Evaluation of Underperforming Rooftop PV Plants in India – Moving from kW to kWh

Part I: Evaluation of 10 Rooftop PV Plants in Delhi

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Document History

Version	Date	Comments
V1	2019-04-16	First release to Customer
V2	2019-05-21	Second release to Customer: Anonymization
V3	2019-06-25	Third release to Customer: Cost estimation added
V4	2019-07-09	Fourth release to Customer: Site details removed

Index

List of abbreviations

AC	Alternating Current	**LTA**	Lender´s Technical Advisor
BOM	Bill of Materials	**LV**	Low Voltage
BOS	Balance of System	**MPP**	Maximum Power Point
CAPEX	Capital Expenditures	**MPPT**	Maximum Power Point Tracker
COD	Commercial Operation Date	**MV**	Middle Voltage
DC	Direct Current	**MWp**	Megawatt peak
DIF	Diffuse Horizontal Irradiance [Wh/m²]	**OE**	Owner´s Engineer
EL	Electroluminescence	**OPEX**	Operating Expense
EOW	End of Warranty	**O&M**	Operations and Maintenance
EPC	Engineering Procurement and Construction	**PAC**	Provisional Acceptance Commissioning
FAC	Final Acceptance Commissioning	**PCU**	Power Central Unit
FC	Financial Close	**PID**	Potential Induced Degradation
GHI	Global horizontal irradiation [Wh/m²]	**POA**	Plane of the Array
Isc	Short-circuit current	**PPA**	Power Purchase Agreement
IR	Infrared	**PR**	Performance Ratio
IV	Irradiation / Voltage	**PV**	Photovoltaic
KVA	Kilo-Volt-Ampere	**SPD**	Solar Project Developer
LCOE	Levelized Cost of Energy	**STC**	Standard Test Conditions
LID	Light Induced Degradation	**Voc**	Open circuit voltage

1. Executive Summary

The Government of India is aiming for an exponential increase in the installation of renewable energy systems in the country including 100 GW capacity of solar power by 2022 out of which 40 GW is targeted on rooftops. While the efforts are being directed towards substantially increasing the rooftop solar capacity, it is imperative to ensure that these systems perform with high yields. The rooftop solar team at Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) has analyzed the specific yields of various systems and has found that many systems are performing sub-optimally. The technical advisory company PI Photovoltaik-Institut Berlin AG (PI Berlin) has been contracted by GIZ to identify the causes of sub-optimal performance in 10 pre-selected rooftop PV plants, quantify those in terms of contribution to loss in generation and propose cost-optimal solutions to address the quality issues. This contract is part of the project Indo-German Solar Energy Partnership – Photovoltaic Rooftop Systems (IGSP-PVRT) and is financed by the German Federal Ministry for Economic Cooperation and Development and implemented by GIZ in partnership with the Ministry of New and Renewable Energy (MNRE)

In cooperation with GIZ and PI Berlin's local partner Global Sustainable Energy Solutions India (GSES), and thanks to the support of private developers and the Distribution Companies BRPL, BYPL and TPDDL, the access to the 10 roofs was secured. The results of the evaluation of each of the PV plants presented in this study show that the low performance of the inspected PV plants is caused by a mix of (i) disregarded design constraints in the development phase, (ii) installation failures, (iii) inaccurate design and (iv) product failures. Heavy soiling and near shading stand out in this group, followed by module damage and self-shading. According to the observations and measurements conducted by PI Berlin during the site assessments, 5 out of the 10 identified findings can contribute individually to losses at the system level between 6% and 30%. The absence of O&M contracts stating clear procedures for the corrective maintenance plan, the reaction times and the contractual availability values, is a factor that also contributes decisively to lowering the PV plant's output.

One of the goals of the project is that future O&M contractors and developers can benefit from the knowledge and conclusions drawn from the evaluation of the PV plants presented in this study. In this sense, PI Berlin suggests for the first group, 5 concrete measures of revamping that, depending on the state of each PV plant, may lead to a performance boost between 5% and 50%. PI Berlin has identified 10 prevention mechanisms that include technical and commercial recommendations to ensure the revenues for the next generation projects.

2. Introduction and Background

The Government of India is aiming for an exponential increase in the installation of renewable energy systems in the country including 100 GW capacity of solar power by 2022 out of which 40 GW is targeted on rooftops. In July 2018, the cumulative installed capacity of grid-connected rooftop photovoltaic systems was around 1,300MW. While the efforts are being directed towards substantially increasing the rooftop solar capacity, it is imperative to ensure that these systems perform with high yields. The rooftop solar team at Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) has analyzed the specific yields of various systems and has found that many systems are performing sub-optimally. The technical advisory company PI Photovoltaik-Institut Berlin AG (PI Berlin) has been contracted by GIZ to identify the causes of sub-optimal performance, quantify those in terms of contribution to loss in generation and propose cost-optimal solutions to fix the quality issues.

Under the Indo-German technical cooperation, the Government of Germany is cooperating with India and has commissioned a project through the German Climate Technology Initiative (DKTI). The project Indo-German Solar Energy Partnership – Photovoltaic Rooftop Systems (IGSP-PVRT) is financed by the German Federal Ministry for Economic Cooperation and Development and implemented by GIZ in partnership with the Ministry of New and Renewable Energy (MNRE). The project aims to support MNRE in achieving the 40 GW targets announced for rooftop solar power plants under the National Solar Mission.

The objective set by the GIZ for this project is to conduct a quality evaluation of 40 selected underperforming rooftop solar PV systems across India and quantify the issues leading to sub-optimal performance and suggest specific measures along with cost benefit analysis to increase their performance. The results will lead to synthesizing a solution, potentially in the form of business models for O&M companies. This report summarizes the results of the assessment of the first set of 10 rooftop PV plants all of them located in the Delhi area.

3. About PI Berlin

PI Berlin is a technical advisory company consisting of a team of international photovoltaic experts, providing quality assurance services along the entire value chain. With the knowledge and insights gained through years of experience in the field, laboratory testing and R&D, PI Berlin offers a full range of engineering services for PV plants from the development and construction phases through project operation. PI Berlin has been involved in the deployment of over 11GW of PV projects across the world in Europe, Asia, Africa and the Americas. PI Berlin owns two DIN/EN/ISO/IEC 17025 accredited laboratories in Berlin, Germany and Suzhou, China. PI Berlin has been actively involved in the Indian PV market since 2010.

4. Description of the Inspection Methodology

PI Berlin has conducted the present study in three steps which will be described in the present chapter.

Preparation Phase

The preparation phase is mainly focused on selecting and securing the access to the roofs. The selection criteria were agreed with GIZ and can be detailed as follows:

1. An equal number of roofs from all DISCOM´s shall be selected
2. PV plants with different nominal capacities shall be selected (50kW to 1000kW)
3. PV plants with low and very low specific yields are preferred. At least one plant with average or above average yield will be selected to be used as a benchmark
4. Plants with consistent data during the last 12 months will be selected

Based on the previous criteria, 28 rooftop PV plants were shortlisted. A list of required technical documents was created and sent to the rooftop owners in order to conduct some intelligence on the PV plant´s history and health. The documents were categorized according to its relevance and applicability. GIZ approached in parallel the DISCOMs and introduced PI Berlin and its local partner GSES to the representatives in charge. The DISCOMS enabled finally the access to the rooftop owners. Based on the meeting outcomes with the owners and the completeness of the shared documentation, 10 roofs were selected for conducting the present study.

Data Acquisition

Ahead of each visit, the available documentation was reviewed in order to maximize the efficiency during the site inspection. PI Berlin and GSES conducted the site visits spending one day per site. The site inspections focused primarily on aspects with direct impact in the performance such as (i) module cleaning, (ii) degraded PV modules, (iii) shadings, (iv) inverter unavailability or poor maintenance. Safety issues without a direct impact on the performance were also be documented.

PI Berlin's evaluation covered 7 main topics as shown in the following scheme.

