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A novel study for determining early life degradation of multi-crystalline-silicon photovoltaic modules observed in western Himalayan Indian climatic conditions

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Abstract

The results of a first time study are reported on the degradation of a roof mounted multi-crystalline-silicon photovoltaic system after 2.5 years of outdoor exposure in a western Himalayan location in India. The main objective of the study is to identify frequently occurring defects in modules to study the change in electrical performance parameters and correlate these with identified defects under Indian climatic conditions. A comprehensive test campaign is conducted by visual inspection, thermal imaging and current–voltage characteristic measurements. Early degradation and recently reported defect: snail trails are observed in all modules along with non-uniform single cell browning and junction box failure. Thermal imaging analysis is carried out which shows that three modules developed serious defects like hotspots, disconnected cells and string interconnect ribbons and a significant result that all solar cells located directly on top of junction boxes were 3–8 °C hotter than other cells indicating higher thermal degradation rate of these cells than others. Peak power degradation of modules is quantified by measuring performance parameters under standard test conditions as a function of field exposure time, using class-A sun-simulator. Three modules showed 50% degradation while remaining seven modules showed 0.6–2.5% degradation in peak power after 2.5 years. PV modules certified as per International Electro-technical Commission (IEC) standards have shown considerable degradation indicating the need to enforce quality control and review qualification standards for Indian climatic conditions if modules have to perform reliably for more than 20 years under field conditions. The outcome of the study will be of importance to enhance the knowledge of climate specific field PV degradation mechanism and to provide inputs to Indian/IEC standards, the improvements of which are being considered currently.

Keywords: Photovoltaics; PV degradation; Multi-crystalline silicon; Snail trails

1. Introduction

Solar photovoltaic (PV) modules convert Sun's energy into electricity thus providing a non-exhaustible energy conversion alternative. With decrease in price of solar panels and increase in conversion efficiencies, a large number of rooftop PV systems and PV plants are being installed worldwide. The cost of PV modules ranges from 40% to 60% or 30% to 50% of the total cost depending on whether it is a stand alone or grid interactive PV system respectively (IRENA, 2015). The advancement in PV technology has led to decline in the cost of PV modules from \$3.3/W_p during early nineties to \$0.6/W_p during 2014 (REN21, 2014) and is expected to decline further to \$0.45/W_p or less. The change in module design, manufacturing processes and development of new low cost materials after 2004 has led to this reduction in cost (Zielnik, 2013). The current

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module designs include thinner silicon (Si) wafer (∼120 μm), less encapsulant layers, thin sized n-type wafers and all back contact technologies to increase efficiency and counter the Potential Induced Degradation (PID) effects. In monolithic thin film modules, frameless designs, alternative back-sheet materials and modified cell interconnect are incorporated to improve reliability and to resist impact due to leakage currents under high temperature, humidity and high voltage environment. However, it is still not clear whether these changes have affected durability and reliability as compared to earlier designs and require in depth studies.

All these issues related to long term reliability of PV modules are gaining more importance. The qualification standards developed by International Electro-technical Commission (IEC), such as IEC61215 (wafer based crystalline Si modules) and IEC 61646 (thin film modules) and IEC61730 have helped to ensure long term reliability of PV modules to some extent (IEC 61730, 2004; IEC 61215, 2005; IEC 61646, 2008). Ideally, it is considered, that these standards are devised to simulate severities which PV modules experience under actual field conditions during a span of 20–25 years. However, qualifying IEC standards, does not guarantee long-term performance or service lifetime (Osterwald and McMahon, 2009). There are number of reports which show that PV modules have survived in field for more than 20 years along with reports where qualified modules have failed in the field before completing the required service lifetime. Thus, it is now broadly believed that these IEC standards are not adequately addressing the real outdoor conditions.

During the outdoor operation, noticeable changes/defects are observed in appearance and performance of the PV modules which indicate that these modules may have degraded resulting in the decrease in the output power of the PV modules. So, it is important to understand the generation of defects and how these defects result in decrease in power output of PV modules with time in order to make technology commercially acceptable. Generation of defects and their growth resulting in degradation is mainly due to environmental stresses such as: temperature, humidity, UV radiation etc. experienced by PV module during the outdoor operation as such generation of defects and degradation are likely to depend on the local climate and climatic zone (Jordan et al., 2012).

Therefore the information on field performance and degradation of PV modules from various climatic zones is required, so that enough details are available to provide quantitative predictions of field performance and service life. Also a reliable database on outdoor weathering is required for developing realistic and effective procedures for accelerated testing to simulate 25 years of operation.

Keeping in view these aspects, results of degradation of PV modules in the western Himalayan region are reported for the first time. The results presented in this study are of significance in the context of quality and problems faced in field installed PV modules. Also such degradation studies have not been carried out at present in detail in different parts of India except at the National Institute of Solar Energy, Gurgaon location.

In the present study degradation analysis of 1 kW_p multi-crystalline silicon (m-C-Si) PV system after 2.5 years of outdoor exposure in the cold climatic conditions of western Himalayan region is carried out. The main objective of the study is to identify frequently occurring defects in the modules to study the change in the electrical performance parameters and correlate these with identified defects under Indian climatic conditions. The main defects observed in the studied modules are junction failure, surface browning, hotspots and snail trails. Some defects reported may be caused due to climatic conditions in the western Himalayan location but other defects are due to poor quality of materials used during manufacturing. The outcome of the study will be helpful to quantify the PV modules degradation and review the accelerated aging qualification tests depending upon the dominant field degradation mechanisms.

The paper is organized as follows: a brief overview of research studies on degradation and defects occurring in photovoltaic panels are presented in Section 2. Details of experimental PV setup are given in Section 3. In Section 4 degradation analysis methodology followed in the present study is described. The results and discussion are presented in Section 5. The conclusions are given in Section 6.

2. Brief overview of degradation in photovoltaic modules

Modules degrade slowly, but some defects can reduce the module performance significantly. A brief overview of main degradation research studies and types of defects are presented in this section.

