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Degradation analysis of a-Si, (HIT) hetro-junction intrinsic thin layer silicon and m-C-Si solar photovoltaic technologies under outdoor conditions

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A B S T R A C T

Understanding degradation mechanism is of utmost importance for long term reliability of photovoltaic technology. In the present study, degradation analysis of three different photovoltaic technology modules namely a-Si (amorphous single junction silicon), HIT (hetro-junction intrinsic thin layer silicon) and m-C-Si (multi-crystalline silicon) is carried out after 28 months of outdoor exposure at Solar Energy Centre, India. A comprehensive test campaign is conducted by visual inspection, thermal imaging and current–voltage characteristic measurements. The soiling of glass is observed in all modules, wavy pattern in back sheet is seen only in a-Si array modules. 50% of m-C-Si modules showed oxidation of silver front grid metallization fingers and antireflective coating at multiple places. Degradation of modules is assessed by measuring characteristic parameters at standard test conditions, before and after outdoor exposure using sun-simulator. The average peak power decay per year is found to be 6.4%, 0.5%, 0.36% in a-Si, m-C-Si and HIT modules respectively. Degradation in each technology array is also calculated analytically and is found to be 5.7 ± 2.5%, 0.51 ± 0.017%, 0.31 ± 0.016% in a-Si, m-C-Si and HIT modules respectively which is in good agreement with experimentally measured results. The study will be useful in further understanding of degradation mechanism under Indian climatic conditions.

1. Introduction

PV (photovoltaic) industry has grown at extraordinary rate in the past decade. In order to maintain the sustainable development of PV industry a number of approaches are adopted ranging from technological development to framing adequate policies [1]. Growth of PV system industry in India has increased after the major policy initiative of MNRE (Ministry of New & Renewable Energy), Government of India by launching JNNSM (Jawaharlal Nehru National Solar Mission) in December 2009 [2]. The installed grid connected PV system capacity, which was 8 MW in 2009, has increased to 2080 MW as on 31 October 2013 [3]. At present the main challenge faced by PV industry is to make PV generated electricity cost effective. So, it is important to identify factors due to which cost of PV generated electricity can be reduced. PV system cost, annual energy yield, annual solar radiation, interest rate are the important parameters which influence the cost of generated electricity. In such an aspect, PV module lifetime is found to be key element, as it directly influence the payback period of the investment, and hence the cost of generated electricity. Long term reliability of PV modules is therefore required to make PV technology a commercially viable source of energy. Reliability of PV modules can be assessed by understanding degradation and indentifying degradation mechanism during the outdoor operation. Studying and understanding degradation of PV modules is of utmost importance, as it helps in developing adequate qualification standards and setting up appropriate guarantee periods. Most of studies related to degradation of PV modules are generally carried out through indoor accelerated aging experiments. In such studies stress or a combination of stresses are applied to reproduce the identified degradation mechanism in shorter period of time. Finally based upon accelerated aging tests qualification standards are developed. At present the qualification testing of PV modules is carried out as per IEC (International Electrotechnical Commission) standards [4,5]. The main objective of the qualification tests is to reproduce the identified degradation mechanisms quickly in the intended environment (s). Quality standards developed through accelerated aging tests have helped considerably to improve

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reliability and durability of PV modules in recent years. However, it is not possible for accelerated tests alone to replicate various possible degradation mechanisms in PV modules occurring during real-time field exposure. During the real outdoor exposure stresses such as; radiation, temperature, humidity, UV (Ultraviolet) radiation, wind and operating voltage are experienced together, whereas during accelerated qualification tests these stresses are applied as per predetermined sequence, which need not necessarily result in generation of same type of defects. This has been shown by Realini [6] who compared the degradation or defects generated in crystalline PV modules under real outdoor conditions and during the accelerated aging tests. Encapsulant delamination has been observed in the modules exposed to outdoor conditions, whereas (damp heat and thermal cycling) accelerated aging tests resulted in detachment of tedlar back sheet thus the defects observed under indoor accelerated tests and real outdoor conditions are found to be quite different. Another approach to study the degradation is to carryout long term outdoor exposure of small PV arrays; perform experimental measurements to evaluate various performance parameters to identify degradation.

The study assumes importance as PV industry has now started finding applications in all climate zones worldwide which emphasizes the need to make PV qualification standards more quantitative. In order to address these issues an International PV module quality assurance forum has been setup and PV quality assurance task force is formed. Presently efforts are underway towards creating a Comparative Rating System for various conditions encountered by PV modules in the field [7].

In the present study degradation analysis is carried out in three arrays of different photovoltaic technologies namely a-Si (amorphous single junction silicon), HIT (hetro-junction intrinsic thin layer silicon) and m-C-Si (multi-crystalline silicon) after 28 months of outdoor exposure. A PV technology test bed research facility consisting of 3 different PV technologies was setup in 2009 at SEC (Solar Energy Centre), Gurgaon under SEC, MNRE, India and AIST (Advanced Industrial, Science and Technology), Japan joint collaboration project. This work is in continuation with previous work [8] in which first year performance of each technology PV array was evaluated as per IEC-61724 guidelines.

The main purpose of work is to identify the frequently occurring defects in PV modules, change in the electrical performance parameters and correlate these with identified defects under Indian climatic conditions. The outcome of the study will be helpful to quantify PV modules degradation and review or revise the accelerated aging qualification tests depending upon the dominant field degradation mechanisms.

The paper is organized as follows: a brief overview of the PV module degradation studies is presented in Section 2 and experimental PV test-bed facility details are given in Section 3. In Section 4 degradation analysis methodology followed in the study is described. The results and discussion are presented in Section 5. The conclusion of the study is given in Section 6.

2. Overview of PV module degradation studies

Oil crisis of 1973 focused the attention to use PV modules for terrestrial applications, especially for remote locations worldwide [9]. The environmental conditions in terrestrial use are quite different from space applications, which posed several challenges for the long term reliability of PV modules. Since then several studies related to degradation of PV modules have been carried out. Degradation studies including multi-technology comparison are of particular importance as they eliminate the effect of local environmental conditions. Recently, Gxasheka et al. [10] evaluated the performance of five different crystalline silicon based PV technology modules. Performance parameters were measured indoor prior to outdoor exposure to provide baseline reference and after 17 months of outdoor operations. Results indicate some of the modules did not perform as expected. Moisture ingress and delamination were found to be the dominant degradation mechanisms resulting in 14% of power degradation. Carr et al. [11] at the Australian Cooperative Research Center Perth, Australia evaluated the performance of five different technology PV modules from seven different manufacturers for 16 months of outdoor operation. The results of the study indicate that mono and polycrystalline silicon PV modules show 2% per year power degradation where as amorphous and CIS (Copper indium gallium selenide) solar modules exhibited a significantly higher power reduction.

