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Field performance and degradation rates of different types of photovoltaic modules: A case study in Thailand

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ABSTRACT

This paper provides field performance and degradation information of Si wafer-based and thin film photovoltaic (PV) modules in a tropical region. We address the importance of temperature coefficient (TC) and the significance of the degradation rate (DR) of the modules operating under tropical climate. The PV modules with TC for power below −0.31%/°C have a great advantage in terms of energy yield. The DRs of various PV module types are widely different, ranging from 0.5 to 4.9%/year, which greatly affect their long-term performance. This paper also presents the degradation behavior of electrical characteristics such as I–V curve, open circuit voltage (V_{oc}), short circuit current (I_{sc}), fill factor (FF) and maximum power output (P_{max}) for each PV type. The DRs of the field-test PV modules in Thailand are first reported in this study. The level of degradation we found in this study suggests a reduction of output power 10–50% over a twenty-five year lifetime, possibly increasing the levelized cost of electricity by up to double cost. The database of this case study is informative and useful for a further study on performance degradation in the tropics and a comparison study with other environmental conditions.

1. Introduction

Environmental conditions strongly influence the performance and reliability of photovoltaic (PV) modules [1,2]. It is important to analyze the field performance of PV modules to estimate their energy yield and degradation rates under specific climatological circumstances. Receiving relatively high average irradiance throughout the year, low latitude regions, 25°N–25°S, have high potential for solar energy usage [3]. Owing to abundant solar energy resources and policy support by its government, Thailand is one of the countries where the growth of solar farms is rapid and it is still expected to be one of the emerging PV markets. Since Thailand locates in the tropics where an average temperature and humidity are relatively high throughout the year, temperature loss of the PV modules is estimated to be high. Moreover, hot and humid conditions in this region have driven the degradation of PV modules more rapidly and severely than other environmental conditions [4]. There is a report on degradation rate (DR) of PV modules in tropical environment [5]. However, it presented only the results of Si wafer-based modules, mono and multi c-Si types. There was no variation in terms of PV technology. Our previous work presented the actual performance and DRs of five different PV technologies including thin film Si, copper indium gallium selenide (CIGS) as well as hetero-junction Si types which had been operating under Thailand's climate for 2 years [6]. In our previous work, the outlier or stability filter for irradiance still had not been applied to eliminate uncertain data. In the data filtering process, the limits of irradiance were simply set at 0 W/m^2 for the lower limit and 1200 W/m^2 for the upper limit. Because data filtering plays a very important role in calculating DRs [7], in this paper, we have taken it into account to achieve more accurate DRs. We also considered the third-year data in estimating the DRs of various types of the PV modules. Furthermore, changes in I–V curves and PV parameters such as open circuit voltage (V_{oc}), short circuit current (I_{sc}), and fill

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factor (FF) after a few years of operation have been analyzed. Long-term impacts of module performance degradation also have been discussed in terms of levelized cost of electricity (LCOE).

2. Experimental details

2.1. PV modules and system description

The 10 kWp grid-connected PV system consisting of five different PV modules has been installed at Thailand Science Park (14° 4′N, 100° 36′E) in the year 2012, providing the opportunity for PV evaluation under Thailand's climate. There are four types of PV modules; (1) multi c-Si, (2) hetero-junction Si, (3) thin film Si, and (4) CIGS, in the systems (about 2 kW each). All the PV modules are commercial products from five different manufacturers. The thin film Si modules in this study are multi-junction amorphous silicon (a-Si)/microcrystalline Si (μc-Si) structure from two different manufacturers. Note that these two thin film Si modules possess different temperature coefficient (TC) values. Even though the rated power of each array is not exactly the same, their energy output is normalized for a comparison at the same capacity. This PV system uses only one power conditioner containing maximum power point tracking (MPPT) separately in every array. The PV modules are mounted on the roof at optimal inclination for annual yield, 14° facing South. As shown in Fig. 1, the PV arrays are arranged side by side in parallel to exposure under nearly uniform conditions. There are (from left to right): CIGS, thin film Si 2, hetero-junction Si, multi c-Si, and thin film Si 1 arrays. The facility is equipped with meteorological instruments connecting to a data acquisition system. The measured parameters include in-plane irradiance (G_i), ambient temperature (T_A) and module temperature (T_M). Two pyranometers have been installed at the same setting angle of 14°; one at the bottom of the Thin film Si 2 array (G1) and another one at the top of the same array (G2), as indicated in Fig. 1. Electrical parameters such as the current and voltage at MPP are collected every 5 min, while I–V curves of the PV arrays are also obtained through an I–V tracer equipment at 5 min intervals. In this study, we used the measured DC-side electrical parameters, for example, V_{oc}, I_{sc} and maximum power output (P_{max}), of each array to evaluate the performance of each PV type. The wind speed is not measured in the monitoring setup because the average wind speed in Thailand is moderate to rather low, usually not above 3 m/s [8]. Note that this test site operates under partial shading of a building in the period of June–July at around 9 AM-10:30 AM. All PV arrays face the partial shading in parallel at the same time. We realize that the partial shading conditions have negative effects on the electrical characteristics of PV power generation and the amount of losses due to the shading also depends on the configuration of each PV array. However, we assumed that the partial shading provided equivalent effects on any PV array and its effects were not significant since the irradiance loss due to shading was estimated to be only about 0.27 kW h/m^2/day, which corresponded to 6–7% loss of daily irradiance during that season (rainy season).