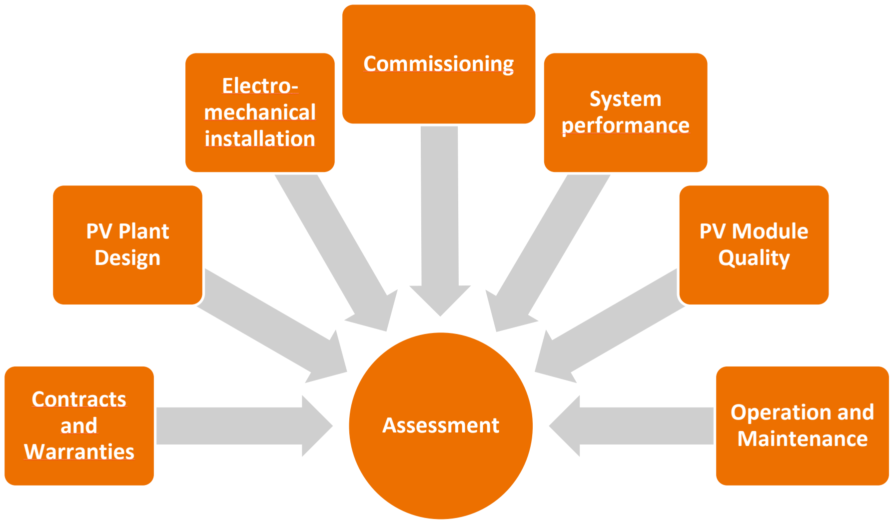

Figure 1: Scope of the evaluation

In the first topic **Contracts and Warranties**, the legal and commercial scenario of the PV project were evaluated from a technical perspective. EPC and O&M contracts along with the performance warranties were analyzed. The suitability of the selected products for a specific location together with the technical design were evaluated in the second topic, **PV Plant Design**. The quality of the **Electromechanical Installation** of the PV plant is the third topic and was covered on site. The fourth topic **Commissioning** covered the review of the tests conducted after the handover. In the fifth topic **System Performance,** the performance indicators of each plant were analyzed. The topic **PV Module Quality** assessed the status of the PV modules on site by conducting a visual inspection and measurements using special equipment. Finally, the last topic **Operation and Maintenance** evaluated the preventive and corrective measures carried out by the O&M team. The described scope was applied separately to each of the 10 PV plants using the checklist shown in Annex III.

Post-processing and Reporting

The information gathered onsite was post-processed and combined with the results of the documentation reviewed ahead of the visit. Each of the findings responsible for a performance drop has been, as far as possible, coupled to an estimated energy loss and to feasible mitigation measures. The final statements of PI Berlin in regards to the quantification of the impact of the identified findings, are based on (i) PI Berlin's long-term experience in the PV sector, (ii) on-site data acquisition and (iii) simulation exercises with PV SYST. The results achieved by PI Berlin will provide answers to the following questions:

1. Which findings arise more often and which have the highest impact on the performance?
2. Which retrofitting solutions can be implemented to boost the energy production of the inspected PV plants?
3. Which mechanisms are needed to avoid underperformance and to ensure the revenues in the next generation projects?

5. List of the Selected Sites

The selected sited analyzed in this study are shown in the following table.

Table 2: List and location of the selected sites

PV Plant	Installed capacity (kWp)	Average specific yield since COD
I.1	180	631 kWh/kWp
I.2	100	1025 kWh/kWp
I.3	100	721 kWh/kWp
I.4	60	1180 kWh/kWp
I.5	125	1204 kWh/kWp
I.6	40	600 kWh/kWp
I.7	70	465 kWh/kWp
I.8	150	775 kWh/kWp
I.9	120	800 kWh/kWp
I.10	60	730 kWh/kWp

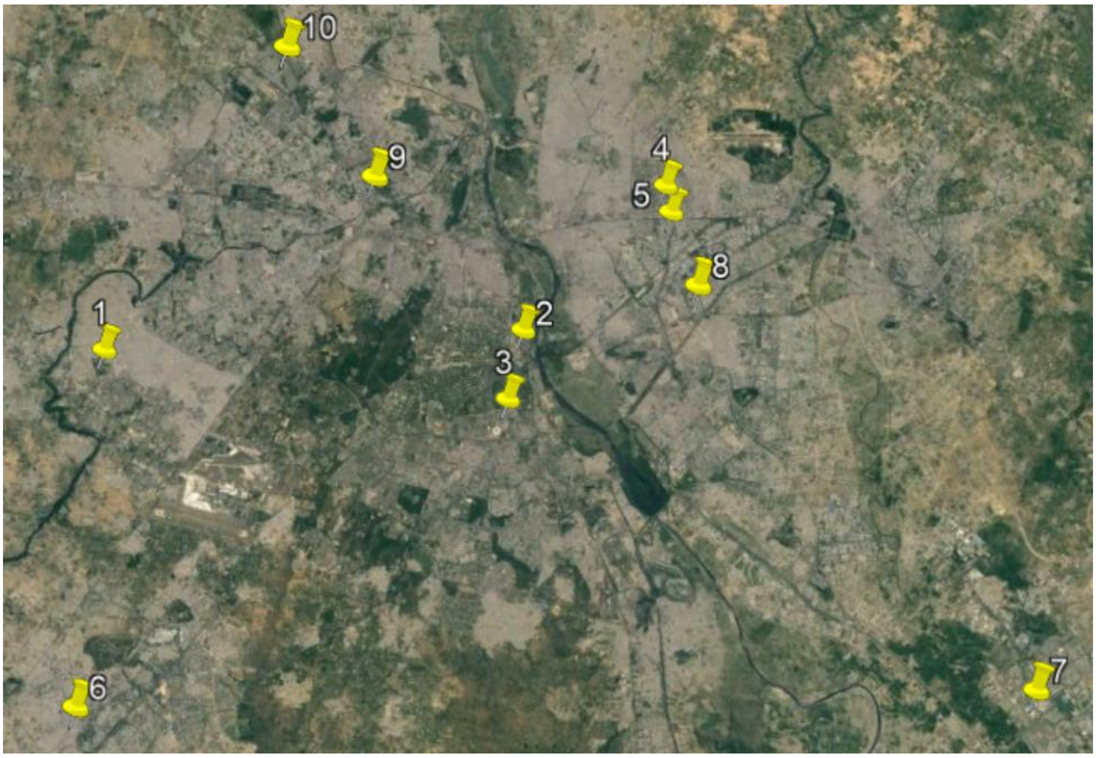

Figure 2: Sites within the greater Delhi area

Climate characteristics: New Delhi

The prevailing climate in the region is known as a local steppe climate. During the year, there is little rainfall and the temperature here averages 25.2 °C. The average annual rainfall is 693 mm and the driest month is April. There is 3 mm of precipitation in April and most precipitation falls in August, with an average of 246 mm. With an average of 34.3 °C, June is the warmest month and January the coldest with an average temperature of 14.2 °C. The precipitation varies 243 mm between the driest month and the wettest month. The average temperatures vary during the year by 20.1 °C [source: climate-data.org]. The Global

Horizontal Irradiation (GHI) is approximately 1,700 kWh/m² and 1,870 kWh/m² per year respectively [source: SolarGIS].