Raghuraman et al. [12] evaluated performance of forty four modules from eight different manufacturers and three different technologies in Mesa, Arizona under hot-arid climatic conditions for 2.4–6.7 years. Mono-crystalline and polycrystalline silicon modules exhibited low power degradation (approx 0.5% per year) while a-Si multi-junction modules degraded more (1.16% per year). Marion and Adelstein [13] reported the performance of two PV systems installed on the roof top of SERF (Solar Energy Research Facility) building at NREL (National Renewable Energy Laboratory), Golden, Colorado from 1994 to 2002. Each PV system consists of 140 PV modules. The performance of both PV systems is found to be reducing at the rate of 1% per year. The reduction in the performance is regarded as an effect of aging or degradation. A study on power degradation of crystalline silicon PV modules is presented jointly by the Japan Quality Assurance Organization and Solar Techno-Center [14]. Modules are operated outdoors for 10 years in Hamamatsu (Japan) and average power degradation is found to be 6.2%, however about 10% of the PV modules have suffered more than 10% power reduction.

Dunlop and Halton [15] at Institute for Environment and Sustainability, Italy, studied the performance of 40 silicon (poly and mono) crystalline PV modules with different encapsulation and from six different manufacturers operating for 20–22 years in the field. Modules encapsulated with silicon sealant showed 6.4% average power degradation while modules encapsulated with EVA (Ethylene-vinyl acetate) and a tedlar aluminium back sheet exhibited 14.8% mean power degradation. Realini et al. [16], before the failure MTBF (Mean time before failure of photovoltaic modules) Project, analysed the performance of a 10 kW PV system installed at Lugano, Switzerland after 21 years of operation. The PV system consisted of crystalline silicon PV modules and after 21 years, 0.5% per year power degradation is reported. Paula et al. [17] investigated the degradation mechanism in the 2 kWp PV installation after 12 years of outdoor operation using various approaches such as visual inspection, thermal imaging and electrical performance measurement.

Glass weathering, delamination at the cell-EVA interface and oxidation of the antireflective coating and the cell metallization grid were found to be the most frequently occurring defects. The degradation in the peak power of the installation was found to be 11.5% which is totally due to the loss in short circuit current. Jordan and Kurtz [18] recently reviewed the degradation rates from the field testing studies carried out during the last 40 years and concluded that the average of power degradation rates distribution is found to be 0.8% per year. Understanding degradation and estimating module lifetime of different commercially available PV technologies are the core experimental research activities carried out at SEC, the R&D division of MNRE, Government of India. Sastry et al. [19] at SEC studied the performance degradation of mono crystalline PV modules supplied by eleven manufacturers during 1998–99, under Indian climatic conditions, for a period of 10 years. The modules from eleven manufactures were divided into five groups for analyzing the data. The degradation in the output power of modules form the manufacturer whose module qualified under IEC 61215 standards was found to range from 5 to 16.5% after 10 years. The degradation in the output power of modules form the manufacturer whose module were not qualified under IEC 61215 standards, was found to range from 17 to 33% after 10 years. In this study it was found that even the well qualified modules have failed or degraded more than the expected levels and suggested that there is a need to review the PV qualification standards especially for Indian climatic conditions, if the modules are to perform for more than 20 years in the field.

Sharma and Chandel [20] presented a detailed review on the degradation of photovoltaic technology for long term reliability. In the review, authors emphasized the need for developing site specific qualification standards and also highlighted the efforts being made for the creation of a comparative rating system to make qualification standard more quantitative. Various analytical tools such as ultrasonic imaging, thermal imaging, electroluminescence imaging and scanning electron imaging useful in understanding degradation mechanism, are also discussed. The highlights of degradation field studies by various authors discussed in this section are summarized in Appendix 1. Despite the progress made in this area, further research is needed in order to establish stringent quality standards to ensure the module lifetime of 30 years.

3. Description of experimental PV test-bed research facility

In order to study the long term performance and degradation of different technology PV modules an experimental test-bed facility consisting of three different PV technology module arrays from different manufacturers was setup at SEC (Solar Energy Centre), Gurgaon (Latitude 28°37 N, Longitude 77°04E). The site is located at an altitude of 215 m (above mean sea level) having composite climate with monthly average ambient temperature varying from 11to 35 °C and relative humidity remaining less than 90% throughout the year. The wind speeds at the location are light and moderate with annual average of 1.5 m/sec and monthly global horizontal solar radiation varies from 2.6 to 6.1 kWh/m^2-day. There are total 40 modules of three PV technologies; a-Si, HIT and m-C-Si placed in the real field conditions with fixed rack mount on the aluminum support structure at tilt 28° as shown in Fig. 1.

The a-Si module array consists of 20 modules with nominal power 75 Wp, out of which 16 modules are connected as; 4 modules are connected in series and 4 such series connected strings are connected in parallel and out of remaining two modules, one module is kept in loaded condition and the other one is kept totally in the open circuit condition. The HIT array consist of 10 modules with nominal power 210 Wp, out of which 8 modules are connected as; 4 modules are connected in series and 2 such series connected strings are connected in parallel and out of remaining two modules, one module is kept in loaded condition and the other one is kept totally in the open circuit condition. The m-C-Si array consist of 12 modules with nominal power 160 Wp, out of which 10 modules are connected in series and out of remaining two modules, one module is kept in loaded condition and the other one is kept totally in the open circuit condition. The three PV technology module arrays along with the comprehensive weather monitoring station and PV measurement systems were installed in October 2009. Since then modules in each array are operated at maximum power point except one which is kept in open circuit and current voltage (*I*–*V*) data is collected routinely after 10 min for each technology array. The details of installation, PV measurement and data collection have already been provided in the previous publication [8].

Fig. 1. Experimental photovoltaic test facility at SEC, Gurgaon, India.

4. Degradation analysis methodology

Prior to the deployment at the experimental test bed facility at SEC, the *I*–*V* characteristics of all the modules of each technology array were measured indoor in October, 2009 using a class–A sun simulator at SEC, in order to keep a baseline data for future comparison. The degradation in the individual PV module of each technology array has been investigated through a comprehensive test campaign as follows:

i. Visual inspection of the modules.
ii. Thermal imaging.
iii. *I*–*V* curve measurement of all modules of each technology array and comparison with the initial measurements.
iv. Analytical calculations of degradation rates.

