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Thermal modelling with experimental validation and economic analysis of mono crystalline silicon photovoltaic module on the basis of degradation study

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ABSTRACT

In this paper, a mathematical model has been developed to calculate solar cell temperature and module efficiency in opaque mono crystalline silicon (sc-Si) PV module on the basis of degradation rate. The calculated results have been validated by experimental investigations for the opaque PV module. Module efficiency and solar cell temperature of the opaque PV module decrease with increase in degradation rate. In this context, energy matrices are developed and enviroeconomic analysis has been done on the basis of annual energy output of PV modules for different degradation rate. Efficiency and temperature of PV module have been decreasing with an increase in the degradation rate. The energy payback time is found to be 8.80 years and 9.29 years for degradation rate 0.3%/year and 0.9%/year, respectively and unit cost (Rs./kWh) increase with an increase in the degradation rate of PV module. Similarly, the environmental cost reduction is higher for 0.3%/year degradation rate and lower for 0.9%/year degradation rate.

1. Introduction

Reliability and degradation of Photovoltaic (PV) module are an important concern to ensure the life of PV module 25–30 years. From last two decades the deployment of the PV modules is increasing rapidly worldwide. During large scale deployment, studies of degradation and performance losses are an important concern to make PV module reliable in an outdoor condition. However, the efficiency of a PV module is affected by the environmental stress and different defects occurring during outdoor exposure [1,2]. The electrical output of PV module also depends on the type of PV technologies, orientation and geographical condition [3]. Performance degradation of PV modules in field condition is caused by packaging materials, semiconductor degradation, interconnection ribbon, adhesion losses [4]. Sanchez-Friera et al. [5] reported that delamination in cell-EVA interface, oxidation of antireflective coating and corrosion in the interconnection in ribbon were the frequently occurring defects in PV modules during long-term outdoor exposure. Delamination between solar cell-EVA and metallization of the solder bond make adverse effect on the performance of PV module and results in 0.5%/year power degradation in c-Si PV modules over 10 years of outdoor exposure [6]. 1%–10%/year performance losses due to EVA discoloration was reported with respect to ultraviolet world–wide location and site dependence [7]. Degradation studies of three different technologies a-Si, HIT (hetro-junction intrinsic thin layer silicon) and mc-Si after 28 months of outdoor exposure in a composite climate of India has been reported by Sharma et al. [8]. Further, they have concluded that 6.4%, 0.5% and 0.36% are the average peak power decay per year found in a-Si, HIT and mc-Si PV module respectively. Further, they have reported that HIT and a-Si technologies are better performed in a similar outdoor condition in comparison to mc-Si technology [9]. 11.2% degradation in power after 70 days of deployment in a-Si PV module installed in Spainwas reported by Kichou et al. [10]. After 9 years of continuous outdoor exposure, annual performance ratio, capacity factor and system efficiency of mc-Si technology were found to be 74%, 9.27% and 8.3% of a 190 kWp grid interactive photovoltaic power plant installed at Khatkar-Kalan India [11]. Dunlop and Halton [12] reveal that module encapsulated with EVA and a tedlar aluminium back sheet exhibited 14.8% mean power degradation while module with encapsulated silicon sealant showed average power degradation of 6.4% after 20–22 years outdoor exposure of c-Si PV modules. Corrosion in interconnection

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ribbon and delamination in cell-EVA interface were the common defects observed in all PV modules. Further, degradation in peak power was found to be 11.5% due to the short circuit current [13]. Chandel et al. [14], reported 1.4%/year average power degradation found in sc-Si PV modules after 28 years field exposure in western Himalayan region of Indian climate. The degradation is mainly found due to encapsulate discoloration, delamination in anti reflecting coating and bubbles in back sheet. Sastry et al. [15], reported 5–16.5% degradation in IEC 61215 qualified sc-Si PV module and 17-13% degradation in output power in not qualified IEC 61215 qualified standards after 10 years. In context, according to all India survey of PV module, most of the modules suffered from EVA discoloration in the hot and dry climatic zone, maximum number of modules suffered from corrosion in interconnection ribbon in the hot and humid zone and modules installed in cold climatic zone suffered from discoloration and corrosion [16]. Rajput et al. [17], also reported that the corrosion in interconnection ribbon is commonly observed defect in sc-Si PV modules after 22 years outdoor exposure in a composite climate of India. The temperature of hot spots decreased with increase in the number of hot spots on the panel [18]. The energy payback time (EPBT) analysis of a PV module is reported by Slesser and Hounam for the PV system. They concluded that the EPBT of system found to be 40 years because of the high initial capital investment [19]. Further, Kato et al. [20], concluded that sc-Si PV modules have shorter payback time period and lower carbon emission as expected. However, mc-Si and a-Si is better in comparison to sc-Si PV module for payback period and carbon emission. Alsema and Nieuwlaar [21] reported that payback time is less than 1.5 years for a rooftop PV system and 2 years for ground mounted PV module. Yamada et al. [22], concluded that (EPBT) is 6 years for the cell production rate for 0.01 GW/y. The CO_2 emission for rooftop PV system and ground mounted are 50–60 g/kWh and 20 g/kWh respectively. Fortunato et al. [23], presented the modelling of performance and economic analysis on the basis of net present value, payback period and life cycle cost analysis of a photovoltaic system. A number of studies have been done on modelling and lifecycle cost analysis of different systems of renewable energy systems like solar PV, solar thermal and biomass [24–26]. In the present work, life cycle cost analysis of a 24 years old PV system installed at National Institute of Solar Energy (NISE), formal known as Solar Energy Center (SEC) has been carried out. Life cycle cost analysis is done taking into account the actual measured power output degradation of the PV modules of the PV system during its outdoor operation which has already been reported in the previous study [17]. Finally a mathematical model for energy output estimation based upon the actual degradation rate of the PV modules has been developed in MATLAB. The results of the study are also validated with the real time measured data. In the present analysis, modelling has been done for different degradation rate viz., 0.3%/year, 0.4%/year, 0.7%/year and 0.9%/year of sc-Si PV modules with experimental validation in composite climate of India. The present study will have importance from the manufacturer/installer as well as a consumer's point of view because this will help them to give the warranty of their product as well as it will help them to accurately estimate the investment returns.