2.1. Research highlights

Various methods to study PV degradation are discussed in a detailed review by Ndiaye et al. (2013). The modules in countries with higher ambient temperatures are found to show enhanced "yellowing" of the encapsulant (Palmblad et al., 2009). PV modules need to be tested to identify the defects using different methods like visual inspection and thermal imaging (Munoz et al., 2011). Djordjevic et al. (2014) studied various defects in PV modules after an exposure of test modules to environmental conditions up to ten years and compared with reported defects to identify defects specific to Western Australia (WA). However, no new defect specific to WA conditions were found. Paul et al. (2011) investigated the degradation mechanism in a 2 kW_p PV installation after 12 years of outdoor operation using 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 peak power of the installation was found to be 11.5%

which was due to the loss in short circuit current. Makrides et al. (2014) recently reported the annual performance loss rates of 12 different grid connected PV technologies using the statistical techniques of linear regression and classical series decompositions (CSD) methods over a five-year period. The performance loss rate obtained by applying CSD was found to be slightly higher than the statistical techniques of linear regression, highlighting the importance of the choice of the analysis technique which affects the results. Jordan and Kurtz (2013) recently reviewed the degradation rates from the field studies carried out during last 40 years and concluded that the average of power degradation rates distribution is found to be 0.8% per year. Va´zquez and Rey-Stolle (2008) developed a photovoltaic reliability model based upon the field degradation studies and discussed the issues related to lifetime and warranty and pointed out that standard deviation in power output of PV modules increases with the time of outdoor exposure.

PV industry has started finding applications with variety of mounting configurations in different climatic zones worldwide. The performance and degradation of PV modules will be different in different climates because the levels of stresses experienced will be different and thus there is a need to make the qualification standards more quantitative (Wohlgemuth and Kurtz, 2014).

The present study is in continuation with earlier degradation studies of different technology PV modules by authors under different climatic conditions in India (Chandel et al., 2015; Sharma et al., 2013, 2014; Sharma and Chandel, 2013).

In the next section we have summarized various types of defects in order to provide the reader basic information.

2.2. Defects observed in PV modules

Based on literature review the types of defects observed in PV modules are:

2.2.1. Discoloration

Discoloration is one of the most common defects in solar modules. This effect is mostly seen in modules that have been operating under outdoor conditions for a long time. It reduces the sunlight reaching on solar cells. The discoloration is most probably caused by internal factors like poor encapsulant quality or external ones such as high temperature and humidity. Discoloration is of two types:

- Yellowing and browning of module surface
- Discoloration of grid fingers

Yellowing and browning can appear in PV modules due to dry heat (e.g., due to desert climate), high UV radiations, and humidity. It also occurs because of insufficient adhesion between cells and glass material (Quater et al., 2014).

2.2.2. Cracking

Cracks can be detected during visual inspection test, if they are large enough. Micro-cracks are formed during manufacturing when mechanical and thermal stress is applied. These cracks can become larger when subjected to further stress by outdoor environmental conditions, after years of operation in the field. Electroluminescence imaging detects micro-cracks very well. Cracks in solar cells can reduce the module output (Köntges et al., 2011).

2.2.3. Snail trails

After some months of operation, a number of PV modules develop a discoloration defect called "snail trails", or "snail tracks", which appear as irregular dark stripes/brownish coloured contact fingers across the cells. It is found that snail tracks appear after 3–5 months of outdoor exposure (Köntges et al., 2008).

2.2.4. Antireflection (AR) coating damage

AR coatings show changes in spectral transmittance mainly in the high visible range (600–700 nm). AR coating damage and performance loss can result from dirt and dust settling (Jorgensen et al., 1999).

2.2.5. Hot spots

When a solar cell within a module generates lesser current than the string current of the module then hot spot appears on that cell. It generally occurs when the cell is shaded, damaged or electrically mismatched. Hot spots are responsible for properties of the solar cell like local shunts, deformations of the p–n junction, impurities, and wafer resistance (Wendlandt et al., 2011).

2.2.6. Soiling

Soiling is a form of shading. It can decrease the module's performance with time. It occurs due to dust concentration. Soiling consists of dust, grime, bird droppings and moss in some situations. It negatively affects the output current of the cells (Solmetric, 2011).

2.2.7. Busbar oxidation and corrosion

It is responsible for diminished output including loss of adhesion and delamination, chemical instability under current collection conditions, and compatibility of materials (Pankow, 2004).

2.2.8. Encapsulant delamination

The encapsulant is made up of EVA (Ethylene Vinyl Acetate), processed under defined temperature and time during the lamination. Use of cheap material and incorrect processing results in delamination. One of the major degradation situations of PV modules is encapsulant delamination. It occurs at the interface between the encapsulant and the front surface of the solar cell and between the encapsulant and the glass cover (Park et al., 2011). Encapsulant should be tested for moisture, resistivity, adhesion, etc. (Jorgensen et al., 2003). In this context Poulek et al.

(2012) developed the silicone gel lamination technology, c-Si PV panels laminated with this were prepared and tested at 3.5 times concentrated solar radiation in the UV chamber. The reduction in the transparency induced by UV radiation in the silicone gel laminated modules was found to be negligible in comparison to EVA-laminated panels. It is finally suggested that silicone gel laminated PV panels can have 50 years lifetime because of the reduced corrosiveness which is main source of failures in commercial PV panels.

2.2.9. Defect due to physical impacts

Modules when subjected to extreme physical impacts result in breakage of the glass on their surface. These physical impacts are generally caused by weather, mishandling upon relocation or major thermal expansion mismatches.

3. Description of roof mounted 1 kW_p PV experimental setup

The 1 kW_p PV system consisting of multi-crystalline Si modules was installed on the roof top of Centre for Energy and Environmental Engineering (CEEE), National Institute of Technology, Hamirpur (NIT-H) in July, 2012. NIT-H is located in the western Himalayan region of Himachal Pradesh (Latitude 31.49°N, Longitude 76.52°E, altitude is 875 m above mean sea level). The array consists of 10 modules of 100 W_p rating each connected in series with number marked on each module to be used as reference for further analysis (Fig. 1).

Modules are mounted on a steel rack facing south and an inclination of 31° from the horizontal. Output of 1 kW_p array is fed into 120 V, 150 A h battery storage bank and used to meet the load of CEEE partially.

