w is the activation energy (eV), k is the Boltzmann constant, and T is temperature (K).

3.2. Accelerated degradation tests

Six-in. (15.24 cm) monocrystalline Si solar cells were used in this study. The typical characteristics of the cells at a light intensity of one sun were approximately as follows: open-circuit voltage (V_{oc}), 0.62 V; short-circuit current (I_{sc}), 370 mA/cm^2; and conversion efficiency, 18.0%.

Copper ribbon wire plated with 62Sn36Pb2Ag solder was used to interconnect cells. The ribbon wires were 0.15 mm in thickness and 2.0 mm in width. These cells were laminated respectively with low-iron glass of 3.2 mm in thickness and 180 mm in length and width, an EVA sheet of 0.35 mm in thickness, and Tedlar/PET/Tedlar (TPT) back-sheets of 0.35 mm in thickness, as shown in Fig. 1. The solar cells were laminated with EVA by heating them up to 150 °C for 12 min. After encapsulation, the samples were divided into five groups and exposed to accelerated stresses, as shown in Table 1. The MC test was designed so that MC would occur during each cycle, as shown in Fig. 2. The MC (NT1200S, ETAC Co., Tokyo,
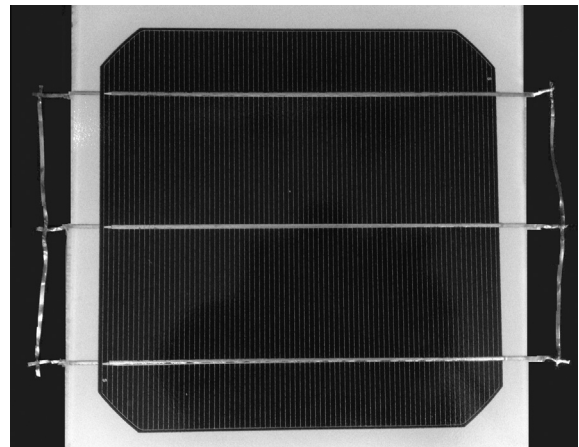

Fig. 1. PV module with a 6 in. (15.24 cm) single cell for accelerated degradation tests.