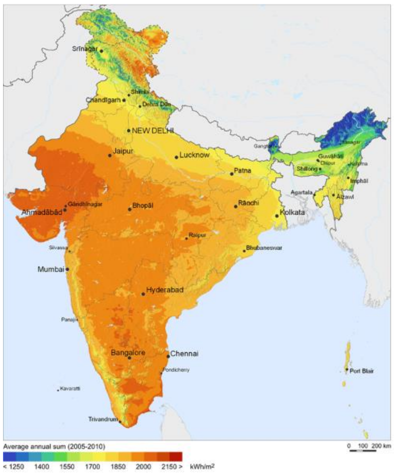
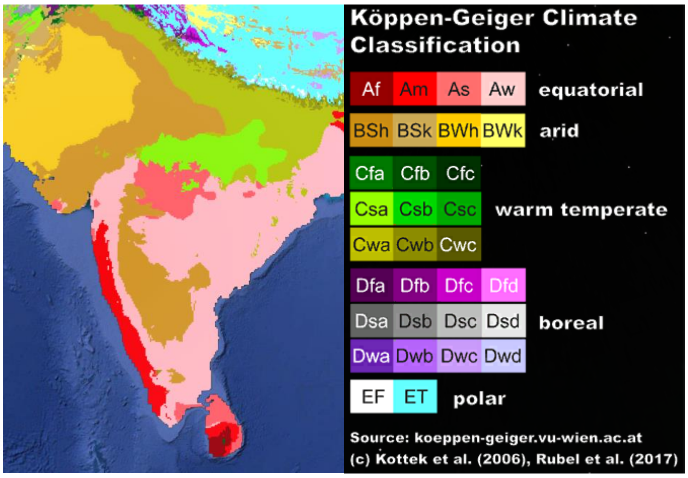

Figure 3: Global horizontal irradiation map of India [source: Solargis]; Figure 4: Köppen-Geiger climate classification map for India (1980-2016) [17]

6. Technical Background

This chapter serves as a guide for the better understanding of some of the module failures mentioned in the present study.

6. 1. Potential-Induced Degradation

The phenomenon of Potential-Induced Degradation (PID) is based on a power loss degradation caused by a negative potential of the solar cells towards earth, which leads to an accumulation of Na^+ located in the glass and migrating into the solar cells damaging the p-n junction responsible for the electron flow [14]. The degree of affection is highly dependent on the level of the potential (voltage stress). The first bibliographic references relate to the investigations carried out by Hoffman and Ross (JPL) in 1978 ("Impact of voltage-biased humidity exposure of solar modules on long-term stability") in which this physical effect was internationally presented for the first time. The PID effect was associated in the past principally to back contact cell technology, TCO corrosion in thin film modules and processes based upon band silicon. In recent years, the PID effect has also been linked to silicon technology; thus, this phenomenon has become more and more relevant due to the enormous amount of solar facilities built with this technology.

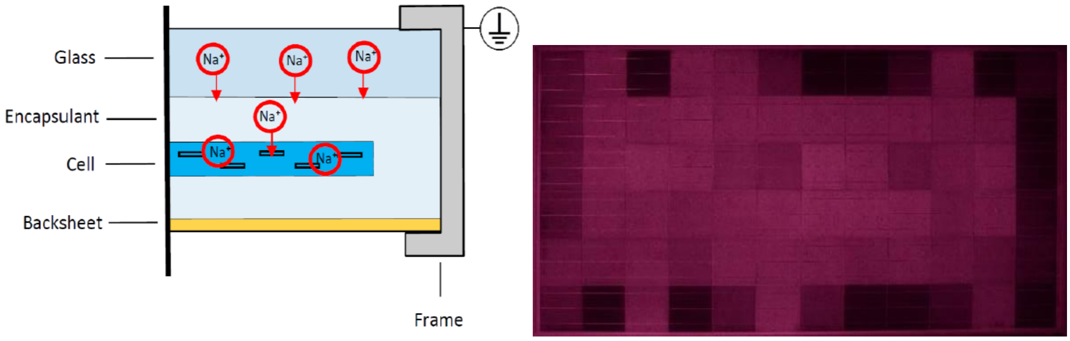

Figure 3: p-n junction damage (left) and typical PID pattern (right) [source: PI Berlin]

The necessary conditions for the appearance of PID in the field can be summarized as follows:

- High system voltage (has increased in the last years in order to minimize transport losses in the string)
- High relative humidity and high temperature
- Certain combination of materials (glass, encapsulate material, etc.)

The degree of PID of the PV modules decreases towards the positive pole, with the first modules of the negative pole being usually the most affected with power drops up to 95% in cases of advanced PID.

6. 2. Snail Trails

It is defined as a grey/black discoloration of the silver paste of the front metallization of screen-printed solar cells. In the PV module the effect looks like a snail trail on the front glass of the module and is visible to the human eye. The discoloration occurs along invisible cell cracks. The discoloration typically occurs 3 months to 1 year after installation of the PV modules. During the summer and in hot climates snail trails occur faster [9]. The area of the snail trail discoloration along the silver finger of the front side cell metallization shows nanometer-sized silver particles in the EVA above the silver finger. These silver particles cause the discoloration [14], [5]. The snail trails appear typically as branched trails across the cells and are a clear sign of hidden cell damages [15], [18].

Figure 4: PV module showing snail trails [source: PI Berlin]

6. 3. Hot Spots

A hot spot is defined as a localized region in a PV module whose operating temperature is very high in comparison with its surroundings. This can occur when a cell generates less current than the rest of cells connected in series as a result of partial shading, cell damage, mismatching or interconnection failure. As a result, the defective cell is reverse biased and behaves like a load that dissipates the power generated by the rest of the cells in the form of heat [14]. The protection against hot spots is also well-known and consists of connecting a bypass diode, with reverse polarity, in parallel with a group of cells, typically 12 or 18 for crystalline silicon modules. Thus, the defective cell is reverse biased to a point that causes the forward conduction of the bypass diode, which almost short circuits the group of cells and ensures that, in the worst case, the aforementioned cell dissipates nearly the power generated by the remaining cells in the group [12]. Hot spots present a potential risk of irreversible damage for PV modules. They can cause, for example, tedlar delamination, glass breakage, loss of electrical insulation or even fire [14].

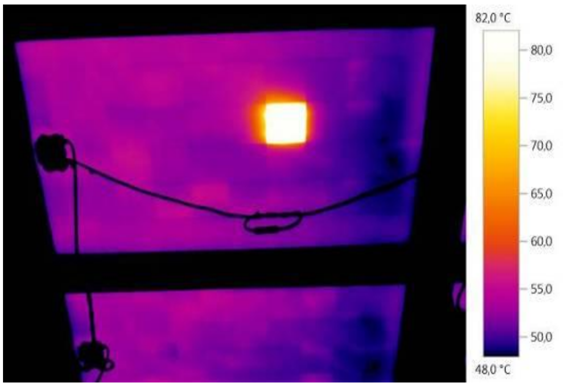

Figure 5: PV Module affected by a hot spot [source: PI Berlin]

6. 4. Soldering Failures during Module Manufacturing

The soldering of the ribbon to the cell busbar is a key process in PV module manufacturing. Soldering may easily provoke perpetual cell damages if not conducted properly. Already slight process issues may create tiny damages that can worsen during field operation of the module. Ultimately, bad soldering quality can lead to a detachment of the ribbon and a consequent reduction of the current flow. The inhomogeneous current guidance leads to a chromatic mismatch in the electroluminescence pictures. One defect busbar forces the other busbars to handle higher currents which might lead to an earlier failure of those busbars as well. A second effect that may occur during an insufficient supervised soldering process is the creation of microcracks and associated cell short-circuits (shunts) due to improper settings such as soldering temperature or duration. These shunts appear as hot spots in the infrared images and as bright dots in the electroluminescence pictures [14].