The average annual global horizontal solar radiation at the location varies between 3 and 6 kW h/m^2/day. The annual average ambient temperature of the location is 22.01 °C with minimum 11 °C in January (winter) to 34 °C in May (summer) respectively where as the average annual relative humidity 66.29% with minimum of 27.53% in May (Summer) and maximum 93.11% in August (rainy season). The yearly average wind speed is 2.07 m/s .The variation of back surface module temperature with monthly ambient temperature is shown in Fig. 2, which is always higher than ambient temperature under outdoor conditions. The higher operating temperature of the modules is due to the fact that the modules are able to convert only a part of incident energy to electrical energy as per the module efficiency and rest is used to generate heat which results in the elevated module temperatures.

Fig. 1. 1 kW_p multi-crystalline Si PV experimental setup at CEEE, NIT Hamirpur.

The manufacturer data of electrical and mechanical specifications of m-C-Si PV modules are given in Table 1.

4. Degradation analysis methodology

The degradation in the individual PV modules of the array was investigated through a comprehensive test campaign by following techniques:

(i) Visual inspection of the modules.
(ii) Infra-red thermal imaging.
(iii) I–V curve measurement of all modules and comparison with the initial measurements.

4.1. Visual inspection

The degradation of PV modules results in generation of various types of defects some of which can be detected by visual inspection. Visual inspection is one of the important methods to identify degradation in PV modules as it can detect encapsulant browning, delamination and bubble formation in the encapsulant, back sheet polymer cracks, front surface soiling, blackening at the bottom edge of the module, junction box connections corrosion, bus bar oxidation and discoloration, junction cables insulation degradation and glass breakage. The details of visual defects observed in field aged modules, is discussed by Polverini et al. (2013). All the 10 modules of the installed 1 kW_p PV system were visually inspected and results are discussed later in Section 5.1.

4.2. Infrared thermal imaging

Infrared thermal imaging is a non-destructive technique to identify defects in field aged modules which are not observed during visual inspection. Outdoor Infrared imaging detects hot spots undergoing excessive heating. The technique consists of using a camera sensitive to infrared radiation of 3–15 μm range by using the concept of localized heat generation due to joule heating effect because of poor contacts, shunted cells, short circuits. This happens because solar cells which are generating less current as compared to 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

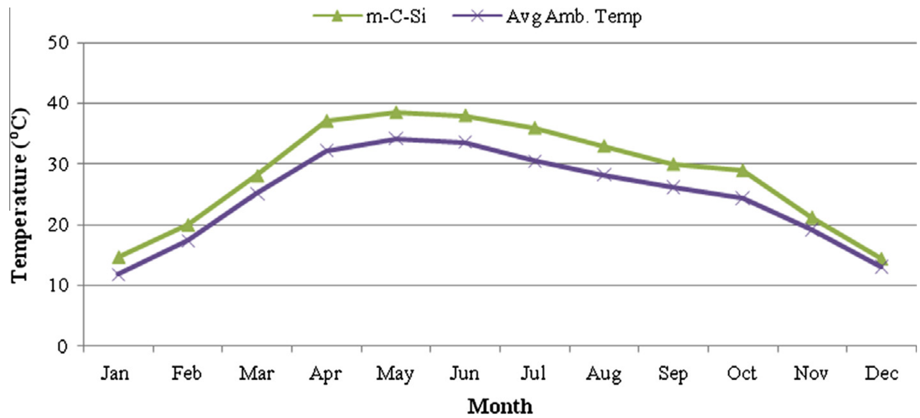

Fig. 2. Variation of back surface module temperature with monthly ambient temperature.

Table 1
Specifications of m-C-Si PV modules.

Parameter	Specifications
Make	Sun Energy Systems, India
Model	SES 100
Technology type	Multi-crystalline Silicon
Open circuit voltage (V_{oc})	21.0 V
Short circuit current (I_{sc})	6.40 A
Maximum voltage (V_{max})	17.0 V
Maximum current (I_{max})	5.90 A
Maximum power rating (P_{max})	100 W_p
Mechanical dimensions ($L \times W$)	1.3 m × 0.65 m

during thermal imaging appear as bright spots. In addition to this there can be other reasons for the hot-spots which are related with the irregularities during the fabrication process such as poor soldering of cell interconnects or bypass diode failure which may result in an increment in temperature. Modules in the 1 kW_p PV array were analysed using a handheld FlukeTi125 Infra-red thermal imager shown in Fig. 3. The technical specifications of the thermal imager are given in Table 2.

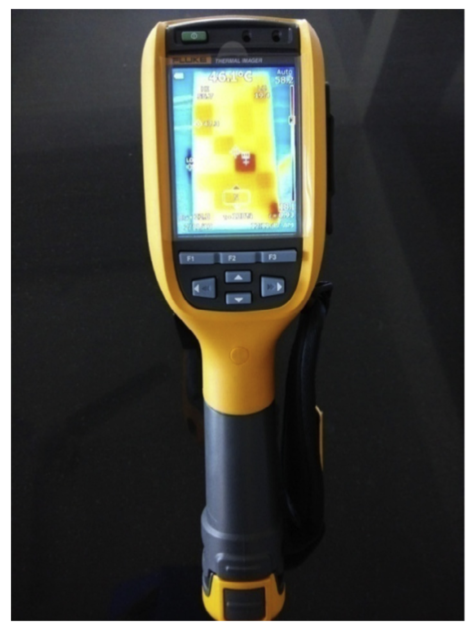

Fig. 3. Hand held Fluke Ti125 thermal imager used in the study.

4.3. I–V characteristic measurements

I–V characteristics of each individual module were measured after the outdoor exposure and compared with initially recorded values using Endeas Quick Sun 700 class-A, sun simulator installed at indoor testing facility of PV research laboratory of CEEE shown in Fig. 4 and schematic of sun simulator is shown in Fig. 5.

A 6000W Xenon flash lamp with AM 1.5G filter to conform class ‘A’ spectrum is used as light source. The electronic unit uses 4-wire parallel voltage sensing terminals for excluding loss in current carrying cables. Also, it has adjustable internal power source for biasing the module to real short circuit. The irradiance no-uniformity is less than ±2% as required for class ‘A’ and power reproducibility is less than ±0.25% for this system. The technical specifications of the sun simulator used are given in Table 3.