4.1. Visual inspection

There are several modes of degradation observed in field aged PV modules and summarized by Quintana et al. [21]. The degradation of PV modules results in generation of various types of visual defects, a detailed list of such visual defects observed in field aged modules, is presented in Refs. [16,22]. All the 40 modules of three different technologies installed in the test bed underwent the visual inspection. Glass soiling was found to appear in almost all the modules because of which the glass has started looking hazy or dark. This was not due to the simple accumulation of dirt as the modules were thoroughly cleaned before the visual inspection and electrical characterization. The soiling of the glass was due to deposition of airborne particles, residues of rainwater deposits and ion exchange between the alkalis in the glass and H+ ions in the water [23]. This weathering of glass was further enhanced due to frames which hold small quantity of water at the edges of the modules. The modules are inclined 28° with respect to the horizontal because of which all the modules were showing this effect at the bottom edges as shown in Fig. 2.

In addition, wavy pattern in back surface is seen in 85% of a-Si modules (Fig. 3). Oxidation of silver front grid metallization fingers and the antireflective coating at multiple places is observed in 50% of m-C-Si modules (Fig. 4). This defect has resulted in blackening of module's blue color indicating oxidation. HIT array modules were found to be operating in excellent condition and no visual defects have been observed at the time of inspection. Frames and the junction boxes of all the three technology modules were found in excellent condition.

In order to further investigate the generation of defects such as hot spot, a thermal analysis of the test bed is carried out.

4.2. Thermal imaging

Thermal imaging is a non destructive technique to identify defects in field aged modules which are not observed during visual inspection. This technique utilizes the concept of localized heat generation because of joule heating effect due to the poor contacts,

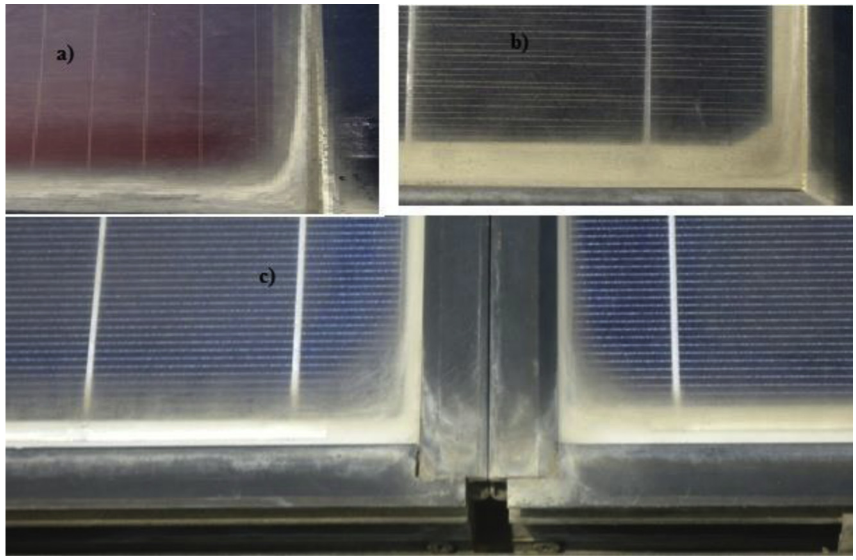

Fig. 2. Glass soiling observed at the bottom edges of modules of three technologies a) a-Si b) HIT and c) m-C-Si.

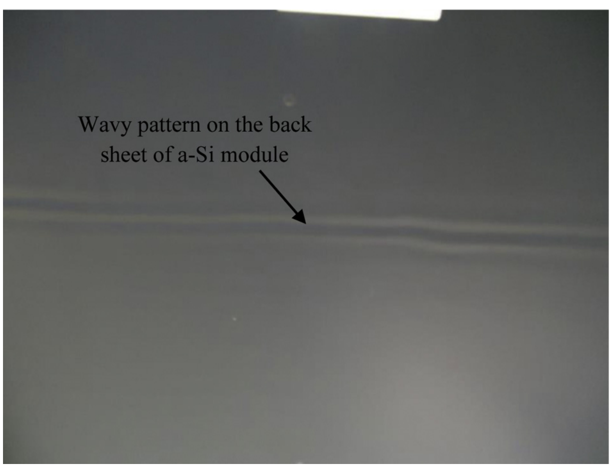

Fig. 3. Wavy pattern at back sheet observed in the modules of a-Si array.

shunted cells, short circuits. This happens because solar cells which are generating less current as compared to the other cells connected in series become reverse biased and start behaving like resistors and dissipate heat. This dissipated heat results in a temperature gradient which during thermal imaging appear as bright spots. This technique consists of a camera sensitive to infrared radiation of 3–15 μm range. PV modules in each technology array were analysed using EasIR™-4 thermal imager with 160X120 pixels. The thermal images were taken outdoors when the modules were operating at their maximum power. The images were taken from both front as well as back side; special care has been taken not to include the reflection of the front glass while taking the images from the front side. The metallic frame enclosing PV module is at 4–7 °C higher temperature than the ambient (Fig. 5). Thus module areas near the frame may be more prone to thermal degradation with higher rates. This effect has been observed in all the modules of three arrays. String to string mismatch in some of the p-C-Si array modules has been observed (Fig. 6) however, it is difficult to say whether this defect is due to degradation or was already present earlier before the outdoor exposure. Fig. 7 shows the cell with higher temperature but despite this, no visual defect was observed around or back sheet of affected area.

4.3. *I–V* Characteristic measurements

I–V characteristics of each individual module are measured and compared using Endeas Quick Sun 700 class A, sun simulator with initial measurements recorded in October 2009. It is important to mention here that initial measurements were made before light soaking or conditioning, therefore, degradation losses should also include the LID (Light Induced Degradation) and preconditioning losses. The variation of the characteristic parameters; short circuit current (I_{sc}), open circuit voltage (V_{oc}), maximum power (P_{max}) and FF (fill factor) has been analysed. Modules were removed from the test bed in February, 2012 after 28 months of outdoor exposure. Prior to *I–V* measurements all the modules underwent a cleaning procedure in order to remove the dust accumulated on the front glass. *I–V* characteristics were measured under STC (standard test

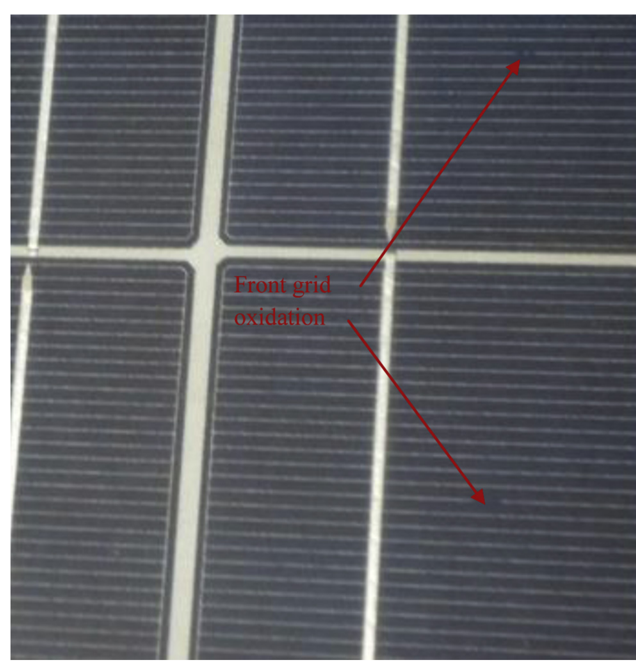

Fig. 4. Front grid oxidation observed in modules of p-C-Si array.

