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Influences of environmental factors on Si-based photovoltaic modules after longtime outdoor exposure by multiple regression analysis

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ABSTRACT

Degradation of Si-based photovoltaic (PV) modules after longtime outdoor exposure is quantitatively investigated using multiple regression analysis. Performance ratios (PR) of the PV modules are primarily influenced not only by irradiation intensity on tilted surface (IrrT), average photon energy (APE), and module temperature (T_{mod}) but also by angle of incidence (AOI). It is demonstrated that multiple regression analysis allows us to independently and quantitatively identify how each IrrT, APE, T_{mod}, or AOI (environmental factors) relates to the PR (outcome), thus leading to the understanding of impacts of environmental factors on physical properties of the Si-based PV modules. After longtime outdoor exposure, the influences of IrrT, APE, and AOI on the PR of multi-crystalline (mc-Si) and single-crystalline (c-Si) modules are severely increased, resulting from the decay of interconnection and discoloration of ethylene vinyl acetate films. The dependences of environmental factors on the PR of hydrogenated amorphous (a-Si) modules do not change as much as those on PR of mc-Si and c-Si modules do because of differences in the module structures.

1. Introduction

Sustainable energy has attracted much attention because it can solve the energy problem by providing a clean and safe energy source [1,2]. One of the most promising technologies for the sustainable energy is photovoltaic (PV), a process of converting light energy into electricity. Presently, silicon (Si)-based PV modules such as single-crystalline Si (sc-Si), multi-crystalline Si (mc-Si), and hydrogenated amorphous Si (a-Si) PV modules are playing a vital role in PV market. It is important to evaluate the performance of PV modules for the credibility of the technology. There are two methods to evaluate the performance of PV modules. The first one is power rating, defined by energy conversion efficiency and the total area of PV modules. For the power rating, the efficiency of PV modules is measured under the condition, which is called the standard test condition (STC), namely incident solar irradiance of 1 kW/m^2, AM 1.5 G solar spectrum distribution, and module temperature (T_{mod}) of 25 °C [3,4]. Nevertheless, the actual outdoor conditions hardly meet STC. Therefore, the energy rating is used as the other method to evaluate the performance of PV module, giving an actual electrical energy generated by PV modules. It consists of measuring module characteristics, and sets of environmental factors, and estimating module performance under given conditions [5]. The energy rating is more complicated than the power rating since the former requires actual data for PV modules and environmental data, at which the modules are installed. The understanding of the relationship between the outdoor performance of PV modules and environmental factors is therefore essential for the energy rating [6]. It has been reported that the performance of PV modules is significantly influenced by environmental factors, namely irradiation intensity on tilted surface (IrrT), average photon energy (APE), and T_{mod} [6–12]. The performance of the PV module generally degrades as a result of outdoor exposure over time. It was consequently reported that output energies of Si-based PV modules were evaluated using the performance ratio (PR) contour map as a function of T_{mod} and APE with the consideration of their time-related degradation [13]. However, it will be exhibited that angle of incident (AOI), deemed as another environmental factor, strongly impacts the performance of PV modules. In this work, it is therefore intriguing to separately and quantitatively analyze how each environmental factor (IrrT, AOI, APE, or T_{mod}) affects PR and discuss degradation mechanisms. The effects of the environmental factors on PR are investigated over time for different kinds of PV modules.

In this work, multiple regression analysis, a statistic tool, was

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utilized to calculate standard partial regression coefficients (SPRC), which relates to PR and the environmental factors (as a dependent variable and independent variables, respectively), and to quantitatively analyze how each environmental factor independently affects PR of Si-based PV modules (sc-Si, mc-Si, and a-Si modules) using long-term data. The degradation mechanisms were moreover discussed by observing changes of SPRC over the years.

2. Experimental procedure

2.1. Si-based PV modules and measurement setup

In August 1998, sc-Si and mc-Si PV modules were installed with capacities of 5.16 and 5.076 kW, respectively. In addition, two a-Si PV systems were placed, where the first one, named a-Si_1 module, with capacity of 3.07 kW and the other, called a-Si_2 module, with capacity of 1.35 kW were installed in August 1998 and July 2009, respectively. All PV modules facing due south with a tilt angle of 15.3° are located at Kusatsu-city, Shiga-prefecture in Japan (north latitude 34°58′, and east longitude 135°57′). In this work, the environmental factors at the installed site were obtained as follows. T_{mod} is measured using the thermocouple attached to the back side of the PV modules. The IrrT is observed by pyranometer (MS62, EKO) recorded every 1 min, which was installed at the same condition as the PV modules.