Appropriate reference cell and calibrated module are used for STC measurements. The poly crystalline silicon module from Naps, Germany (Naps-85) and reference cells p-C-Si (Ref. No. NS73) calibrated at Fraunhofer Institute of Solar Energy, Germany were used for characteristic measurements of PV modules. Before starting the STC measurements, calibration of monitor cell was carried out using the reference cell and module. This was done in order to ensure that there was no major difference in the subsequent measuring conditions. Prior to I–V measurements all the modules were cleaned to remove the dust accumulated on the front glass. I–V characteristics were measured under standard test conditions (STC), i.e. 1000 W/m^2 irradiance, Air Mass 1.5 and ambient temperature 25 °C as per in IEC 60904-1 standard guidelines (IEC, 2006). A pulsed light of few milliseconds is triggered through Xenon flash lamp to illuminate the PV module under test. Module is swept from short circuit to open circuit in

Table 2
Technical specifications of Fluke Ti125 Infrared thermal imager.

Parameter	Range
Temperature range	−20 °C to 250 °C
Accuracy	±2 °C
Emissivity correction	Variable from 0.01 to 1.00 (in 0.01 increment)
Display	Color LCD, 3.5″ diagonal
Field of view	31° × 22.5°
Spatial range	3.39 m rad
Minimum focus distance	15 cm (approx)
Image capture rate	9 Hz or 30 Hz
Detector type	160 × 120 focal plane array
Thermal sensitivity (NETD)	⩽80 mK

2 ms (approximately) and current, voltage and irradiance signals are recorded simultaneously. The measured raw data is transformed to define irradiance and temperature condition of 1000 W/m^2 and 25 °C respectively. Transformation of raw data to STC condition is done by the software running the electronic measurement unit of the sun simulator internally. From the transformed data the I–V curve is generated along with relevant performance parameters.

5. Results and discussion

The results of degradation analysis are presented in this section.

5.1. Visual inspection results

Visual inspection of 10 m-C-Si PV modules of 1 kW array showed generation of snail trails and browning of a single cell.

5.1.1. Snail trails

Snail trail is a discoloration of the silver paste used for the gridlines on the cells. The discoloration appears along

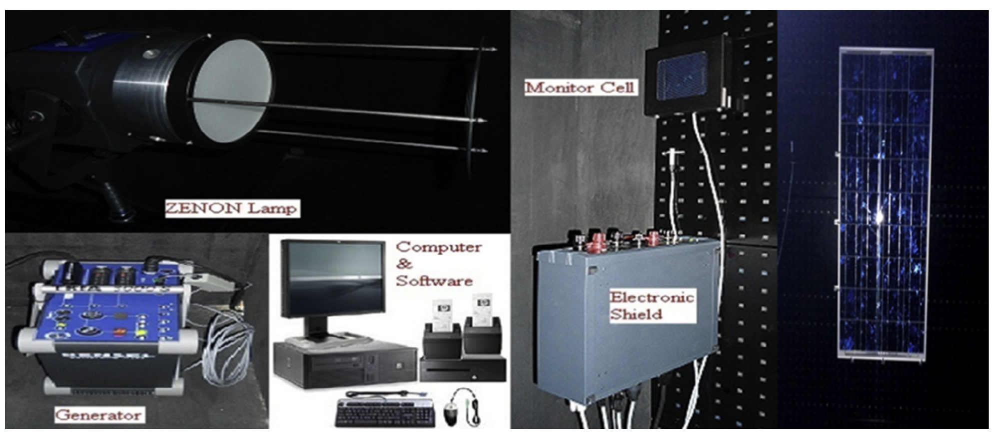

Fig. 4. Large area sun simulator at PV research laboratory, CEEE.

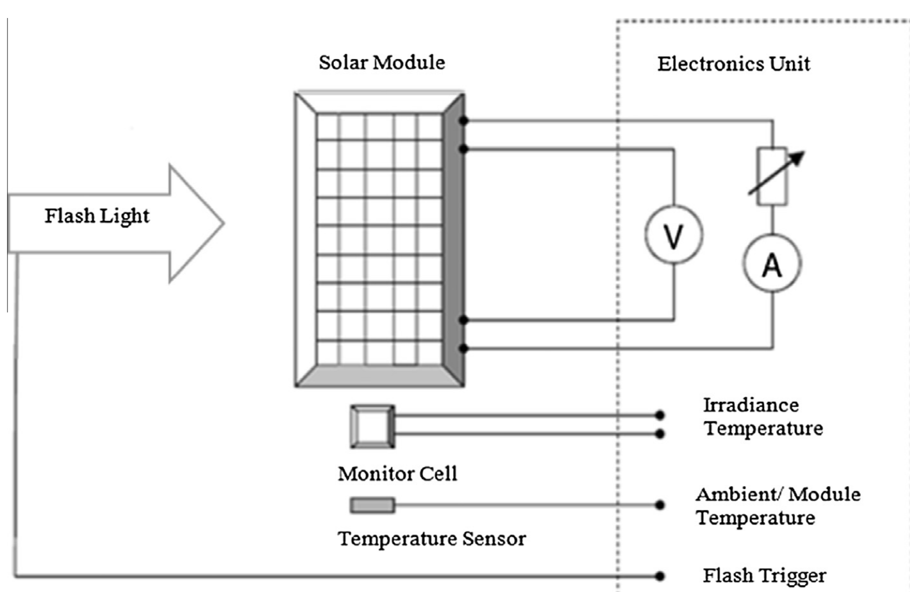

Fig. 5. Schematic of sun simulator.

Table 3
Technical specifications of large area Class-A sun simulator at CEEE, NIT Hamirpur.

Parameter	Specifications
Lamp life	40,000 flashes
Irradiance uniformity	±2%
Current variation	0.25–6 A, 0.5–12 A and 1–25 A
Voltage variation	1–50 V, 1–100 V and 2–200 V
Irradiance level	200–1200 W/m^2
Resolution	1 W/m^2
Reproducibility	±0.25%
Ambient temperature	10–40 °C
Operation temperature	15–35 °C
Mains 115/230 V ac, 50/60 Hz	115/230 V ac, 50/60 Hz
Nominal test area	200 cm × 160 cm

cell cracks. Almost all the modules showed generation of snail tracks which is moving in 50–70% modules area. Snail trails generated in the modules is shown in Fig. 6.