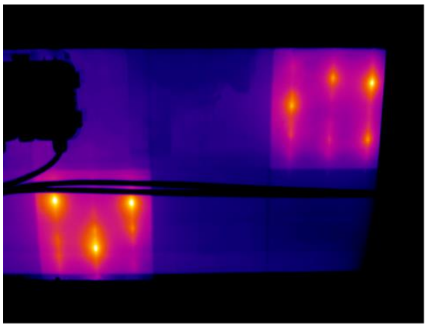

Figure 6: Cells affected by bad soldering [source: PI Berlin]

6. 5. Inactive Cell String

In parallel to a certain number of solar cells, bypass diodes are integrated into the PV module. These bypass diodes reduce the power loss caused by partial shading on the PV module. Besides the power loss, the diode avoids the reverse biasing of single solar cells higher than the allowed cell reverse bias voltage of the solar cells. If a cell is reversed with a higher voltage than it is designed for, the cell may create hot spots that may cause browning, burn marks or, in the worst case, fire. Typically, Schottky diodes are used as bypass diodes in PV modules. Schottky diodes are very susceptible to static high voltage discharges and mechanical stress. So they should be handled with care and human contact without grounding should be avoided [14]. Consequently, many bypass diode failures may occur. But it is difficult to find them because they only attract attention when the PV modules have severe mismatch in the individual IV characteristic of single cells, e.g. caused by shading or disconnected parts of a cell due to cell cracks [9].

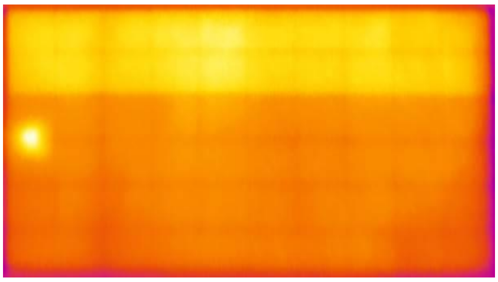

Figure 7: PV Module with an inactive cell string [source: PI Berlin]

6. 6. Cell Breakage and Microcracks

Photovoltaic cells are made of silicon. This makes the cells very fragile. Cell cracks are cracks in the silicon substrate of the photovoltaic cells that often cannot be seen by the naked eye. Cell cracks can form in different lengths and orientations in a solar cell. The wafer slicing, cell production, stringing, the embedding process during the production of the solar cell and module, transport, handling and installation are all sources of cell cracks in the photovoltaic cells [5],[14]. The cracks and microcracks can be detected easily with electroluminescence technique as shown in the picture below.

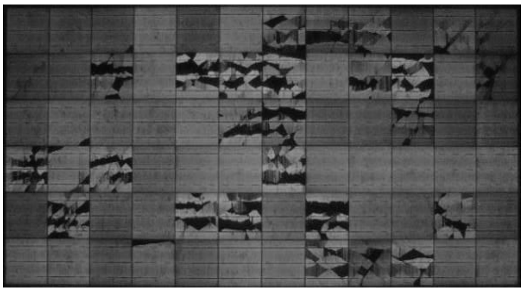

Figure 8: PV Module showing cracks and microcracks [source: PI Berlin]

The associated power losses to the aforementioned phenomenon will depend on the size and depth of the crack, while the crack propagation is purely influenced by the site conditions (for instance, wind, temperature and snow).

6. 7. Delamination

Delamination that occurs at the beginning of the lifetime of a module indicates a disadvantageous material combination or sub-optimal production (e.g. bad lamination). Delamination that occurs towards the end of the lifetime of a module can have multiple reasons. Typically, the adhesion is compromised because of contamination (e.g. improper cleaning of the glass) and environmental factors [8].

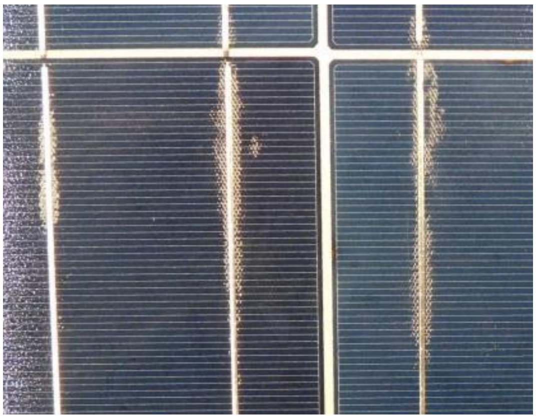

Figure 9: Delamination on the PV cells [source: PI Berlin]

This defect has different degrees of impact, depending mainly on the size and the location. For small delamination with a size of less than 1 cm² and not touching the edge of the modules, there is no impact. Larger delamination not touching the edge can reduce the module insulation resistance, while one touching the edge not only compromises the insulation but also leads to ingress of water and humidity over time, further degrading the insulation resistance and causing corrosion of the components inside the module. Moreover, delamination above the cells near the cell interconnect ribbons can lead to corrosion if water ingress occurs and aggregates. Most likely, the cell degradation process will be accelerated. Delamination at interfaces within the optical paths will result in optical reflection and subsequent loss of current (power) from the module.

7. Results of the Analysis

The following section summarizes the outcomes of the investigations conducted by PI Berlin on the 10 rooftop PV plants.

1

PV plant: ***I.1***

Nominal capacity: ***180kWp – Inspected 87 kWp***

Average specific yield since COD (2016): ***631 kWh/kWp***

Abstract: *The PV plant shows high levels of soiling, as well as losses of production due to near shadings and an inconsistency of the inclination and orientation of the modules. The modules are very hotspot sensitive and show also significant mechanical damages. It is recommended to (i) conduct a reengineering of the modules and strings with individual MPPT assignments, (ii) increase the cleaning frequency to at least twice per month and (iii) use of gravel that increases the reflective properties of the ground. The estimated production boost expected by the retrofitting actions lies between 13% and 17%.*

PV Plant's health

Main Findings

- Heavy soiling even though the visit took place 3 days after a heavy rain and hail storm fell. However, in this period the soiling on the modules was already evident and likely to have an impact on the performance.
- Shading is another common issue throughout the system. Small walls, antennas and other objects are the main source of near shading.
- The PV tables have multiple azimuthal orientations. This leads to current mismatch on string and voltage mismatch on inverter level.

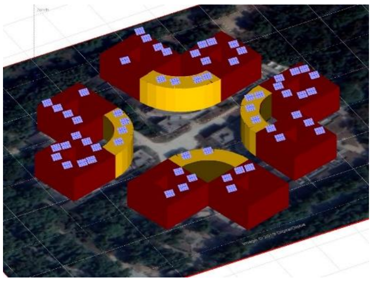

Figure 10: 3D scene

- The installed modules are very hotspot sensitive, which could be detected during the infrared analysis.
- The irradiation sensor is improperly installed providing inaccurate readings, and thus, leading to an inaccurate PR calculation.

Figure 11: Irradiation sensor misaligned

Impact on Performance

- Soiling measurements were conducted measuring both the short circuit current and nominal power before and after cleaning at irradiations of > 700 W/m².
- The estimated soiling factor is in the range of 5% - 12% depending on the location at site.
- The near shadings are responsible for an irradiation reduction on the tilted plane of approx. 3% at system level.

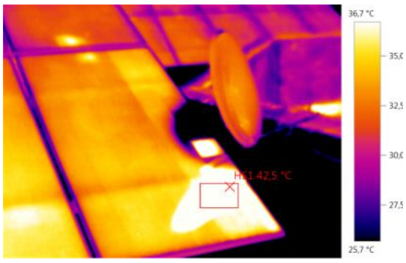

Figure 12: Hot spots caused by near shadings

- The inconsistency of the azimuthal orientation leads to a mismatch loss of approximately 1.5%.
- The amount and type of cracks, and cells in short circuit found in the selected modules during the electroluminescence inspection, reduce the nominal power of the PV plant by 2% - 4%. This statement bases on the extrapolation of the results of the sample measures.

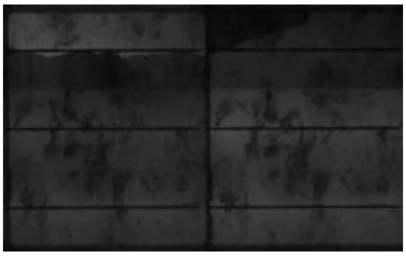

Figure 53: Cells cracks

Proposed Solutions

- A regrouping of the modules shall be conducted in the following way: modules with similar shading conditions shall be installed in the same string or at least assigned to one MPPT.
- Additionally, modules with heavy cracks shall be grouped in the same string or at least assigned to one MPPT. The grouping will be conducted based on infrared inspection with high irradiation levels and after cleaning.

