All-India Survey of Photovoltaic Module Reliability: 2016

Executive Summary

National Centre for Photovoltaic Research and Education (NCPRE), IIT Bombay &
National Institute of Solar Energy (NISE), Gurugram

March-May 2016
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Survey conducted in March-May 2016

Report and Executive Summary © 2017
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The 2016 All-India PV Survey of Photovoltaic Module Reliability is the third in a series of such surveys conducted to assess the health, reliability and durability of photovoltaic (PV) modules put up in different parts of India. It was conducted between March and May 2016. The suggestion that such surveys be conducted arose at a meeting in March 2013 of the “High Powered Task Force under JNNSM for Solar Photovoltaics”. As in the case with the 2013 and 2014 Surveys, the 2016 Survey was also conducted jointly by the National Centre for Photovoltaic Research and Education (NCPRE) at the Indian Institute of Technology Bombay (IITB) and the National Institute of Solar Energy (NISE).

The 2016 Survey was similar to the 2014 Survey, with a major difference: the number of large power plants surveyed was increased at the expense of small/medium plants. A total of 925 modules were inspected at 37 sites in all the 6 climatic zones of India. The age of the modules varied between 1 year to more than 25 years, and 6 different technology types were represented. The sites visited are shown in Fig. 1. The types of inspection undertaken in 2016 included: visual inspection, measurement of I-V characteristics under light and dark conditions, infra-red (IR) thermography under light and dark conditions, electroluminescence (EL) imaging, interconnect integrity test, insulation resistance test, and measurement of irradiance and ambient and module temperatures. We also performed a detailed analysis to ascertain the statistical significance of our data. Another important difference from the 2014 Survey was that we also calculated the Linear Degradation Rate for $P_{\text{max}}$ (in %/year) in addition to the Overall Degradation Rate. We assume that there is a rapid initial degradation of 2% (for c-Si modules only) due to Light Induced Degradation (LID), followed by an almost linear fall in power; the Linear Degradation Rate refers to the latter (which discounts the initial LID), whereas the Overall Degradation Rate refers to the net rate including LID. This distinction is useful while comparing the performance of young and old modules.

![Climatic zones of India and sites visited during the 2016 All-India Survey.](image)

The distribution of the 925 modules surveyed in the 37 sites was as shown in Fig. 2. At each site, about 25 to 30 modules were typically taken up for the survey. Some modules (34 in number) showed Overall Degradation Rates of more than 5.12 %/year, and these modules, termed ‘outliers’, were not included in the
main analysis as they appeared to suffer from serious quality problems and other extraneous issues, such as over-rating.

Fig. 2: Distribution of sites and modules in terms of installation size, technology used, climatic zone, and age. Large size refers to installations > 100 kW, and small/medium to installations < 100 kW.

One of the most significant observations of the survey was that there was a wide distribution in the performance of the modules. The histogram of the Overall Degradation Rate of the modules, that is, the rate at which the output power $P_{\text{max}}$ decreases per year without discounting for LID, is shown in Fig. 3. It can be seen that the rates vary over a large range, from less than 0 %/year to more than 4 %/year, with the average at 1.55 %/year. (This average is lower than the 2.07 %/year seen in the 2014 Survey, mainly due to more large power plants included in 2016.) It can also be seen that some modules show negative rates; this is mainly due to under-rating and also light-soaking and spectral mismatch issues associated with thin film modules.
As can be seen, many of the modules are performing well with low degradation rates, while others are not. To understand and analyze this wide variation, we have divided only the c-Si sites (which form the majority of sites and modules surveyed) into two categories: Group X sites and Group Y sites. The criterion for the division is that sites whose modules show an average Overall Degradation Rate of less than 2 %/year were considered to be ‘good’ sites, and labelled as Group X; and sites whose modules show an average Overall Degradation Rate of more than 2 %/year were considered to be ‘problematic’ sites, and labelled as Group Y. We emphasize that the 2% criterion is based on the site average, (since performance depends on both intrinsic module quality and installation procedures), and individual modules in Group X sites may show degradation rates of more than 2 %/year, just as individual modules in Group Y sites may show degradation rates of less than 2 %/year. Having made this distinction, we now plot the histogram for the Overall Degradation Rates for the c-Si modules. Fig. 4(a) shows the histogram for all 712 c-Si modules (called Group A), and Figs. 4(b) and 4(c) show the histograms for the modules in the Group X and Group Y sites respectively. It can be seen that the average for Group A is 1.90 %/year, which is rather high (the accepted international benchmark is between 0.6 to 1.0 %/year). It may be noted that 1.90 %/year is higher than the 1.55 %/year for all technologies, since thin films modules show lower rates, partly because of the point mentioned earlier. The modules in Group X (‘good’) sites do better at 1.22 %/year (but still higher than the benchmark), and, as expected, the modules in Group Y sites perform significantly worse.