The origin and loss in power due to generation of this defect is still not understood. However a number of authors have tried to explain the origin of the defect. Peng et al. (2012) has explained the origin of snail trails due to the formation of silver carbonate nano particles. Experimental analysis indicates that presence of a large number of nano particles (<30 nm) is responsible for darker colour or discoloration of the surface of the modules. The presence of nano particles on a material will often darken it as they can scatter and more specifically, absorb a wide range of visible light wavelengths resulting in dark discoloration. Thus, the presence of nano particles on Ag grids gives incrementally darker coloration than normal grids that are free of nano particles.

Additionally, snail trail discolorations within the cells are also associated with cell micro cracks on the SiN films which act as secondary light trapping sites to promote the dark discoloration. Moisture, oxygen, carbon dioxide and other compounds could gain access through micro pores, cracks and cell edges or pass through the de-bonded areas between the encapsulation layer and the Si substrates to interact with and oxidize the silver grid. Snail trails can be also related to moisture reacting with PV module materials as polymers. The front sunny side of the module acts as an effective barrier to protect it from moisture.

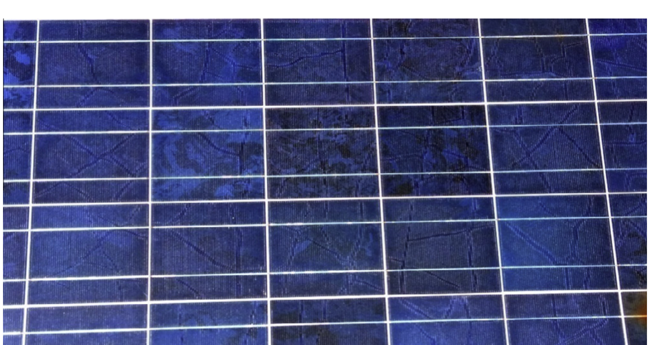

Fig. 6. Snail tracks generated in the modules of 1 kW$_p$ PV array.

Meyer et al. (2013a,b) suggested that moisture is the main cause of snail trail formation. The air moisture penetrates the PV module from the back sheet, cell edges or micro cracks from where water enters and may diffuse onto the cell surface where a small fraction of silver from the grid fingers may dissolve and migrate into the encapsulation foil on top of the grid fingers and through a chemical reaction. The dissolved silver ions are reduced and form metallic nanoparticles exhibiting a typical brownish colour.

Richter et al. (2012) concluded that the snail trail effect is correlated with Ag containing particle clusters which diffuse through the EVA (Ethylene Vinyl Acetate) polymer. The involvement and chemical binding with S and/or P seems to cause the discoloration. Also Cl might have an initial influence on the chemical reaction chain. Another explanation is that the presence of an electrical field, temperature and UV irradiation corrode the interface between silver contact and encapsulation foil leading to a migration of silver into the EVA foil and forming Ag containing particles (Meyer et al. 2013a,b; Köntges et al., 2012).

Few researchers have investigated the effect of snail tracks/micro cracks on PV module performance. However, the results found are contradictory as some studies show that there is decrease in performance of PV modules affected with snail trails while others found no deviation in module performance compared with reference modules with no snail tracks.

Dolara et al. (2014) carried out two different experimental analyses to evaluate the effect of snail trails on the PV modules performance under real conditions. The results suggested that it is more likely the cell cracks instead of snail trails are the reason for decrease in performance loss. It was also found that when the solar radiation is low and the contribution of the diffuse radiation is higher, the performance of snail track affected PV module are close to the reference panel, thus suggesting that snails trails negatively affect the conversion efficiency of the direct solar radiation.

5.1.2. Single cell browning

A single cell showed browning or discoloration in module no. 6 (Fig. 7). Faster browning of this cell clearly shows that this portion is operating at higher temperature than the rest of the modules area and indicates the generation of hotspots at this place. The thermal images of module were taken to identify the presence of hotspots and discussed in the next Section 5.2.

5.1.3. Junction box failure

The junction box (JB) is the container fixed on the backside of the module which protects the connection of cell strings of the modules to the external terminals. Generally the junction box contains the bypass diodes to protect the cells in a string in case of hot spot or shadowing.

During visual inspection it was observed that the junction boxes of module no. 2 and 10 showed burnt marks outside (Fig. 8). Junction boxes of these two modules were then opened and it was found that the plastic covering over

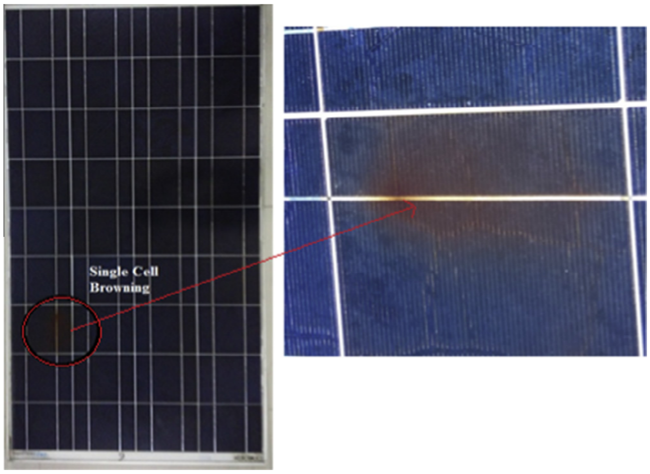

Fig. 7. A single cell showing non uniform browning in PV module no. 6.

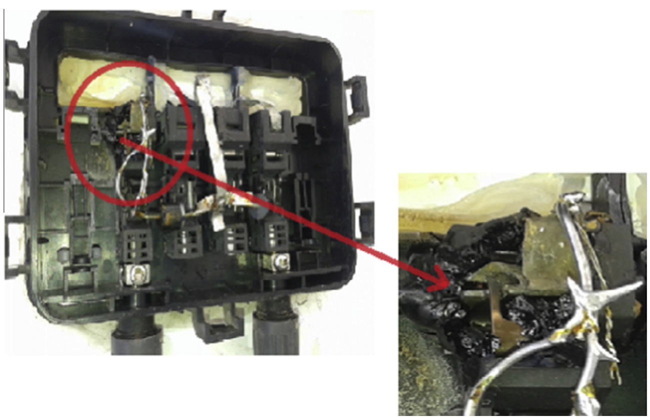

Fig. 8. Junction box failure in PV modules no. 2 and 10.

the joint (between the terminal in the junction box and terminal from the string interconnect) was burnt and melted.