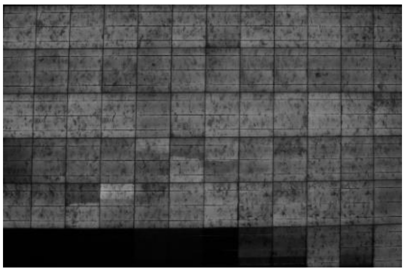

Figure 14: Inactive cells

- A modification of the tilt angle to 24° will generate a performance boost of approx. 0.5%.
- Additionally, it is advisable to create strings with less modules in series in order to reduce the near shading effect. A DC/DC converter at the inverter entrance will be needed to reach the minimal MPP voltage. This represents a performance boost of approx. 2%-3%.
- The irradiation sensor should be reinstalled to provide accurate readings.
- The cleaning cycles shall be increased based on the results of a soiling study that adjusts the cleaning needs to each season.
- Covering the ground with white gravel increases the albedo factor to 0.5, leading to performance boost of 1.7%.

Estimated energy boost after conducting the suggested retrofitting actions: 13% to 17%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 1.3 ₹/Wp, 1.2 ₹/Wp/a

Picture Gallery

Figure 15: Panorama picture

Figure 16: Degraded bar code

Figure 17: Near shadings on the PV surface

Figure 18: Cleaning prior to IV curve tracing

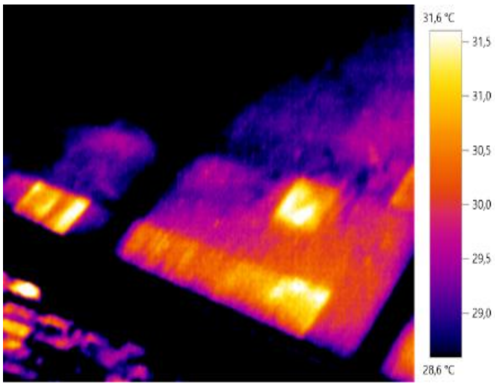

Figure 19: Shadings induced hot spots

Figure 20: Near shadings on the PV surface

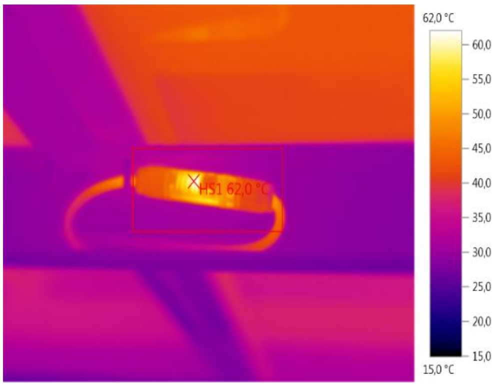

Figure 21: Hot connectors

Figure 22: Dirty irradiation sensor

2

PV plant: ***I.2***

Nominal capacity: ***100 kWp***

Average specific yield since COD (2016): ***1025 kWh/kWp***

Abstract*: The PV plant shows high levels of soiling, as well as hotspots and inactive cell strings caused by the impact of near shading and inconsistencies of the inclination and orientation of the modules. The foundation used for the mounting tables is not robust. It is recommended to (i) conduct a reengineering of the modules and strings with individual MPPT assignments, (ii) double the cleaning frequency, (iii) replace the defect modules, (iv) use gravel that increases the reflective properties of the soil, and (v) relocate some shading objects. The estimated production boost caused by the retrofitting actions lies between 14% and 18%.*

PV Plant's health

Main Findings

- Heavy soiling detected even though the visit took place 4 days after a heavy rain and hail storm fell.
- A significant amount of modules with inactive cell strings were found during the infrared inspection.
- Near shadings effects are caused by water tanks and metal structures located in the south part of the system
- Wind gusts are able to slowly move the structure due to weak concrete foundations not properly attached to the ground.

Figure 23: Weak foundations

- The tilt angle of the modules is not homogeneous with values varying from 10° to 22°
- The installed modules are very hotspot sensitive.
- The irradiation sensor is installed "on top" of the PV modules.

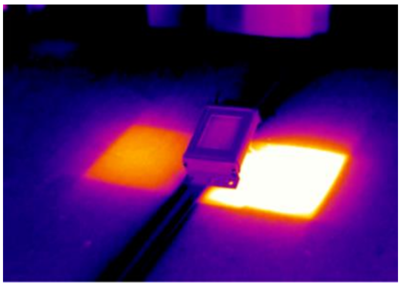

Figure 24: Sensor shading the PV modules

Impact on Performance

- Soiling measurements were conducted measuring both the short circuit current and nominal power before and after cleaning at irradiations of 600 - 780 W/m². The estimated soiling loss of the nominal power is in the range of 4%.
- Modules with active cell strings underperform 33% to 66% depending on the amount of affected strings. The extrapolation of the inspected sample to the whole system leads to a loss of 6% on system level.

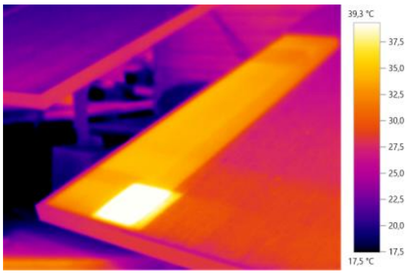

Figure 25: Inactive cells strings

- The near shadings are responsible for an irradiation reduction on the tilted plane of approx. 0.5% at system level.

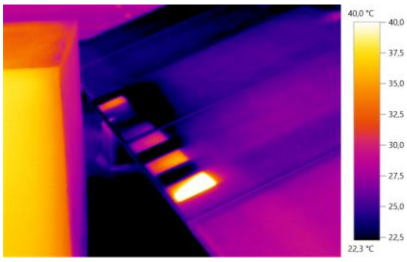

Figure 26: Hot spots caused by near shading

- The inhomogeneous tilt and azimuthal angle leads to a mismatch loss of approximately 0.4%.

Proposed Solutions

- A regrouping of the modules shall be conducted in the following way: modules with similar shading conditions shall be installed in the same string or at least assigned to one MPPT.

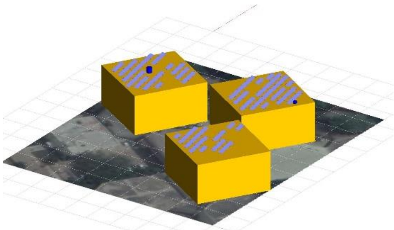

Figure 67: 3D scene

- Modules with inactive cell strings should be replaced according to the performance warranty terms of the module supplier.
- The irradiation sensor should be properly reinstalled to ensure accurate readings.
- The modules with the same tilt and azimuth will be grouped in strings with the same MPPT.
- A modification of the tilt angle to 24° would lead to a performance boost of 1.7%.

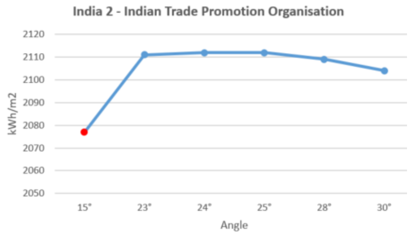

Figure 28: Irradiation increase vs. tilt angle

- The cleaning cycles shall be increased based on the results of a soiling study that adjusts the cleaning needs to each season.
- Objects that cause shading in the south part shall be removed. This exercise is key due to the high hotspot sensitivity of the PV modules.

