Renewable Energy 102 (2017) 199–204

Contents lists available at ScienceDirect

Renewable Energy

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

Degradation analysis of photovoltaic modules under tropical climatic conditions and its impacts on LCOE

Amornrat Limmanee [a, *], Sasiwimon Songtrai [a], Nuttakarn Udomdachanut [a], Songpakit Kaewniyompanit [b], Yukinobu Sato [c], Masaki Nakaishi [c], Songkiate Kittisontirak [a], Kobsak Sriprapha [a], Yukitaka Sakamoto [c]

[a] Solar Energy Technology Laboratory, NECTEC, National Science and Technology Development Agency (NSTDA), 112 Thailand Science Park, Thanon Phahonyothin, Tambon Klong Nueng, Amphoe Klong Luang, Pathum Thani, 12120, Thailand

[b] Thai Tabuchi Electric Co., Ltd., 88 Moo 5, Bangna-Trad Highway, Bangsamuk, Bangpakong, Chachoengsao, 24180, Thailand

[c] Tabuchi Electric Co., Ltd., Nissay Shin-osaka Bldg. 10F, 3-4-30 Miyahara, Yodogawa-ku, Osaka, 532-0003, Japan

A R T I C L E I N F O

Article history:
Received 5 September 2016
Received in revised form
17 October 2016
Accepted 22 October 2016
Available online 24 October 2016

Keywords:
Photovoltaic
Degradation rate
Tropics
Climate effect
LCOE

A B S T R A C T

After 4 years of operation at Thailand Science Park, degradation analysis of 73 photovoltaic (PV) modules of four different PV technologies; multi c-Si, hetero-junction Si, micromorph and CIGS, has been carried out. The degradation rate (DR) of individual modules and array performance are presented. It was found that some micromorph (thin film Si 1) modules seriously degraded and were in failure mode, resulting in a severe degradation of the thin Si 1 array's performance. The average DR of other PV modules was found to range between 0.3 and 1.9%/year. The standard deviation (SD) of data from modules in the same array indicates the level of mismatch, which plays a role in evaluating array's performance. The levelized cost of electricity (LCOE) in this study was found to range between 4.1 and 14 baht/kWh, depending on PV technology and its DR. The results suggest that, without any reduction of costs, the LCOE of solar PV electricity in Thailand would possibly be comparable with the retail price when the present PV technology has DR of about 0.2%/year or lower. The database we obtained is informative and useful for a further study on PV reliability and cost of solar PV electricity in the tropics.

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1. Introduction

The cost of generating electricity from renewable energy is generally presented and compared by use of levelized cost electricity (LCOE) [1]. The LCOE is calculated by accounting all costs of a system throughout its lifetime, which are then divided by sum of electrical energy produced over its lifetime. Power output of solar photovoltaic (PV) systems strongly depends on available solar radiation, which varies with location. System performance and degradation rate (DR) of PV systems are also significant contributors to the variation in LCOE [2]. Real-world performance databases are thus necessary in estimating LCOE for the specific location since energy yield and degradation behavior of PV modules and systems are greatly influenced by environmental and climatic conditions [3]. In recent years, reliability of PV modules in high-solar-potential regions, i.e. desert, arid and tropical zones, has been intensively investigated [4–8]. Hot and humid conditions in the tropics have been reported to drive the degradation of PV modules more rapidly and severely than other environmental conditions [9]. Several reports suggest a possibility that PV modules, even Si wafer based modules, could not satisfy the 25-year warranty in the tropics [7–10]. Most of the attention had been focused on the degradation behavior and operational lifetime of different types of PV modules from various manufactures. However, impacts of degradation on LCOE of solar PV in this region still had not been reported. Our previous work presented the actual performance and DRs of various PV technologies which had been operating under Thailand's climate for 3 years [10]. In our previous work, the DRs of the PV arrays had been evaluated, not individual PV modules. The performance ratio (PR) and I–V curves for whole array had been measured. The trend of the PV arrays represented each PV type under the assumption that all modules in the same array perform equally. In this paper, the outdoor I–V results of the individual PV modules after 4 years of operation have been taken into account in

* Corresponding author.
E-mail address: amornrat.limmanee@nectec.or.th (A. Limmanee).

http://dx.doi.org/10.1016/j.renene.2016.10.052
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estimating the DRs of the PV modules. Comparison of degradation behavior between each PV module and whole PV array is shown. Effects of DR dispersion on array performance are also discussed. Furthermore, the impacts of DR on the LCOE of PV systems in Thailand are presented.