The cause of burning and melting was due to sparking in the joint between the terminal of the junction box and string interconnect terminal. It was due to poor design of contacts made for joining junction box terminal with the string interconnect terminal. There was no rigid contact made, but rather some sort of plug in the system that too without any screws, leading to free joints.

Bad wiring resulted in internal arcing (burn marks) in the junction box. This failure is particularly dangerous because the arcing can initiate fire. Poor soldering contacts of the string interconnects could cause high resistance and consequent heating in the junction box. In extreme cases the fire danger increases. These bad soldering contacts are caused by low soldering temperature or chemical residuals of the previous production process on the solder joints.

5.2. Infrared thermal imaging results

Thermal image of the entire 1 kW_p PV array along with visual image is shown in Fig. 9. Hotspots are clearly visible in the module no. 6 of the array.

One of the most significant findings from the thermal imaging analysis was the fact that all solar cells lying directly on top of the junction boxes were approximately 3–8 °C hotter than the rest which indicates higher thermal degradation of the cells at these locations could be taking place at higher rates. In order to have more clear view, thermal image of 1 kW_p system is again shown in Fig. 10.

The important finding from Fig. 10 is that module no. 6 clearly shows the hotspots. Conventionally wafer-based c-Si PV modules have number of solar cells, which are interconnected in series with cell interconnect ribbons to obtain higher voltage. These cell interconnect ribbons are connected from the front side to the rear side of the solar cells. A series of interconnected cells is called a string. These cell strings are typically interconnected in series or sometime in parallel by string interconnect ribbons. A weak cell or string interconnect ribbon can result in disconnections. There may be several possible causes of this PV module failure. Poor soldering in the PV module production process of the connection between cell interconnect ribbon and string interconnect is the most important reason for disconnections. A too intense deformation during the fabrication of the ribbon kink between the cells mechanically weakens the cell interconnect ribbon. A narrow distance between the cells promotes cell interconnect ribbon breakage. Physical stress during PV module transportation, thermal cycle, and/or hot spots by partial cell shading during long-term PV system operation forces mechanical

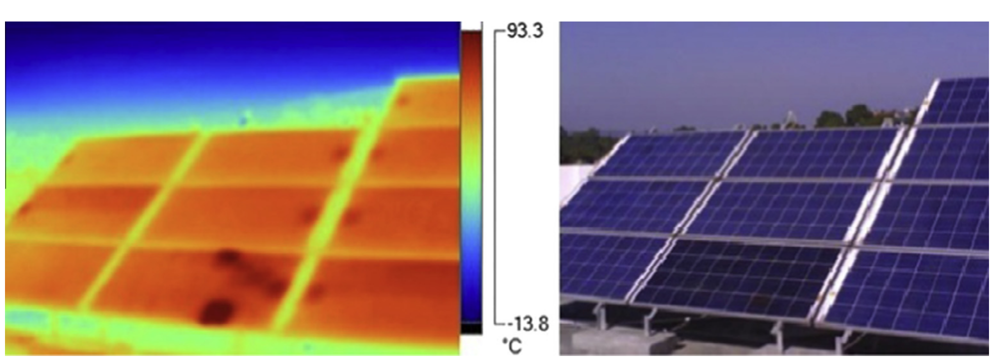

Fig. 9. Infra-red thermal image of roof mounted 1 kW_p PV array.

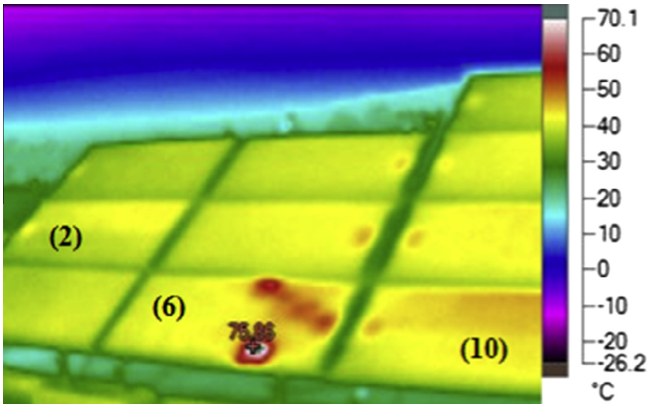

Fig. 10. A disconnected cell interconnections found in the module no. 6.

weak ribbon kinks to break. The photograph of disconnected cell interconnect ribbon of module no. 6 near the hot spot area is shown in Fig. 11.

The module no. 2 and 10 have shown half of the portions at higher temperatures. The junction box failure of module no. 2 and 10 discussed in Section 5.1.3 is again highlighted in the thermal image as half of the portions of these modules are showing higher operating temperatures. The results of the visual inspection and thermal imaging of 1 kW_p m-C-Si array are summarized in Table 4.

5.3. I–V characteristics measurement results

Prior to the deployment at the PV outdoor experimental setup at CEEE, I–V characteristic measurement of one module (module no. 7) of PV array was carried out on 7th May 2012 using the Class-A sun simulator of PV Research laboratory at CEEE and kept as a reference. The STC measurements of all 10 modules were again carried out on 7th November 2014 after 2.5 years of outdoor exposure. In order to keep the reference initially only one module is measured under sun simulator because of the fact that the standard deviation of power output of batch of PV modules of same technology, model, manufacturer and capacity is negligible or very less before the outdoor

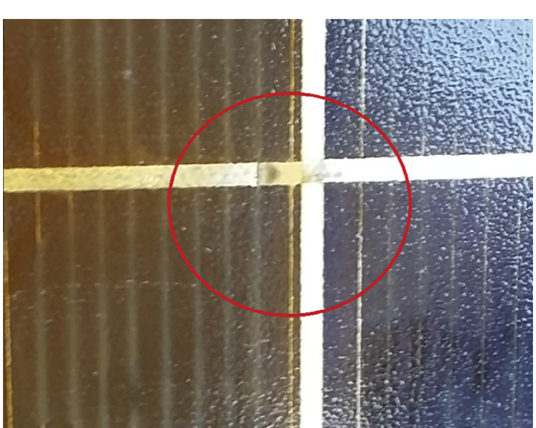

Fig. 11. Image of disconnected cell interconnect ribbon.