Since the Overall Degradation Rate includes the 2% rapid LID drop for c-Si modules, we have also plotted histograms for the Linear Degradation Rates. These are shown in Figs. 5(a)-(c) for Group A, Group X and Group Y modules. (We will sometimes refer to modules in Group X sites as ‘Group X modules’, and similarly for Group Y). Naturally, these linear rates are improved, but still higher than the benchmark rates.

Fig. 3: Histogram of Overall $P_{\text{max}}$ Degradation Rate (%/year) for all modules of all technologies.

Fig. 4: Histogram of Overall $P_{\text{max}}$ Degradation Rate (%/year) for c-Si (mono and multi) technologies only for (a) all modules (Group A) (b) modules in Group X sites (c) modules in Group Y sites.
The climatic variation is analyzed for modules falling in Group X. This is done since these are the ‘good’ sites, where extraneous effects are presumably not playing a role, and therefore the effect of climate is being correctly captured. While we have looked at the rates in all the 6 climatic zones, we find it is most instructive to separate these zones into two broad categories: ‘Hot’ zones (comprising the Hot & Dry, Warm & Humid, and Composite zones), and ‘Non-Hot’ zones (comprising Moderate, Cold & Sunny and Cold & Cloudy zones). The Linear Degradation Rates for Group X c-Si modules in the Hot and Non-Hot zones is shown in Fig. 6 (the open and filled symbols respectively represent young (<5 year) and old (>5 year) modules. It is clear that modules in the Hot zones degrade distinctly faster. This is a cause for concern since many of the solar installations in India will come up in Hot zones (which also have plentiful sunshine). Our detailed visual, IR and EL analysis indicates that the main reasons for modules to degrade faster in Hot zones is that the encapsulant (EVA) discolors faster, there is more metal and interconnect corrosion, and there are more interconnect breakages in the Hot zones.

The histograms shown in Figs. 4 and 5 refer to all the 712 c-Si modules which have been analyzed. To see how the large power plants in Group X perform, we have looked at the breakup of Linear Degradation Rates
in terms of size of the installation. This is shown in Fig. 7(a). It is comforting to note that modules in large (>100 kW) sites perform better than modules in small/medium sites. However, it is illuminating to do a more fine-grained analysis. Figure 7(b) shows the degradation rates for a subset of Group X modules in Hot climates, and Fig. 7(c) shows how the modules in large Group X sites separate out in terms of young and old sites. As can be seen, even among the large sites, in Hot zones the rate is 1.12 %/year, and more worrisome, for young large sites in Hot zones it is 1.43 %/year. These findings reinforce the observation that Hot climates enhance degradation, and also show that young sites are performing worse than old sites. This indicates that the quality of the modules themselves or the installation practices being adopted in recent years are inadequate. Also, the possibility that some of the young modules are over-rated cannot be ruled out. The latter point is especially true for modules in Group Y sites, though the corresponding data is not shown here.

![Fig. 7: (a) Effect of installation size on Linear $P_{\text{max}}$ Degradation Rate for Group X modules (b) in Hot zones only and (c) the >100 kW sites in Hot zones separated for clarity into Young and Old sites.](image)

The problem of young modules as compared to old modules emerges clearly in Fig. 8 which shows the age-wise histograms for all c-Si modules (Group A). The young c-Si modules have an average Linear Degradation Rate of 1.68 %/year, and the many modules with rates > 3 %/year hint at the possibility of unethical over-rating. For the young modules, the main contributor for $P_{\text{max}}$ degradation is the fill factor ($FF$) which is often related to poor quality and cracks (and may also be indicative of over-rating), whereas for the old modules, it is short circuit current ($I_{sc}$) degradation, symptomatic of encapsulant discoloration.

![Fig. 8: Histograms of Linear $P_{\text{max}}$ Degradation Rates for Young and Old Group A (all c-Si) modules.](image)

Another observation which calls for serious consideration relates to the relative performance of roof-mounted versus ground-mounted modules. To make a fair comparison, roof-(rack)-mounted and ground-mounted c-Si modules of only the small/medium size (<100 kW) were compared, and these showed Linear Degradation Rates of 2.02 %/year and 0.99 %/year respectively. The higher rate for roof-mounted modules is correlated with more cracks in the cells seen on rooftops, indicating poor quality of modules and/or improper installation.
This means special attention is needed for the design and deployment of PV systems for India’s 40 GW rooftop target.