2. Experimental details

2.1. PV modules and system description

The 10 kWp grid-connected system consisting of 73 modules from five different PV manufacturers is located at latitude of 14° 4′N, longitude of 100° 36′E and elevation from sea level of 9 m. The system consists of three main parts, i.e. PV arrays, power conditioner, and monitoring system. To evaluate the performance and reliability of various PV technologies, five different PV arrays; 1) multi c-Si, 2) hetero-junction Si, 3) thin film Si 1, 4) thin film Si 2 and 5) copper indium gallium diselenide (CIGS), have been installed at Thailand Science Park in April 2012. The thin film Si modules in this study are multi-junction amorphous silicon (a-Si)/microcrystalline Si (μc-Si) structure from two different manufacturers, which possess different temperature coefficient (TC). The PV modules are supported at a fixed inclination of 14° and mounted to face the south. Technical specifications of these five different PV arrays are mentioned elsewhere [11]. This PV system uses only one power conditioner containing maximum power point tracking (MPPT) separately in every array. The facility is equipped with meteorological instruments connecting to data acquisition system. The weather parameters logged are in-plane irradiance (P_{in}), ambient temperature (T_A), and module temperature (T_M). The electrical parameters include voltage, current, and output power of both DC and AC sides. The I-V curves are also obtained through I–V tracer equipment. All those parameters are collected every 5 min.

2.2. Methods of analysis

2.2.1. Data filtering process

The upper limit for P_{in} was set at 1200 W/m^2 and the lower limit was kept at 0 W/m^2. The outlier and stability filters were applied to eliminate uncertain data before performing an analysis [12]. In this study, the stability filter was used to eliminate data points when the P_{in} changes more than 20 W/m^2/min. The outlier filter, which used the ratio between temperature corrected DC output of the arrays and the P_{in} as an indicator, was performed to get rid of extremely variable days and partial-shading conditions.

2.2.2. Performance evaluation of PV arrays

In order to compare actual production of the various kinds of PV arrays, we use performance ratio (PR) as a normalized performance indicator. The time interval in which the performance metric is evaluated is given in monthly increment. The definition of the PR is as follows.

$$PR = Y_A/Y_r \tag{1}$$

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

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

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 standard test condition (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. Monthly PR is presented by irradiance weighted average performance ratio (PR_{WA}) [13]. The degradation analysis was done by using the PR of each array, with compensation of irradiance and temperature. The temperature-corrected PV array output (E_{AT}) was calculated by using the following formula:

$$E_{AT} = E_i/\{1 + \gamma \times (T_M - 25)\} \tag{4}$$

where E_i is measured array output, γ is a temperature coefficient for power (%/°C), and T_M denotes module temperature. Then, the E_{AT} was used to calculate the array yield (Y_A) and derive the PR with temperature compensation. The degradation rates were derived through the simple linear regression model [14]. A linear least square fit was applied to the extracted trend of the monthly PR. The equation of the fitted trend line for the PV performance time series is $y = ax + b$. The gradient of the fit represents the linear monthly performance loss, which can be multiplied by 12 to obtain the annual degradation rate. The measured DC-side electrical parameters such as open circuit voltage (V_{oc}), short circuit current (I_{sc}), fill factor (FF), and maximum output power (P_{max}) of each array were also used to evaluate performance of each PV type. The values of P_{max}, I_{sc} and V_{oc} were performed the temperature correction with respect to the STC values (P_{max_STC}, I_{sc_STC} and V_{oc_STC}) using the simplified formulas as follows [5]:

$$P_{max\_STC} = P_{max}/\{1 + \gamma \times (T_M - 25)\} \tag{5}$$

$$I_{sc\_STC} = I_{sc} \times (1000/P_{in})/\{1 + \alpha \times (T_M - 25)\} \tag{6}$$

$$V_{oc\_STC} = V_{oc}/\{1 + \beta \times (T_M - 25)\} \tag{7}$$

where α is a temperature coefficient for current (%/°C) and β is a temperature coefficient for voltage (%/°C). The temperature coefficients from manufacturers' datasheets were used in the calculation. Then, the monthly irradiance weighted average of those parameters including the FF was calculated. Their DRs were estimated by a linear regression model. The outdoor I–V curves of the PV arrays measured under almost exactly the same operating conditions were used for comparison between the first and the fourth year performance.

2.2.3. Performance evaluation of PV modules

After 4 years of operation, all PV module in the system was individually measured by outdoor I–V tracer (EKO M-170 IV checker). The outdoor electrical measurement values were then translated into the STC by using Equations (5)–(7). The annual DRs of electrical parameters for each PV module were calculated using the following equation [15].

$$\{(Z_{label})/Z_{label} \times 100\}/\Delta t \tag{8}$$

where Z_{label} denotes labelled value of electrical parameter from manufacturers' datasheet, Z_f denotes the measured values of electrical parameter which is corrected with respect to the STC, and Δt is years of operation. The standard deviation (SD) of data from modules in the same array was calculated to indicate the level of mismatch among modules.

2.2.4. LCOE calculation

The DR of PV module is strongly influenced by technology type and actual operating conditions. PV modules thus possibly exhibit lifetimes significantly different from manufacturer estimation. The operational lifetime (N), when PV modules reach 80% of their initial energy conversion efficiency, can be expressed as follows:

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