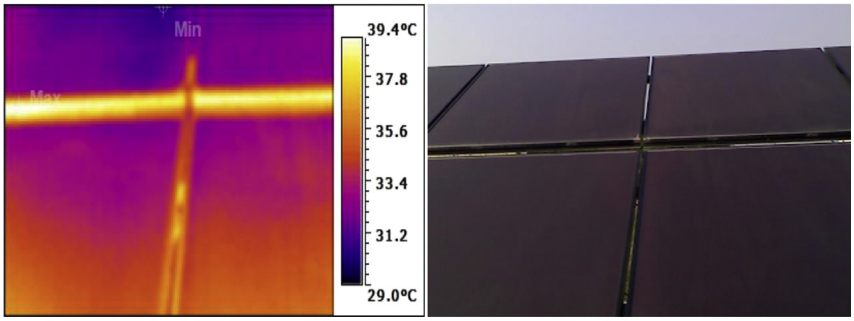

Fig. 5. Thermal and visual image of the modules showing higher temperatures observed near the frames.

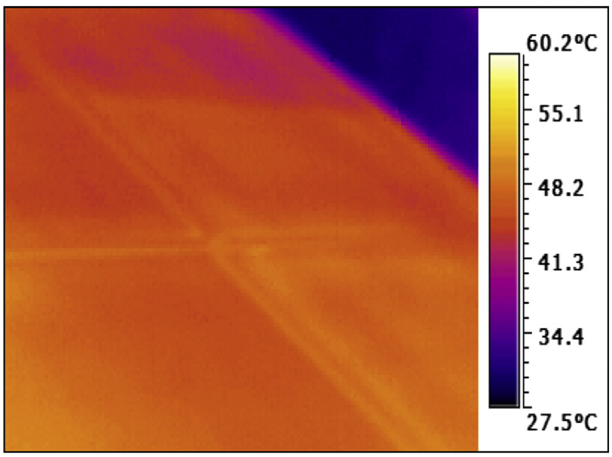

Fig. 6. Mismatch observed in modules of m-C-Si array.

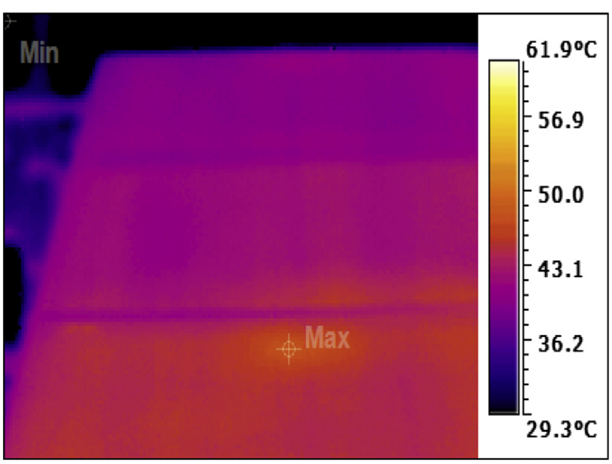

Fig. 7. Cell with higher temperature.

conditions), i.e. 1000 W/m^2 irradiance, Air Mass 1.5 and ambient temperature 25 °C as per in IEC 60904-1 standard guidelines [24]. The expanded ($k = 2$) combined measurement uncertainty of the sun simulator for I_{sc}, Voc, FF and Pmax for both initial and after outdoor exposure set of measurement is reported in Table 1.

Table 1
Expanded ($k = 2$) combined measurement uncertainty of characteristic parameters.

Characteristic parameter	2009 Measurement (%)	2012 Measurement (%)
I_{sc} (A)	±2.80	±2.80
V_{oc} (V)	±0.80	±0.85
FF (%)	±0.72	±0.72
Pmax (W)	±2.91	±2.93

4.4. Analytical calculations of degradation rates

The power output of PV modules in each technology array depends on climatic factors like incident solar radiation on POA (plane of array) and ambient temperature. Thus, in order to understand and quantify degradation of each PV technology module, current (I_{max}), voltage (V_{max}), and maximum power (P_{max}) are recorded, along with environmental parameters like POA irradiance and ambient temperature with 10 min interval. The details of data collecting system and measuring instruments are given in previous publication [8]. After collecting the data a filtering process is applied to it. It is important to point out here, that when no data filtering is applied the uncertainty of degradation rate determination is quite high which can be minimized after applying proper filter to the data set [25]. Also the degradation rate determined after filtering the data is found to be in close agreement with the degradation rate obtained from the indoor characterization. The following sets of restrictions are used to obtain data sets from each technology PV array:

- Eliminate the data where irradiance is too low to produce enough power, thus keeping the irradiance range between 500 to 1200 W/m^2.
- Eliminate the data where power is too low, thus keeping the power output range between 0.60(P_{STC})−1.25(P_{STC}) W.
- Eliminate the data points where the temperature is too low or too high, keeping temperature range between −20 to 60 °C.

After filtering, only the valid data are kept for the analysis. The degradation in each technology array is quantified using PVUSA (Photovoltaics for Utility Systems Applications) methodology [26]. According to PVUSA regression analysis, power is considered to be a function of irradiance, temperature and wind speed and is given as.

$$P = E(A + B \cdot E + C \cdot T_a + D \cdot W_S) \quad (1)$$

where:
P = Power in Watt at the specific test conditions.
E = Plane of array irradiance (W/m^2),
T_a = Ambient temperature (°C),
W_S = Wind speed (m/s),
$A - D$ = Regression constants for a month and derived from operational data.