Estimated energy boost after conducting the suggested retrofitting actions: 14% to 18%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 1 ₹/Wp, 0.5 ₹/Wp/a

Picture Gallery


Figure 29: Panorama picture

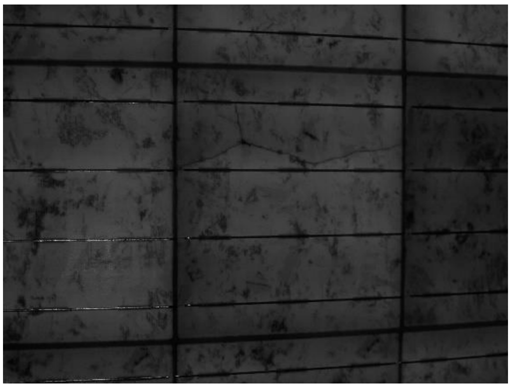
Figure 30: Cell cracks

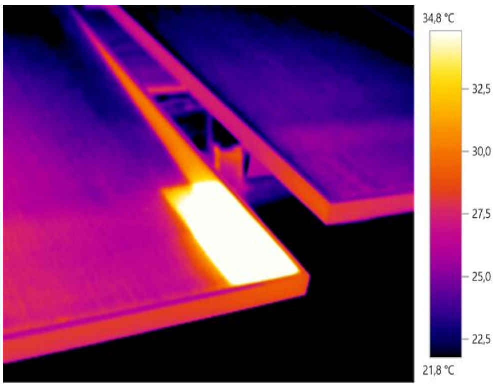

Figure 31: Self shading in E-W direction

Figure 32: Tilt measurement


Figure 33: Inconsistent tilt


Figure 34: Inaccurate DC cable routing

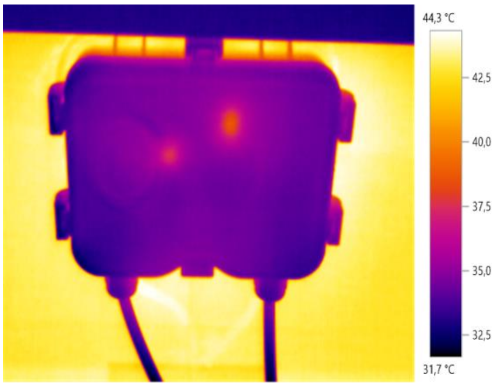

Figure 35: Hot junction box


Figure 36: Dirty filters

3

PV plant: ***I.3***

Nominal capacity: ***100 kWp***

Average specific yield since COD (2016): ***721 kWh/kWp***

Abstract*: The PV plant shows very high levels of soiling caused by pollution, bird drops and low module tilts, a severe module degradation caused by PID and significant mechanical damages at the module level. It is recommended to (i) increase the cleaning frequency to at least 3 times per month, (ii) install an anti-PID box to stop the PID degradation, (iii) replace the PV modules exceeding the guaranteed performance drop given by the manufacturer and (iv) remove all shading object on the module surface. The estimated production boost caused by the retrofitting actions lies between 39% and 50%.*

PV Plant's health

Main Findings

- Heavy soiling caused by bird drops has been detected. A large amount of birds gather on the rooftop system every day.
- Significant cell and modules damages caused by personnel during the installation and O&M activities.

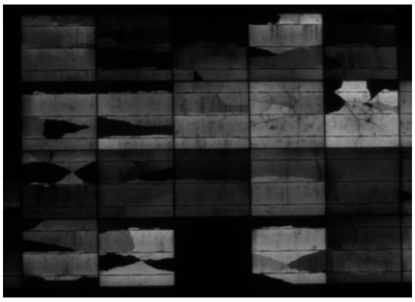

Figure 37: Cells cracks

- The infrared and electroluminescence measurements confirm the presence of Potential Induced Degradation. A big reduction of the open circuit voltage has been detected in the IV curve measurement results.

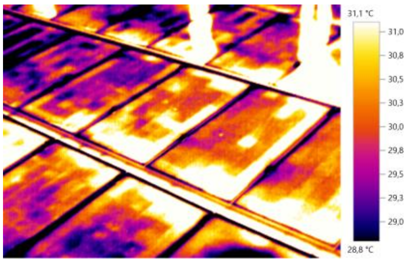

Figure 38: Potential Induced Degradation

- The hose and other objects left on top of the modules are sources of near shading.
- The installed modules are very hotspot sensitive.
- A large section of the rooftop system is shaded by the higher roof.

Impact on Performance

- The severe cracks on module level account for approximately 4-6% of nominal power drop on system level. This statement bases on the extrapolation of the results of the inspected samples.
- Soiling measurements were conducted measuring both the short circuit current and nominal power before and after cleaning at irradiations close to 800 W/m². The estimated soiling loss of the nominal power is in the range of 4%-13% depending on the location of the analyzed module.

Figure 39: Cleaned modules prior to IV tracing

- The PID effect is responsible for more than 30% of performance losses on system level. Individual module measurements showed nominal power drops higher than 80% in the most negative modules.

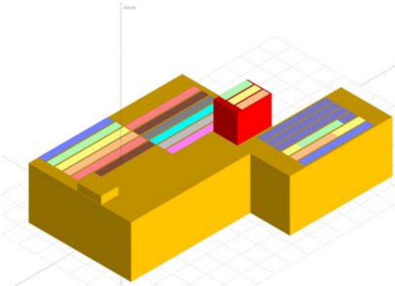

Figure 40: 3D scene

Proposed Solutions

- A regrouping of the modules shall be conducted. Modules with similar shading conditions shall be installed in the same string or at least assigned to one MPPT.
- Due to the large number of cracks discovered during the site assessment, a further regrouping of the modules according to their level of affection shall be conducted. The categorization shall be conducted by means of an infrared camera at high irradiations and after the modules have been cleaned.
- An anti-PID box shall be installed in order to stop the module degradation. PV modules showing power drops above the warranty conditions shall be replaced. If the replacement is not possible, the modules shall be regrouped in power classes within the same string and assigned to individual MPPT.

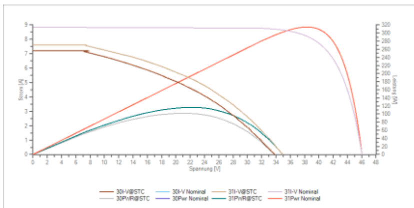

Figure 71: Reduction of V_{oc} due to PID

- An improvement of the cleaning activities shall be conducted by increasing the cleaning cycles.
- Spikes against birds shall be installed at the upper edge of the modules.

Figure 42: Birds on the PV modules

Estimated energy boost after conducting the suggested retrofitting actions: 39% to 50%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 2 ₹/Wp, 0.5 ₹/Wp/a