We performed a detailed study of the visual degradation seen in modules, using an enhanced NREL visual checklist. Some of the key results are as follows. Encapsulant discoloration (yellowing or browning), shown in Fig. 9(a), occurs in all climatic zones, but at a faster rate in Hot zones. Though discoloration is generally seen in older modules, we have seen discoloration also in young Group Y modules, indicating poor quality, and this is one of the reasons for the poor performance of Group Y modules. Delamination (Fig. 9(b)) is seen to occur most frequently in Warm & Humid climates, and again is more widespread among Group Y modules. Snail trails, shown in Fig. 9(c), are usually associated with cracks in the cells, and are seen mainly in Hot climates. Further, many young modules (especially in Group Y sites) show snail trails. Metallization discoloration or staining (Fig. 9(d)) is seen in all climatic zones, but the severity is higher in Hot zones. Metal discoloration/staining can be due to corrosion or improper soldering. Many young modules, especially in Group Y sites, also show metal discoloration, indicating poor soldering quality. Backsheet degradation, including chalking and cracking, has been seen in both old and young modules. 40% of the young modules display backsheet problems, indicating again issues with quality and/or installation in recent years.

Fig. 9: (a) Encapsulant browning (b) Delamination (c) Snail trails (d) Metallization discoloration.

We have correlated the visual defects with power degradation. Fig. 10 shows the correlation between power degradation and (a) encapsulant discoloration, (b) metal discoloration and (c) backsheet degradation. Note that in all cases, the y-axis shows the total percentage power loss suffered by the module since installation, and not the annual power degradation rate. It can be clearly seen that visible defects do indeed result in power loss.

Fig. 10: Correlation of Total $P_{max}$ degradation with (a) Encapsulation Discoloration Category, (b) Metallization Discoloration Category and (c) Backsheet Degradation Category. A higher Category number indicates more visible degradation. Group A refers to all c-Si modules.

Using a special low-light electroluminescence (EL) technique developed for the 2014 Survey, and a rugged lightweight DSLR based EL camera developed for the 2016 Survey, we have taken EL images of 202 modules during the survey. The EL images allow us to detect microcracks in the c-Si solar cells which cannot be seen.
with the naked eye, and help to ascertain the origin of snail trails, identify interconnect breakage and diode failure in short circuit, and indicate the presence of PID. Thus EL is a very powerful technique to identify problems in modules in the field. Fig. 11(a) shows an example of an EL image of a module in the Hot climate. Using EL, we have observed: (i) there are about 6 times more cracks in Group Y modules than Group X modules; (ii) there are about 50% more cracks in young modules compared to old modules; (iii) there are about 50% more cracks in rooftop modules compared to ground-mounted; and (iv) there are about 20% times more cracks in modules in small/medium installations compared to large installations. Power output decreases with number of cracks, as shown in Fig. 11(b). This data shows that microcracks are a major cause of poor performance in Group Y modules, and also contribute to the poorer performance of modules which are young, rooftop-mounted or in small installations. Prevalence of large number of cracks indicates low manufacturing quality, poor packaging/transport and/or improper/hasty installation.

![Field EL image](image1)

![EL degradation rate graph](image2)

**Fig. 11:** (a) Field EL image of a module seen in Hot & Dry climate (b) Correlation of Linear $P_{max}$ Degradation Rate with number of cracks in the module. The green and red bars indicate the instrument/STC translation error and nameplate error respectively.

We also used infra-red (IR) thermography, which shows the temperature distribution over the module. This is particularly useful for identifying hot spots, which can cause significant long-term degradation. The highest modal temperature seen during the Survey for a module operating under MPPT conditions was 67 °C, and highest hot cell temperature seen was 89 °C. We have defined a Thermal Mismatch Index (TMI), where a higher TMI indicates the possibility of hot spots. Fig. 12(a) shows a typical IR image and Fig 12(b) shows how the Total $P_{max}$ Degradation is correlated with the presence of hot spots as measured by the TMI category.

![IR image](image3)

![Total Pmax degradation vs TMI category](image4)

**Fig. 12:** (a) IR image of a module in Warm & Humid climate (b) correlation of Total $P_{max}$ Degradation with Temperature Mismatch Index (TMI) category. Group A refers to all c-Si modules.
The 2016 Survey also undertook measurements of dark $I-V$ characteristics, dark IR, insulation resistance and interconnect breakage occurrence. The dark $I-V$ measurements yield the ideality factor $n$ of the diode in the forward bias region. It was seen that $n$, which can be related to series resistance and/or cell quality, increases with age, and shows more degradation in Hot than Non-Hot climates. Further, increasing (worsening) values of $n$ correlate well with power loss. The dry insulation resistance test showed that most modules (99%) pass the test, and all (100%) in the large-size category pass. The interconnect breakage (measured by a cell line tester and shown in Fig 13(a)) is most prevalent in the Hot & Dry zone, the reason most likely being thermal cycling caused by a large difference in the day and night temperature. The power degradation correlates well with the severity of interconnect breakage, as shown in Fig. 13(b).