In the present analysis wind speed is not taken into account as the contribution of co-efficient of wind speed "D" is 0.4% to the total calculated value of PVUSA power [27]. The coefficients A, B, C are

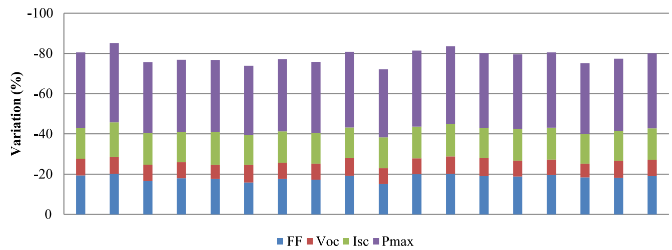

Fig. 8. Variation of characteristic parameters of a-Si array modules after 28 months of outdoor exposure.

estimated by regression analysis for each month. These coefficients are then used to calculate normalized power at PTC (performance test conditions) i.e irradiance ($E = 1000$ W/m^2), temperature ($T = 20$ °C) for each month. PVUSA regression analysis is applied to the systematically collected and filtered monthly block-wise data using MS excel software.

In order to obtain long term degradation rate a linear least-square fitting method is applied to the monthly PTC power calculated by PVUSA regression analysis. Using the trend lines, the degradation per year can be calculated as follows;

Equation of line:

$$y = mx + c \tag{2}$$

where m is the slope of line and c is the intercept, thus % degradation per year in each technology array can be calculated as:

$$\%\text{Degradation/year} = \frac{(m \times 12)}{c} \times 100 \tag{3}$$

5. Results and discussion

The characteristic parameters of PV modules in each array are measured before and after outdoor exposure and the statistical analysis is carried out. Fig. 8 shows the variation of characteristic parameters for 18 modules of a-Si array. It has been found that the major loss in peak power (P_{max}) of a-Si array modules corresponds to I_{sc} and FF decay. Fig. 9 (a), (b), (c) & (d) show the frequency distributions of characteristic electrical parameters before and after the degradation, along with the corresponding Gaussian distributions. In a-Si array the average peak power is reduced to 36.56% in 28 months. This decay is mostly due to the decay of 15.54% in I_{sc} and 19.68% in FF. Taking into account the fact that the initial measurements were taken without preconditioning and a-Si modules get stabilized 20% below the initial power [28], the average annual degradation of the peak power in a-Si array modules is found to be 6.4% which is in agreement with the previous findings [29–30]. The average and standard deviation of characteristic parameters before and after 28 months of outdoor exposure are shown in Table 2. It is remarkable to note that the standard deviation of Pmax has reduced by 31% between the initial and final measurements. This is contrary observation, as generally the standard deviation of the peak power is found to increase with time [3]. A possible explanation could be that amorphous thin film modules stabilize to same level even when they are exposed to outdoor conditions during different times or seasons of the year [28].

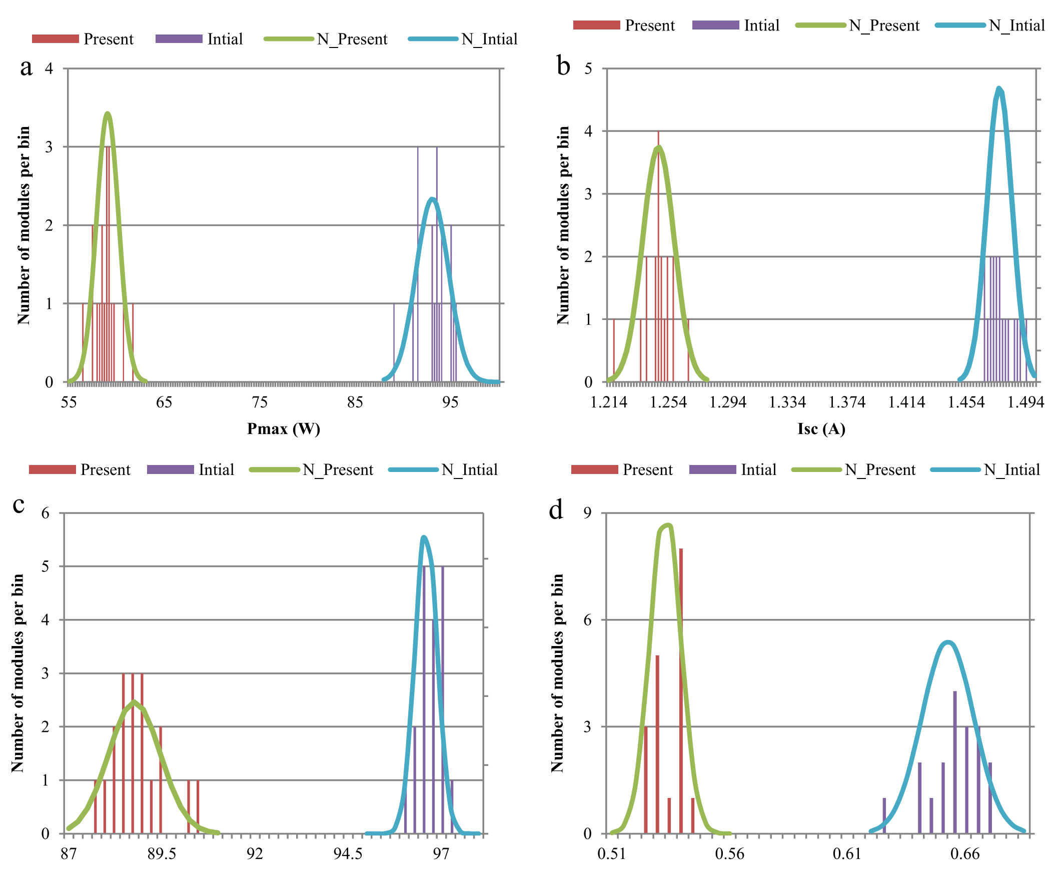

Fig. 9. Distribution of characteristic parameters of a-Si array modules before (Initial) and after (Present) the outdoor exposure along with Gaussian distribution (a) for Pmax, (b) for I_{sc}, (c) for Voc, (d) for FF.

Table 2
Average and Standard deviation (SD) of characteristic parameters of a-Si array before and after 28 months of outdoor exposure.

Parameter	Initial measurement		After 28 months		% Variation	
	Average	SD	Average	SD	Average	SD
V_{oc} (V)	96.58	0.29	86.78	0.69	−10.14	+137.93
I_{sc} (A)	1.48	0.0085	1.25	0.0106	−15.54	+24.71
V_{max}(V)	75.65	1.09	59.89	0.93	−20.83	−14.67
I_{max} (A)	1.23	0.0083	0.99	0.0191	−19.51	+130.12
P_{max} (W)	93.07	1.7	59.04	1.16	−36.56	−31.76
FF	0.66	0.011	0.53	0.0065	−19.68	−40.90
Rs (Ω)	8.8	0.74	21.6	0.92	+145.45	+24.32
Rsh (Ω)	357	16	551	83	+54.34	+418.75

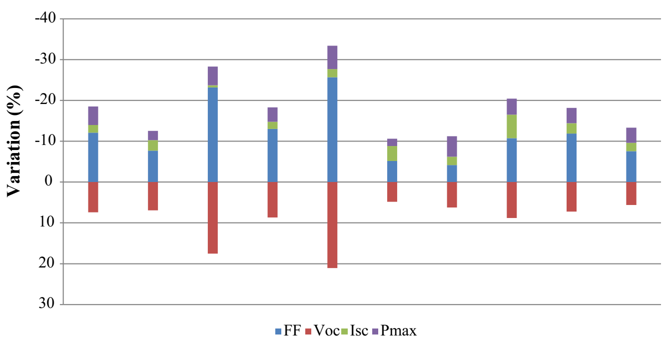

Fig. 10. Variation of characteristic parameters of HIT array modules after 28 months of outdoor exposure.