Table 4
Summary of visual and thermal imaging analysis.

Type of defect	Number of PV modules affected	Percentage of solar cell area affected (%)
Glass soiling	0	N.A.
Delamination	0	N.A.
Front grid oxidation	0	N.A.
AR coating oxidation	0	N.A.
Cell cracks	0	N.A.
Hot spots	3	30–50
Back sheet delamination	0	N.A.
Frame defects	0	N.A.
Junction box defects	2	N.A.
Defective by-pass diodes	0	N.A.
Bus bar corrosion	0	N.A.
Major bubbles	0	N.A.
EVA browning	1	2
Snail trails	10	30–70
Disconnected cell, interconnect ribbon	1	N.A.

exposure and increases with time in the outdoor exposure (Paul et al., 2011; Sharma et al., 2014; Va´zquez and Rey-Stolle, 2008). It may be pointed out that most of the studies on degradation are reported with respect to the rated values provided by the manufacturer whereas in the present study we have used actual measured values rather than the rated values of characteristic parameters which are expected more accurate results. This is because the datasheet information may not necessarily match the actual values measured under sun-simulator (Carr and Pryor, 2004). A comparison of manufacturer's specifications and actual measured values of characteristic parameters of reference module no. 7 under sun-simulator before the outdoor deployment is given in Table 5.

The deviation between the values of characteristic parameters measured initially (reference module 7) and after the outdoor exposure (all the 10 modules) were calculated and plotted in Fig. 12 showing the degradation in each characteristic parameter of the PV modules.

Module no. 2, 6 and 10 have shown 50% average degradation in power in just 2.5 years of outdoor exposure while the remaining modules showed reasonable degradation in their peak power between 0.6% and 2.5% in 2.5 years. A comparison of I–V curves of module no. 2, 6 and 10 with the I–V curve of reference module measured under STC is shown in Fig. 13.

Table 5
Comparison of manufacturer and sun simulator measured characteristic parameters at STC.

Parameter at STC	Manufacturer's data	Actually measured data using sun-simulator
P_{max}	100 W	114.8 W
V_{oc}	21.6 V	21.7 V
I_{sc}	6.40 A	7.16 A
V_{max}	17.0 V	17.2 V
I_{max}	5.90 A	6.68 A

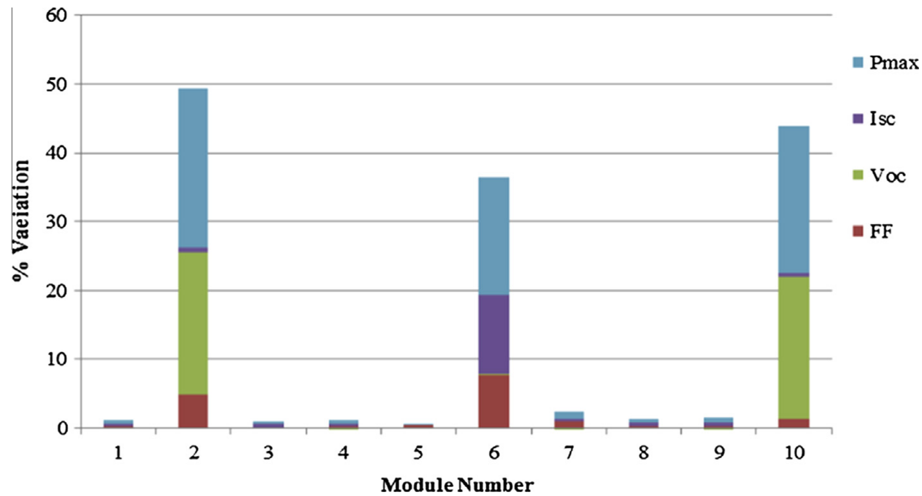

Fig. 12. Percentage variation in characteristic parameters of modules.

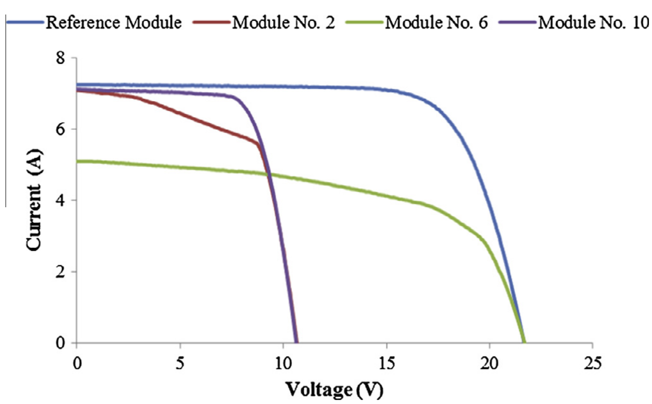

Fig. 13. I–V curve comparison of degraded modules (no. 2, 6 and 10) with the reference module (module no. 7).

The degradation of power in module no. 2 and 10 is clearly visible because of the degradation in their V_{oc} values, while degradation in the power of module no. 6 is due to reduction in the I_{sc} and FF. The module no. 6 is the one which has hotspots. It is important to note that module no. 2 and 10 are those which have shown the temperature gradient as shown in Fig. 9. The degradation in V_{oc} values is attributed to the fact that half of the series connected strings of solar cells in these modules got disconnected because of the junction box failure. The contact between the terminal in the junction box and terminal from the string interconnect through bypass diode of both the modules (2 and 10) were damaged due to this by pass diodes were not able to perform the normal function. This is due to poor quality control and soldering practices during the manufacturing process which require to be improved.

The two bypass diodes are used in the junction box of each module. The configuration of bypass diodes in the module is shown in Fig. 14.

The remaining modules of the array are also showing reasonable degradation in their characteristic parameters as shown in Fig. 15.

P_{max} degradation was found to be between 0.6% and 2.5% in just 2.5 years with an average degradation rate of 0.51% per year. The results show that three modules (no. 2, 6 and 10) have shown 50% average degradation in power in just 2.5 years of outdoor exposure while the remaining modules showed reasonable degradation of around 0.51% per year.