An important question which arises is whether it is possible to identify the risk associated with various defects or degradation modes in different climatic zones. If so, it would be possible to check for those defects more regularly, and thus pre-empt both performance and safety failures. The method of assigning a Risk Priority Number (RPN) allows this to be done. The RPN depends on the severity of the defect ($S$), its frequency of occurrence ($O$), and how easily detectable ($D$) it is. RPN is defined as $S \times O \times D$. The RPN methodology has been used for analyzing the field data collected for the modules during the survey. One example of the results of the RPN analysis is presented in Fig. 14, which shows the Performance RPN versus failure modes for old modules in the Hot & Dry climatic zones (a higher RPN number indicate more risk). It can be seen that solder bond fatigue/failure has the highest RPN, which agrees with the observation noted earlier that interconnect breakage is seen most often in this climate.

Fig. 13: (a) Module showing point (a) and line (b) breakage (b) power degradation rate versus severity of interconnect breakage.
Fig. 14: Performance RPN for different failure modes for old modules (more than 5 year outdoor exposure) for Hot & Dry climate. RPN_SO designates a modified RPN calculation, where only Severity and Occurrence frequency are included (that is, ease of Detection is ignored).

In summary, a good picture of the durability and reliability of PV modules in the country has emerged from the 2016 All-India Survey. Broadly, the results agree with those of the previous 2014 Survey. One of the important observations is that there is wide variability in the quality and degradation rates. Many modules show excellent performance, but there are many others showing alarmingly high degradation rates. Crystalline-silicon modules show an average Linear Degradation Rate of 1.47 %/year; c-Si modules in Group X sites show reasonably good performance with an average Linear Degradation Rate of 0.89 %/year; but modules in Group Y sites show an average rate of 2.21 %/year, which is cause for concern. Large-size (>100 kW) Group X installations perform well (0.71 %/year), which is good news, but if one focuses on a subset of such installations which are young and in Hot zones, the degradation seen is 1.43 %/year. This highlights the problems being seen in recent installations, and also flags a warning for future installations, most of which will come up in Hot climates. Further, it is seen that roof-mounted systems perform worse than ground-mounted systems. This means that due consideration must be given to the long-term durability of small/medium roof-top systems. The modules in the underperforming Group Y sites suffer from material quality issues, including encapsulant and backsheets quality, as well as improper transport/installation procedures that show up as microcracks in the cells, scratches in the backsheets, etc, all of which cause a decrease in the module power. These problems have perhaps been caused by the aggressive pricing and deadlines associated with solar PV projects in recent years.

Based on the field observations, analysis and results, some high-level recommendations which can be made are the following:

- Due diligence should be exercised while selecting and procuring modules. This may include verifying the antecedents of the manufacturer, and independent checks on the quality of the module(s). Although most modules available in the market carry the IEC certification, it should be noted that the IEC certification is
really a qualification of module design, and does not guarantee that the module will perform adequately through its intended life.

- Materials used in modules are important. EVA and backsheet particularly can be of different qualities, and should be specified by the manufacturer in the datasheet, and also in the tender for procurement.

- An independent audit of modules and installations by third party is strongly recommended. This may include detailed testing of randomly selected modules before as well as after shipment.

- Some cases of ‘over-rating’ of modules cannot be ruled out. This may be one of the reasons for high calculated degradation rates, especially for young modules. Owners and installers should be vigilant about this malpractice.

- Module manufacturers and installers should place more emphasis on proper packaging and handling of the modules during transportation since improper handling can induce cracks in the solar cells and lead to long-term degradation.

- Installation procedures and protocols are important, and standard procedures as recommended should be strictly followed.

- It is recommended that a random field-based electroluminescence (EL) testing be performed after receiving the modules at site and after installation to reveal micro-cracks which may have been caused during the transport and installation phases.

- It has been noted that the ‘Hot’ climates present a harsh operating environment for PV modules. An intensive study of degradation phenomena in Hot climates, which has not been emphasized sufficiently by the PV community so far, is needed. This is particularly important for India, where much of the 100 GW is expected to come up.

- The IEC certification protocols (eg. 61215), and the BIS standards, which are currently being updated, need to take into account the Hot climate phenomena, and to develop more aggressive test protocols going to higher temperatures.

- Modules and sites perform very well in the ‘Cold & Sunny’ climate of Ladakh. Power plants set up in this region will enjoy not only low degradation rates, but also excellent irradiance.

- It is possible that some of the quality issues seen, especially in the young modules, are the result of very aggressive pricing and commissioning deadlines for PV plants in India in recent years.

- Given the reliability issues observed for small/medium rooftop installations, it would be prudent to reduce the 40 GW rooftop target, and instead enhance the ground-mounted capacity.

The full report can be downloaded from

http://www.ncpre.iitb.ac.in/research/pdf/All_India_Survey_of_Photovoltaic_Module_Reliability_2016.pdf

and