Fig. 10 shows the variation of characteristic parameters for the 10 modules of HIT array. It is found that the majority of the loss in peak power of HIT array modules corresponds to FF decay. Fig. 11 (a), (b), (c) & (d) show the frequency distributions of characteristic electrical parameters before and after degradation, along with corresponding Gaussian distributions. In HIT array modules the average peak power reduction is found to be 3.9% in 28 months. Taking into account that 3% of degradation takes place during first hours of exposure [32], the average annual degradation of the peak power of HIT array modules is found to be 0.36% which is in agreement with the previous findings [29–30]. This decay in peak power corresponds to the decay of 14.10% in FF. Average and standard deviation of characteristic parameters of HIT array modules before and after 28 months of outdoor exposure is given Table 3. The standard deviation of Pmax has increased by 113.33% between the initial and final measurements which is in agreement with the previous finding [31].

Fig. 12 shows the variations of characteristic parameters for the 11 modules of m-C-Si array. It is found that major peak power loss of m-C-Si array modules corresponds to I_{sc} decay. Fig. 13 (a), (b), (c) & (d) show the frequency distributions of characteristic electrical parameters before and after degradation, along with the corresponding Gaussian distributions. In m-C-Si array modules the average peak power is reduced to 4.24% in 2.5 years. Taking into account that 3% of degradation have taken place during first hours of exposure [32], the average annual degradation of the peak power of m-C-Si array modules is found to be 0.5% which is again in agreement with the previous findings [29–30]. This decay mostly

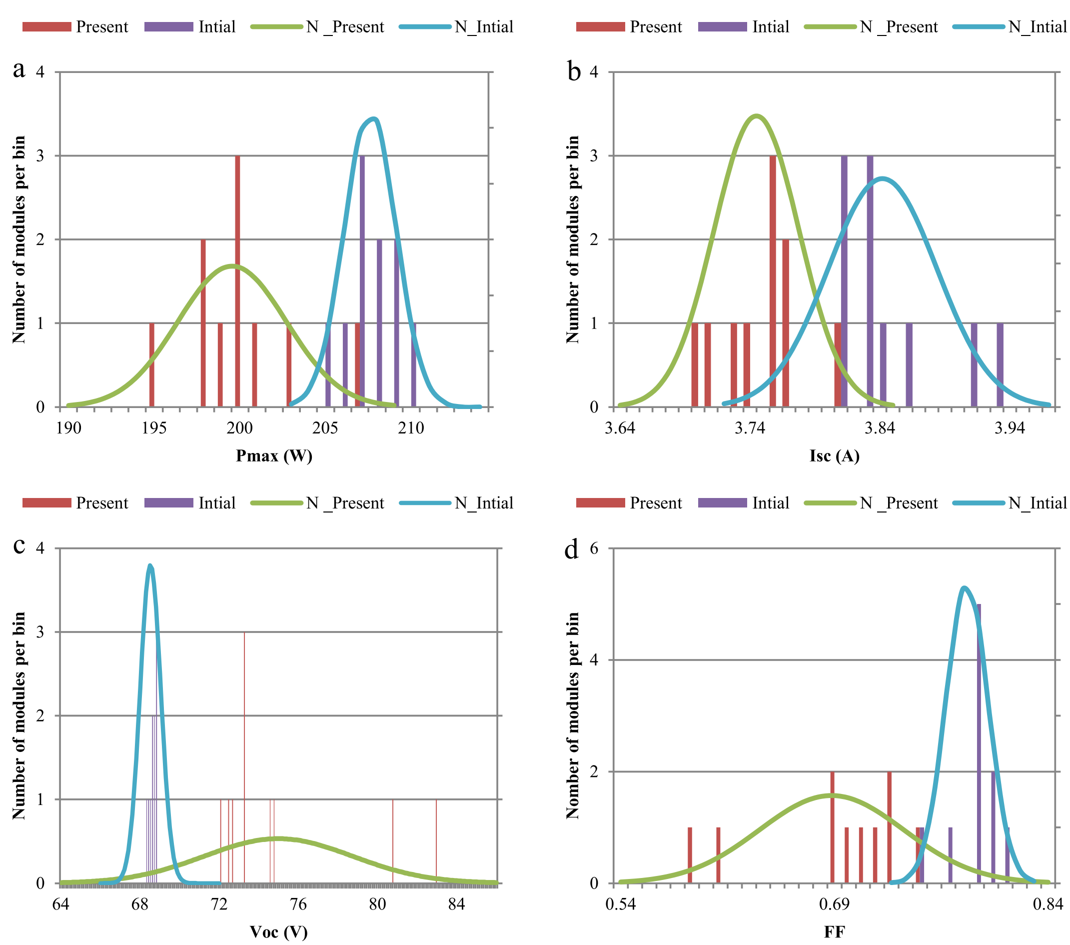

Fig. 11. Distribution of characteristic parameters of HIT array modules before (Initial) and after (Present) the outdoor exposure along with Gaussian distribution (a) for Pmax, (b) for I_{sc}, (c) for Voc, (d) for FF.

Table 3
Average and Standard deviation (SD) of characteristic parameters of HIT array before and after 28 months of outdoor exposure.