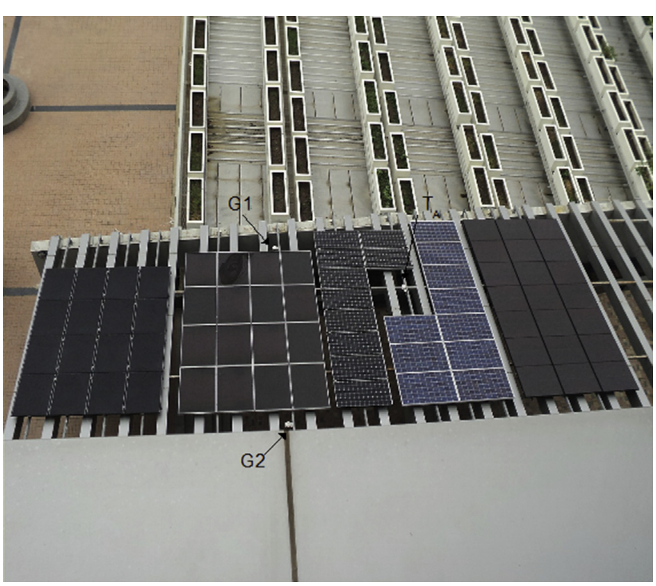

Fig. 1. A 10 kW grid-connected PV system consisting of five different PV types installed at Thailand Science Park.

2.2. Methods of analysis

In order to compare actual production of the various kinds of PV modules, we use performance ratio (PR) as a normalized performance indicator.

$$PR = Y_A/Y_r \quad (1)$$

$$Y_A = E/P_{STC}(\text{kWh/kW}) \text{ or } (\text{hours}) \quad (2)$$

$$Y_r = H/G(\text{hours}) \quad (3)$$

where Y_A is array yield, Y_r is reference yield, E is array output energy, P_{STC} is nominal array power, H is total in-plane insolation and G is in-plane irradiance at STC. The Y_r can be obtained by dividing the relevant energy by in-plane irradiance at STC, G = 1 kW/m^2. Array yield is obtained by dividing the relevant energy by the nominal array power. Here, the PR indicates the effect of losses on the nominal power of arrays which are mainly due to array temperature and incomplete utilization of irradiance. Monthly PR is presented by irradiance weighted average performance ratio (PR_{WA}) as the following equation [9]:

$$PR_{WA} = \frac{\sum H_i * PR}{\sum H_i} \quad (4)$$

where H_i denotes the total insolation received during the period where PR was evaluated. Here, H_i is assigned as weight based on the PR's relative importance. The degradation analysis was done by using the PR of each array (each PV type), with compensation of irradiance and temperature [10]. The temperature-corrected PV array output (E_{AT}) was calculated by using the following formula:

$$E_{AT} = E_i/\{1 + \gamma * (T_M - 25)\} \quad (5)$$

where E_i is measured array output, γ is a temperature coefficient for power (%/°C), and T_M denotes module temperature [10]. Then, the E_{AT} was used to calculate the array yield (Y_A) and derive the PR with temperature compensation by using Equations (2) and (1), respectively. The degradation rates were derived through the simple linear regression model [11]. The time interval in which the performance metric is evaluated is given in monthly increment. Filtering conditions for the irradiance were as follows. The upper limit for G_i was set at 1200 W/m^2 and the lower limit was varied between 0 and 800 W/m^2. The G_i which changed more than 20 W/m^2/min was eliminated; this is the stability filter process. Moreover, outlier filter, which used the ratio between temperature corrected DC output and the in-plane solar irradiance as an indicator, was conducted to remove extremely variable days and partial-shading conditions [7]. Note that the partial-shading data was not taken into account in this study. The impact of data filtering – the stability