The defects like single cell browning and hotspots occurring inside the laminate cannot be tackled, however, the possible solutions to manufacturing defects are as follows:

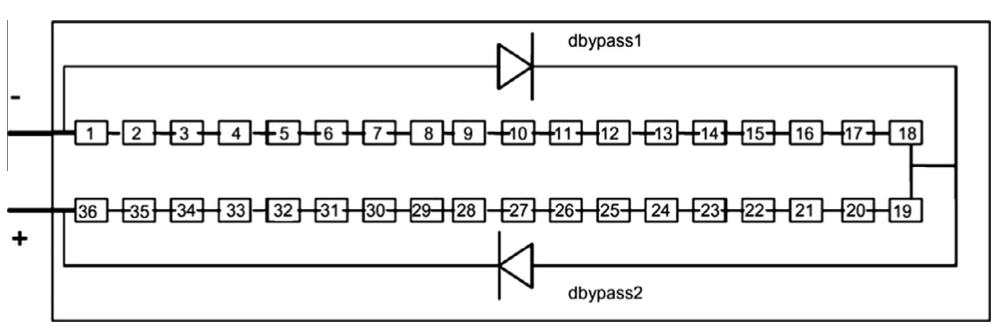

Fig. 14. Configuration of bypass diodes used in the junction box of each PV module.

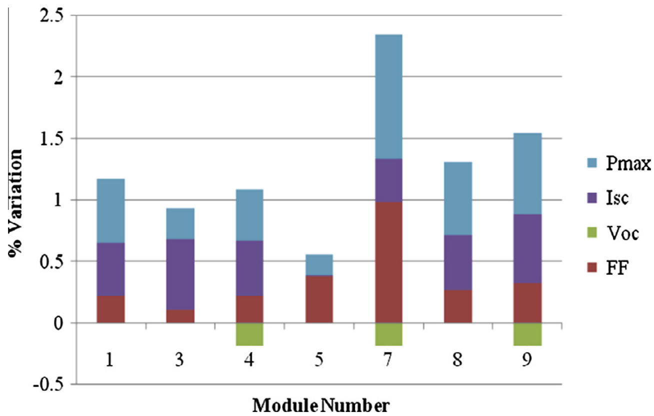

Fig. 15. Percentage variation in characteristic parameters of remaining modules excluding most degraded modules (no. 2, 6 and 10).

- Failures due to junction box and detachment of terminals are due to the poor quality of supplied modules and are repairable. However, the solution for avoiding these defects is not to use poor quality material, connectors', etc. by the manufacturer.
- The modules (2 and 10) which showed these defects can be repaired to make the modules functional but the issue is to improve the quality of material used by the manufacturer in the first instance to avoid such defects appearing at early stage keeping in view 25 years of guaranteed life of modules.

As all these modules are certified as per International Electro-technical Commission (IEC) standards, so much degradation within 2.5 years indicates that qualification standards needs to be reviewed for Indian climatic conditions if the modules are to perform reliably for more than 20 years under the actual field conditions in India.

6. Conclusions

In this study the degradation analysis of multi-crystalline-Silicon photovoltaic modules of a 1 kW_p roof mounted system is carried out after outdoor exposure of 2.5 years in western Himalayan region of India. Based on the study following conclusions are drawn:

- The visual inspection and infrared thermal imaging analysis of m-C-Si modules showed that three modules out of ten developed serious defects such as hotspots, disconnected cells and string interconnect ribbons in just 2.5 years of operation resulting in the 50% degradation in their peak power. This is of serious concern, as these PV modules were IEC certified and such a large degradation within 2.5 years is higher than the reported expected degradation rate of 0.5% per year which is necessary to meet the requirement of 25 years commercial lifetime (Jordan and Kurtz, 2013). The modules showing more than 1% per year degradation will fail most of warranties given by manufacturers.
- The average annual degradation rate per year calculated from STC measurements before and after the outdoor exposure was found to be 0.51% in the remaining seven m-C-Si modules excluding the modules which have shown higher degradation. This points the need for serious adherence for quality testing of modules by manufacturers.
- The degradation of peak power in IEC certified modules was found to be more than the expected level in some modules. The degradation of more than the certified level, under actual field conditions indicates that the present qualification standards, tests are not adequately addressing the real outdoor conditions and the stresses experienced by the modules in such locations as in India. Although PV module qualification standards ensure reliable field performance to some extent, it may be required to change the sequence of some of the tests and also raise severity levels of tests like damp heat and UV exposure in terms of magnitude and time, to match harsh Indian field conditions. This will require further follow up research.
- A recently reported defect known as snail trail is observed in all the modules of the m-C-Si array. Although various explanations are given by various authors as already discussed in results section but the origin and loss in power due to generation of this defect is still not well understood and is an important area of further research especially in this region where PV modules are expected to perform efficiently due to low ambient temperatures.
- Visual inspection and thermal imaging techniques are found to be quite effective for identifying hot spots (burn marks), disconnected cells and string interconnect ribbons and many others.
- Methodology used to analyse the degradation through comprehensive test campaign using visual inspection; infra-red thermal imaging and I–V characteristic measurements are found to be powerful tools to identify causes of degradation or failures of PV modules under real outdoor conditions.
- It is further important to understand various modes and mechanisms of failure. The data on outdoor performance and degradation of PV modules and various recent analysis techniques can be used to further understand the module degradation and failures under different climatic conditions.
- The results of study in this climatic region in a hilly terrain are of significance for further follow up in the context of quality, defects and problems faced in field installed PV modules. Similar studies on degradation of PV modules of same technology in the different parts of India with varied climatic conditions are suggested to be carried out in detail. The extension of such studies to different climatic regions in India is also underway under a programme of Ministry of New and Renewable Energy, Govt. of India for which an All India Survey of PV module has been carried out (Chattopadhyay et al., 2013).

The early generation of defects in three modules is due to the poor manufacturing practices or the poor quality material used for large scale propagation. Results of study will also be shared with the PV manufacturers and developers for further improving the quality of manufacturing.

The massive thrust on the propagation of PV power generation worldwide including India, has also led to the supply of poor quality modules without following stringent quality control measures which require to be enforced by concerned agencies.

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