Parameter	Initial measurement		After 28 months		% Variation	
	Average	SD	Average	SD	Average	SD
V_{oc} (V)	68.52	0.17	74.98	3.75	+9.42	+2105.88
I_{sc} (A)	3.842	0.041	3.745	0.032	−2.52	−21.95
V_{max} (V)	56.58	0.4	57.26	1.2	+1.20	+200
I_{max} (A)	3.66	0.019	3.49	0.093	−4.64	+389.47
P_{max} (W)	207.6	1.5	199.5	3.2	−3.90	+113.33
FF	0.78	0.015	0.67	0.051	−14.10	+240
Rs (Ω)	2.5	0.1	3.9	0.08	+56	−20
Rsh (Ω)	238	119	75	4	−68.48	−96.63

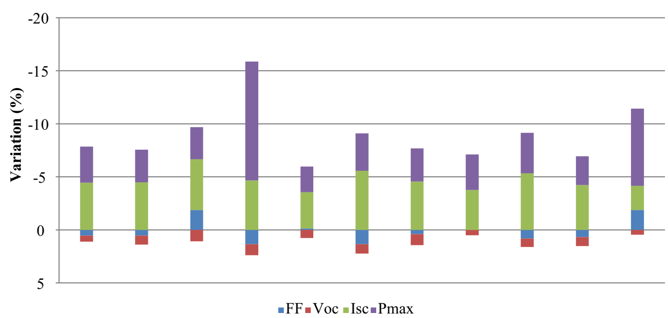

Fig. 12. Variation of characteristic parameters of m-C-Si array modules after 28 months of outdoor exposure.

corresponds to the decay of 4.9% in I_{SC}. The FF and Voc show very little variation, on the average. Average and standard deviation of characteristic parameters of p-c-Si array modules before and after 28 months of outdoor exposure is given Table 4. The standard deviation of Pmax has increased significantly between the initial and final measurements, which are in agreement with the previous finding [31].

The PV module performance loss in all three technologies has been found to be due to the decay in either short circuit current or fill factor or both of these. The performance loss of m-C-Si PV modules was mainly due to decay in short circuit current which can be related to the soiling of the glass due to which photon availability may be reduced and due to oxidation of antireflective coating observed in these modules. The performance loss of HIT modules was mainly due to decay in fill factor which can be attributed to an increase in the series resistance (Rs) or decrease in the shunt resistance (Rsh) or both. The values of series and shunt resistance estimated before and after 28 months of outdoor exposure during the STC measurements are presented in Table 3. It is clearly seen that average series resistance of HIT array modules has increased from 2.5 Ω to 3.9 Ω, showing an increase of 56%. Similarly, average shunt resistance of HIT array modules has decreased from 238 Ω to 75 Ω, showing a reduction of 68%. Despite significant change in the characteristic resistance of HIT array modules, no visual defects such as moisture ingress, oxidation of metallization grid are observed which can be correlated to the performance loss. The performance loss in a-Si PV modules is found to be due to decay in both short circuit and fill factor. The loss in short circuit current

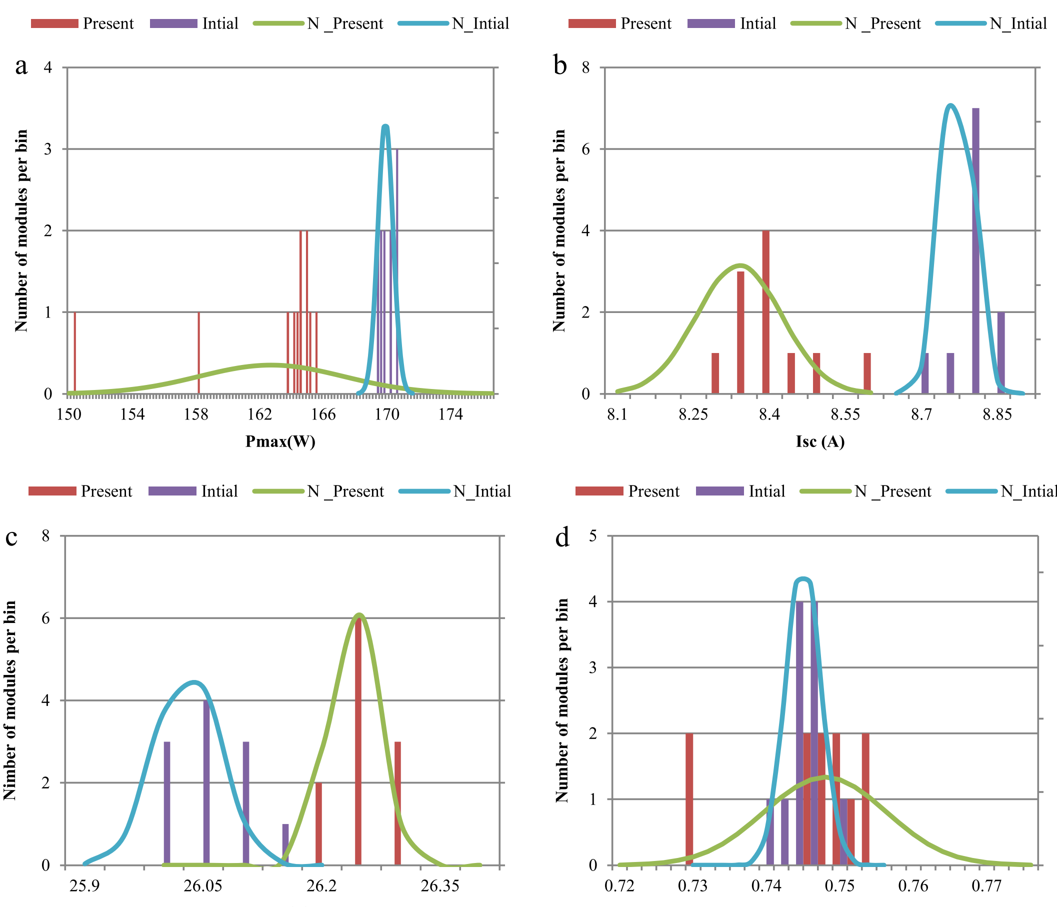

Fig. 13. Distribution of characteristic parameters of m-C-Si array modules before (Initial) and after (Present) the outdoor exposure along with Gaussian distribution (a) for Pmax, (b) for I_{sc}, (c) for Voc, (d) for FF.

Table 4
Average and Standard deviation (SD) of characteristic parameters of m-C-Si array before and after 28 months of outdoor exposure.

Parameter	Initial measurement		After 28 months		% Variation	
	Average	SD	Average	SD	Average	SD
V_{oc} (V)	26.03	0.041	26.24	0.031	+0.81	−24.39
I_{sc} (A)	8.77	0.031	8.34	0.084	−4.90	+170.96
V_{max} (V)	20.76	0.046	21	0.086	+1.16	+86.95
I_{max} (A)	8.19	0.0098	7.76	0.18	−5.25	+1736.73
P_{max} (W)	169.9	0.48	162.7	4.5	−4.24	+837.5
FF	0.746	0.0023	0.748	0.0081	+0.27	+252.17
Rs (Ω)	0.34	0.01	0.36	0.015	+5.88	+50
Rsh (Ω)	74	26	78	50	+5.41	+92.31

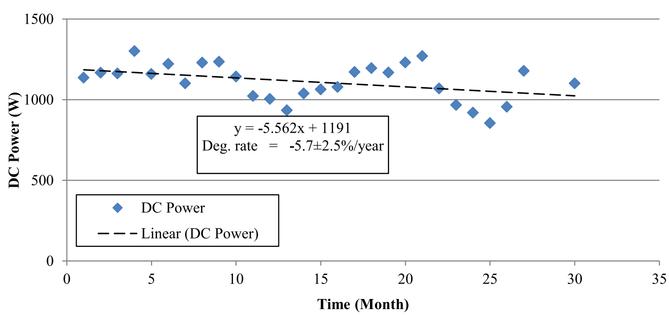

Fig. 14. PTC Power trend for a-Si PV array.

can again be related to the soiling of front glass. The fill factor decay can be attributed to increase in average series resistance (Rs) of a-Si PV modules (Table 2) but no visual defects are observed which can be correlated to it.