2. Theory and modelling

2.1. Thermal modelling of opaque PV module

In the present study, thermal modelling and simulation has been done for estimating the temperature and efficiency of different degradation rate PV module, which has been further compared with experimental result.

To write the energy balance equations for c-Si (sc-Si and mc-Si) opaque PV modules, the following assumptions have been considered:

(i) One-dimensional heat conduction,
(ii) Encapsulant, ethylene vinyl acetate (EVA) is purely transparent,
(iii) The i^2r losses in solar cells and PV modules are negligible.
(iv) The equation is validated for $0 < = d_{sc} < = 1$

The energy balance equation for opaque sc-Si and mc-Si PV module can be written as:

$$\alpha_c \tau_g \beta_c I(t) A_m + \alpha_T \tau_g (1-\beta_c) I(t) A_m = U_{tca}(T_c - T_a) A_m + U_{bca}(T_c - T_a) A_m + \eta_c \tau_g \beta_c I(t) A_m (1 - d_{sc}) \quad (1)$$

Where,

$$U_{bca} = \left[\frac{L_g}{K_g} + \frac{1}{h_i}\right]^{-1}$$

$$U_{tca} = \left[\frac{L_g}{K_g} + \frac{1}{h_o}\right]^{-1}$$

The first term on the left hand side shows the total solar radiation received by the solar cells (area covered by the solar cells) and the second term shows the total solar radiation received by the non packing area. The first and second term on the right hand side shows the total thermal energy losses from solar cells of the PV module through top and bottom surface. The last term in the right hand side shows the rate of the electrical energy generated by solar cells of PV module.

From Eqn. (1), T_c can be written as

$$T_c = [\tau_g\{\alpha_c\beta_c + (1-\beta_c)\alpha_T - \eta_c\beta_c(1-d_{sc})\}] I(t) + U_L T_a / U_L \quad (2)$$

Where, $U_L = [U_{tca} + U_{bca}]$

Putting the value of T_c from Eqn. (2) into Eqn. (3)

$$\eta_c = \eta_o[1 - \beta_o(T_c - T_o)] \quad (3)$$

$$\eta_c = \eta_o\left[1 - \beta_o(T_a - T_o) + \frac{\{\tau_g\alpha_c\beta_c + \alpha_T\tau_g(1-\beta_c)\}I(t)}{U_L}\right] \Big/ [1 - \eta_o\beta_o\beta_c\tau_g I(t)(1-d_{sc})/U_L] \quad (4)$$

Module efficiency written as

$$\eta_m = \frac{P_o}{P_{in}} = \frac{\eta_c\beta_c\tau_g I(t)}{I(t)} \quad (5)$$

$$\eta_m = \tau_g\beta_c\eta_c \quad (6)$$

Correlation coefficient (r) and root mean square percent deviation (e) are important procedure for comparing the theoretical results with experimental data. These values are calculated by the following expression [27].

$$\text{Correlation coefficient (r)} = \frac{N\sum X_i Y_i - (\sum X_i)(\sum Y_i)}{\sqrt{N\sum X_i^2 - (\sum X_i)^2}\sqrt{N\sum Y_i^2 - (\sum Y_i)^2}} \quad (7)$$

If, r > 0 indicates a positive linear relationship.
r < 0 indicates a negative linear relationship.
r = 0 implies no linear relationship between two variables.