Picture Gallery

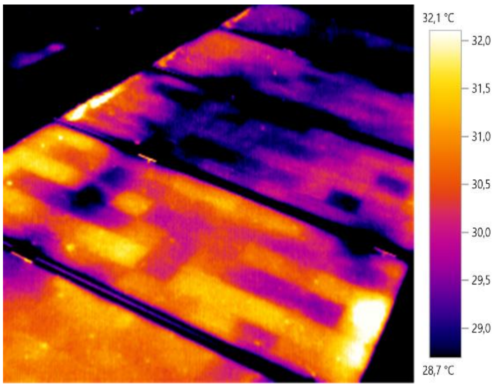

Figure 43: Potential Induced Degradation

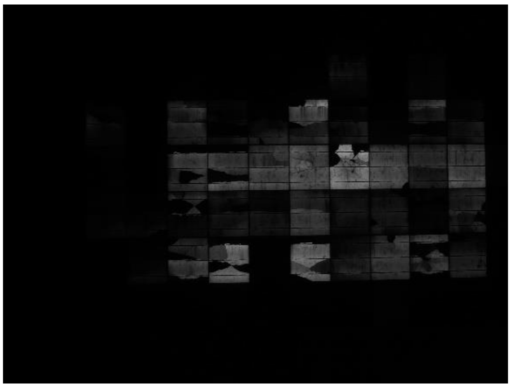

Figure 44: Cell cracks combined with PID

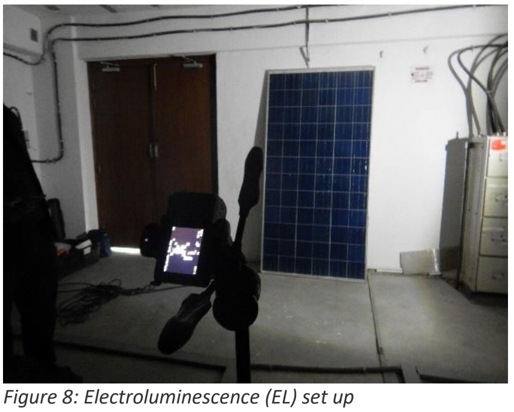

Figure 8: Electroluminescence (EL) set up

Figure 9: Marked modules for EL-inspection

Figure 45: Panorama picture

Figure 46: Infrared inspection

Figure 47: Inverter display

Figure 48: Mounting structure and module anchorage

4

PV plant: ***I.4***

Nominal capacity: ***60 kWp***

Average specific yield since COD (2015): ***1180 kWh/kWp***

Abstract*: The PV plant shows high levels of soiling caused by pollution, bird droppings and hard water, and significant module damages caused by bad handling. The modules are also affected by product defects. The mounting structure is in very bad shape and will likely not last for the whole project lifetime. It is recommended to (i) increase the cleaning frequency to at least 3 times per month (ii) replace the modules exceeding the manufacturer's guaranteed performance drop and (iii) reinforce immediately the structural integrity of the mounting structure. The estimated production boost caused by the retrofitting actions lies between 5% and 7%.*

PV Plant's health

Main Findings

- Heavy soiling has been detected on site. The use of hard water for cleaning increases the accumulation if soil on the module surface. This leads to soiling induced hotspots.
- The mounting structure is heavily rusted and likely not to last until the end of the project's lifetime. Besides, the structure is not robust for the height and number of the installed modules.

Figure 49: Rusted mounting structure

- Loose connectors were found in many PV modules
- Near shadings are caused by the fence, water tank and surrounding structures.
- A significant amount of PV modules show inactive cells strings, scratches and cuts at the backside, junction boxes without lid and browning of the EVA.
- The high amount of cracked cells detected, point towards technicians walking regularly on the modules during installation and maintenance activities.

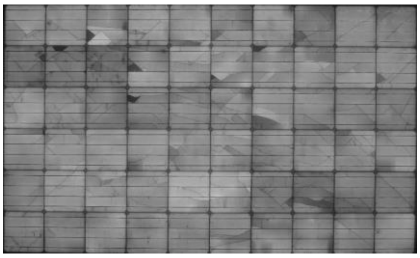

Figure 50: Cell cracks

Impact on Performance

- The irradiance losses caused by near shading is quantified as ca. 3%.
- Based on the crack distribution and types detected with electroluminescence, is it likely that the modules perform 2-4% less. Furthermore, these types of crack could eventually lead to inactive areas and higher power losses in the midterm.
- Modules with inactive cell strings underperform 33% to 66% depending on the amount of affected strings. The extrapolation of the inspected sample to the whole system leads to a loss of 3% at system level.

Proposed Solutions

- The mounting structure should be retrofitted immediately.
- Defective and loose connectors should be replaced and the connectors should be homogenized.
- The irradiation sensor should be properly installed in order to ensure accurate performance ratio calculations.
- All modules with inactive cell strings shall be replaced according to the warranty terms. A similar exercise shall be conducted with all modules showing product defects.

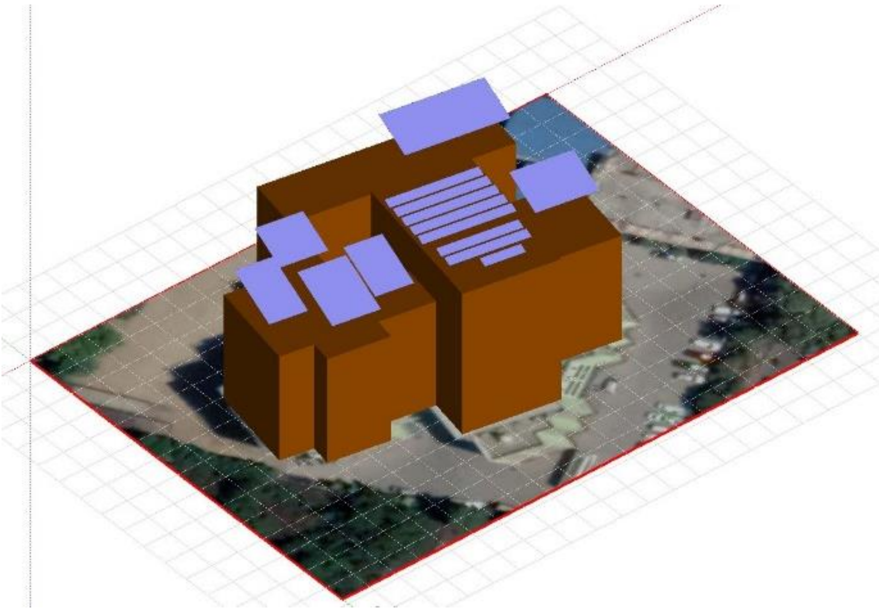

Figure 51: 3D scene

Estimated energy boost after conducting the suggested retrofitting actions: 5% to 7%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 4.4 ₹/Wp, 0.4 ₹/Wp/a

Picture Gallery

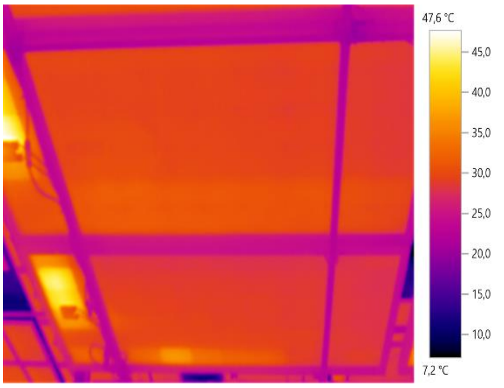

Figure 52: Hot spots

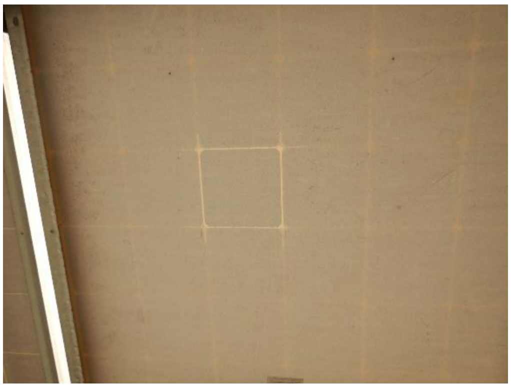

Figure 53: Degraded backsheet

Figure 54: Rusted clamps

Figure 55: Scratched backsheet

Figure 56: Inaccurate DC cabling

Figure 57: Junction box without lid

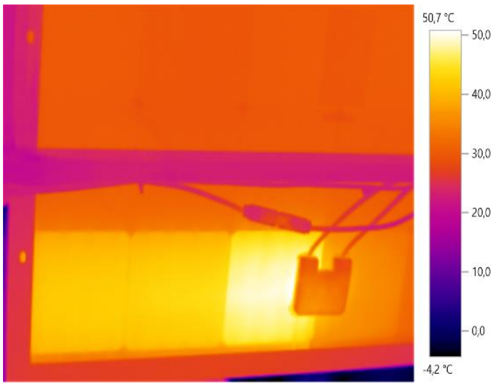

Figure 58: Hot spots

Figure 59: Panorama picture

5

PV plant: ***I.5***

Nominal capacity: ***125 kWp***

Average specific yield since COD (2016): ***1204 kWh/kWp***

Abstract*: The PV plant shows significant soiling caused by bird droppings, inconsistencies of the module orientation, disconnected cables at the inverter input, a significant amount of inactive cell strings and mutual shading between the subsystems. The modules are also affected by product defects. It is recommended to (i) increase the cleaning frequency to at least twice per month (ii) replace defect modules, (iii) rearrange the strings based on shading categories, and (iv) check all inverter cable connections. The estimated production boost caused by the retrofitting actions lies between 6% and 10%.*

PV Plant's health

Main Findings

- Heavy soiling caused by bird droppings has been detected. A large amount of birds gather on the rooftop system every day.
- The PV tables have multiple orientations and tilts lacking homogeneity. The Adani modules in the third system were shaded by the system containing the Medors modules.
- The system containing JJ modules showed a significant amount of snail trails, multicracks, hotspots and broken junction boxes.