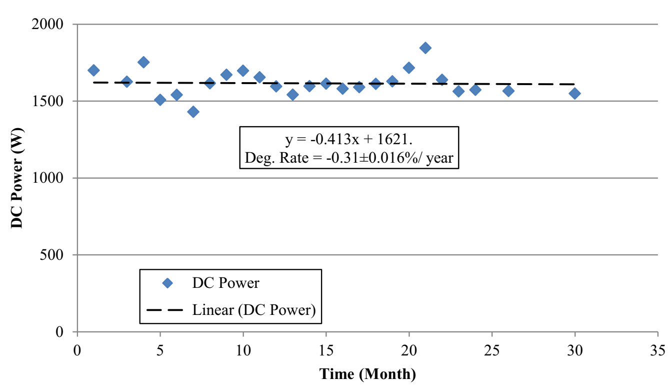

Fig. 15. PTC Power trend for HIT PV array.

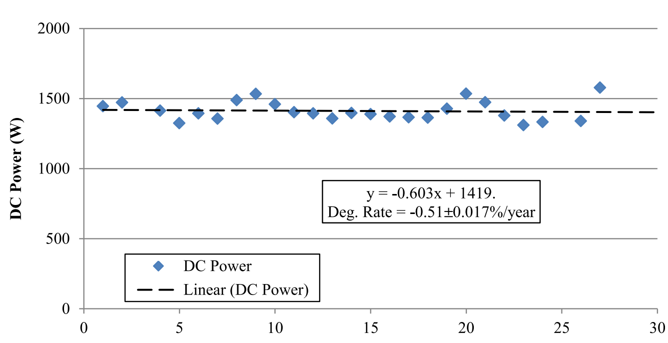

Fig. 16. PTC Power trend for m-C-Si PV array.

Table 5
Comparison of experimental and analytical degradation rates.

Array	Experimentally evaluated degradation rate using Sun-Simulator (%/year)	Analytically calculated degradation rate using PVUSA methodology (%/year)
a-Si	6.4	5.7
HIT	0.36	0.31
m-C-Si	0.5	0.51

The degradation in each technology is also calculated analytically through PVUSA regression methodology. The calculated monthly PTC power for each technology array is plotted along with the trend line as shown in Figs. 14–16. The degradation rates calculated from the trend line are found to be (−5.2 ± 2.5%/year), (−0.31 ± 0.016%/year) and (−0.51 ± 0.017%/year) for a-Si, HIT and m-C-Si arrays respectively. The analytical uncertainty reported along with the degradation rate is determined from the standard errors of the linear fit.

The analytically calculated degradation rates for each technology array are found to be in good agreement with the experimentally measured degradation rates. Table 5 summarizes the degradation rate of each technology array evaluated analytically and experimentally.

6. Conclusion

Degradation analysis of a-Si, HIT and m-C-Si PV technology modules of three different manufacturers is carried out at the outdoor test-bed research facility after 28 months of field exposure under Indian climatic conditions. Based on the analysis, the main conclusions are as follows:

- Soiling of glass, oxidation of antireflective coating, wavy pattern in the back sheet are the most frequent defects observed under Indian climatic conditions.
- No visual defects are observed in the HIT PV modules except soiling of glass, which indicate better stability of HIT technology under Indian climatic conditions.
- The Pmax decay in m-C-Si, HIT and a-Si PV modules is found to be due to decay in Isc, and FF.
- A comparison of degradation rates evaluated experimentally and analytically using PVUSA regression methodology shows that absolute percentage difference between degradation rates range between 2 to 14%.

Performance and degradation of these three PV technology modules will further be studied after a prolonged outdoor exposure to at least 10 years. The ongoing research with this test-bed facility will be helpful in providing inputs to review or revise PV testing standards according to Indian climatic conditions so as to ensure longer module lifetimes.

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Appendix 1

Table 6
Highlights of some of relevant PV module field degradation studies.

Sr. No	Location	Type of PV technologies studied	Duration of outdoor exposure	Degradation rate (%/year)	Comments	Reference number
1.	Port Elizabeth (South Africa)	c-Si m-c-Si EFG-Si	17 months	14% (in 17 months EFG-Si)	Degradation is evaluated by indoor *I–V* measurements. Moisture ingress and delamination are found to be dominant degradation mechanisms	[10]
2.	Perth (Australia)	c-Si p-c-Si a-Si CIS	16 months	0.5–2.7 1.0–2.9 18.8 12.6	degradation is evaluated through indoor *I–V* measurements	[11]
3.	Mesa, Arizona (USA)	c-Si p-c-Si a-Si	2.4–6.7 years	0.4 0.53 1.16–3.2	degradation is evaluated through indoor *I–V* measurements	[12]
4.	Golden Colorado (USA)	c-Si	8 years	1.0	Continuously outdoor recorded data is used to evaluate degradation rate using PVUSA methodology and power equation	[13]
5.	Hamamatsu (Japan)	c-Si	10 years	0.6–1.0	degradation is evaluated through indoor *I–V* measurements	[14]
6.	Ispra (Italy)	p-c-Si	22 years	0.3	degradation is evaluated through indoor *I–V* measurements Modules encapsulated with silicon sealant showed less power degradation than modules encapsulated with EVA.	[15]
7.	Lugano (Switzerland)	c-Si	21 years	0.5	Outdoor measurements are used to evaluate degradation rate.	[16]
8.	Ma'laga (Spain)	c-Si	12 years	0.7	Continuously outdoor measured data is used to evaluate degradation rate.	[17]
9.	Gurgaon (India)	c-Si	10 years	5–16.5 (IEC qualified modules) 17–33 (not IEC qualified modules)	In door *I–V* measurements are done to evaluate degradation before and after the outdoor exposure.	[19]
10.	Gurgaon (India)	a-Si HIT m-c-Si	28 months	6.4 0.3 0.5	Both indoor I–V measured data and continuously outdoor recorded data is used to evaluate degradation rate and a comparison of both approaches is also presented.	Present study

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