A value of APE is obtained and defined as the integrated irradiance divided by the integrated photon flux density, as demonstrated:

$$APE_{x-y}(eV) = \frac{\int_x^y E(\lambda)\mathrm{d}\lambda}{q\int_x^y \Phi(\lambda)\mathrm{d}\lambda} \quad \text{and} \quad \Phi(\lambda) = \frac{E(\lambda)}{E_{photon}(\lambda)} \qquad (1)$$

where q (C) is electronic charge, E (W m^{-2} nm^{-1}) is the spectral irradiance, Φ (s^{-1} m^{-2} nm^{-1}) is the spectral photon flux density, and E_{photon} (eV) is the energy of single photon with each wavelength [12,14–16]. Because of the limitation of the measuring instrument, x and y in Equation (1) are set to be 350 and 1050 nm, respectively. The APE is utilized as an index to indicate solar spectral irradiance distribution, where its value of the AM 1.5 global (AM 1.5G) reference spectrum calculated in the wavelength range of 350–1050 nm is 1.88 eV [12,16,17].

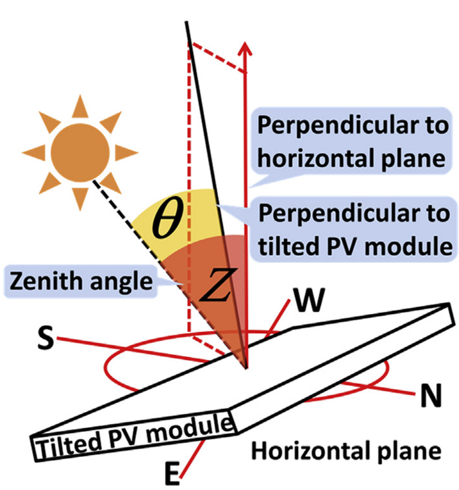

Fig. 1. Determination of angle of incidence (AOI), which is θ between the solar beam and axis perpendicular to tilted PV module.

In addition, θ is the angle of incident (AOI), which is the angle between the solar beam and axis perpendicular to tilted PV module, as shown in Fig. 1. Since air mass is defined by 1/cos (zenith angle) or sec (zenith angle), AOI is considered in term of sec (θ). Performance ratio (PR) is additionally used as an indicator of the outdoor PV module performance. PR, which is a ratio of the actual and theoretically energy output, indicates the PV module efficiency normalized by the irradiance intensity, and it is defined as the actual output energy divided by the nominal output energy calculated from the PV module performance under STC [18]:

$$PR(\%) = \frac{E_{load}/P_{\max}}{H_A/G_S} \times 100 \qquad (2)$$

where E_{load} (kWh) is output energy, $P_{\max}$ (kW) is rated power, H_A (kWh/m^2) is integrated tilt irradiance, and G_S is standard irradiance of 1.0 kW/m^2. The contour graph of PR as functions of APE and T_{mod} was made, where the process was discussed in our previous work [6].

2.2. Quantification of impacts of environmental factors on Si-based PV modules

PR of the PV module is affected by environmental factors (IrrT, AOI, APE, and T_{mod}). To quantify the influence of each environmental factor on the PR, multiple regression analysis is utilized in this work. The multiple regression analysis is a statistic tool, enabling us to investigate how multiple independent variables are related to a dependent variable [19]. If there is one independent variable, the method is called least square regressing. In this work, as IrrT, AOI, APE, and T_{mod} affect PR, they are considered as multiple independent variables (predictors), and the PR is deemed a dependent variable (outcome) under multiple regression analysis. According to multiple regression analysis, PR is expressed in a term of IrrT, AOI, APE, and T_{mod}, as presented:

$$PR = a \times IrrT + b \times \sec(\theta) + c \times APE + d \times T_{\mathrm{mod}} \qquad (3)$$

where a, b, c, and d, which are called standardized partial regression coefficients (SPRC), are slopes of the regression lines between each environmental factor (IrrT, sec (θ), APE, or T_{mod}) and the PR value, respectively. The a, b, c, and d demonstrate the correlations between environmental factors (IrrT, sec (θ), APE, and T_{mod}) and PR, respectively. For instance, if the SPRC (a, b, c, or d) is +1 or −1, it implies that PR is increased by +1 unit or decreased by −1 unit, with the increase in the IrrT, sec (θ), APE, or T_{mod} by +1 unit. If the SPRC (a, b, c, or d) is zero, PR is independent from the IrrT, sec (θ), APE, or T_{mod}. It is noted that AOI is expressed in a term of sec (θ) under the multiple regression analysis in order to be the same format as air mass defined by sec (zenith angle). All statistic calculations in this work were performed using R programming language, which is a free software environment for statistical computing and graphics, which are developed by Ross Ihaka and Robert Gentleman at the University of Auckland [20]. When we have quantitatively identified how IrrT, AOI, APE, and T_{mod} (predictors) relate to PR (outcome) by observing the SPRC (a, b, c, or d), we can estimate the PR based on IrrT, AOI, APE, and T_{mod}. It will be exhibited that the changes of SPRC over time for PV modules allow us to understand their physical properties relating to IrrT, AOI, APE, and T_{mod}, which is useful for the development of PV modules for longevity in the future.