Figure 60: Loose junction box lid

- The system showed hotspots as well as a significant amount of inactive cells strings.

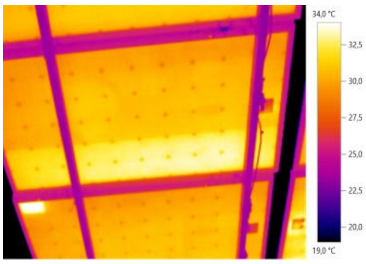

Figure 61: Inactive cell strings

- The infrared analysis showed hot junctions at the DC cable entry. In some inverters disconnected cables were found.
- The irradiation sensor was improperly installed and soiled.

Impact on Performance

- Based on the crack distribution and type found during the electroluminescence inspection, is it likely that the module's nominal power has been reduces by approximately 4%. Furthermore, these types of cracks could eventually lead to inactive areas and higher power loss in the midterm.

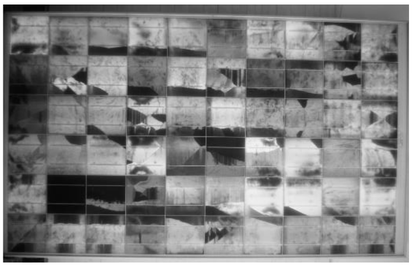

Figure 102: Cell cracks

- The string cables disconnected from the inverter had an impact of 7% on the overall installed capacity at the time of the visit.
- The short circuited modules and the modules with inactive cell strings lead to an overall reduction of the nominal power of around 3%. This statement bases on the extrapolation of the results of the inspected samples.

Proposed Solutions

- The irradiation sensor should be properly reinstalled in order to ensure an accurate PR calculation.
- Spikes against birds shall be installed at the upper edge of the modules.
- The beam from the mounting structure on the west side of the system should be shortened in order to avoid shadings on the Adani modules.
- The cleaning frequency shall be increased due to the low tilt angles that accelerate the soil accumulation.
- All objects on top of the modules shall be immediately removed. The white traces on the module surface shall be removed.
- A regrouping of the modules shall be conducted according to the shading conditions. Modules from the same category shall be installed in the same string or at least assigned to one unique MPPT.
- All modules showing product and performance issues shall be replaced according to the warranty terms.
- All cable connections to the inverter shall be checked.

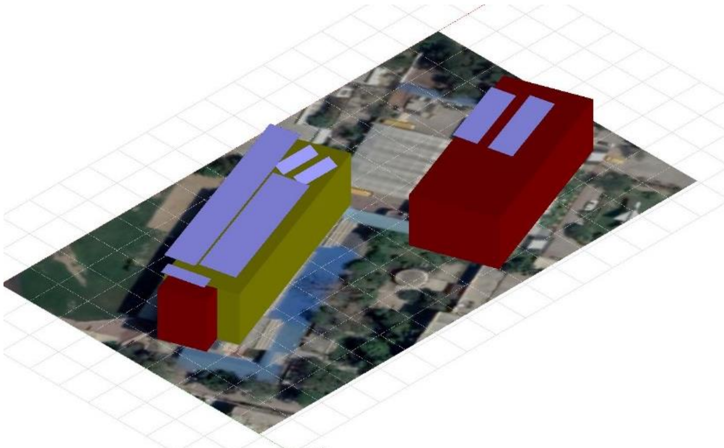

Figure 63: 3D scene

Estimated energy boost after conducting the suggested retrofitting actions: 5% to 10%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 1.8 ₹/Wp, 0.6 ₹/Wp/a

Picture Gallery

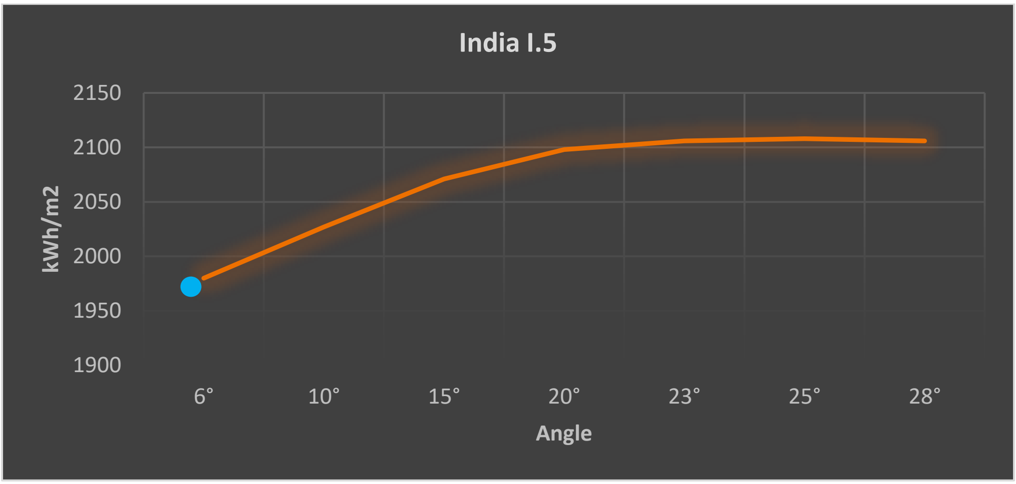

Figure 64: Irradiation increase vs. module tilt

Figure 65: Panorama picture

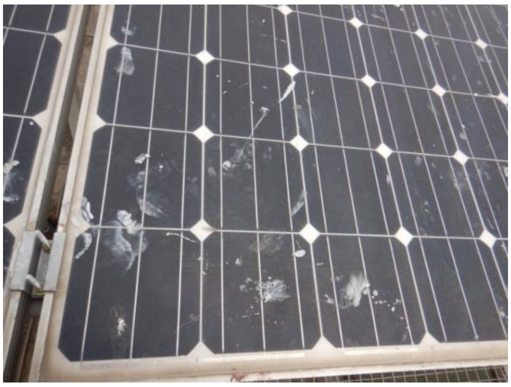

Figure 116: Dirty module surface

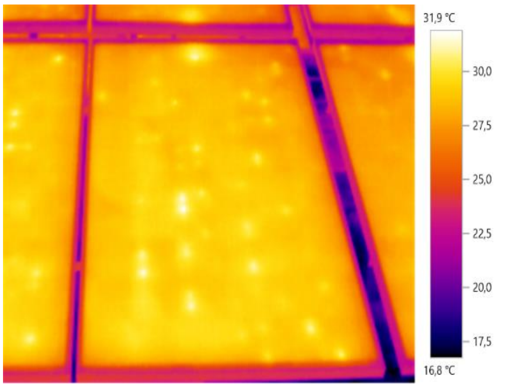

Figure 67: Hot spots cause by bad soldering

Figure 68: Misaligned irradiation sensor

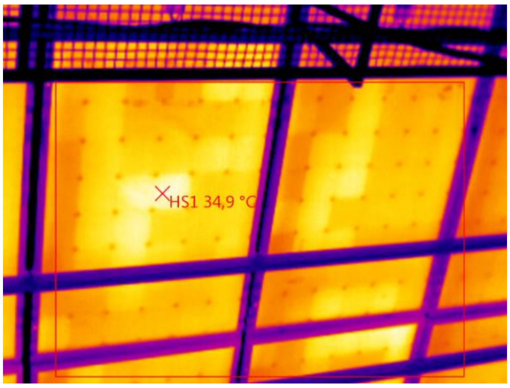

Figure 69: Hot spots

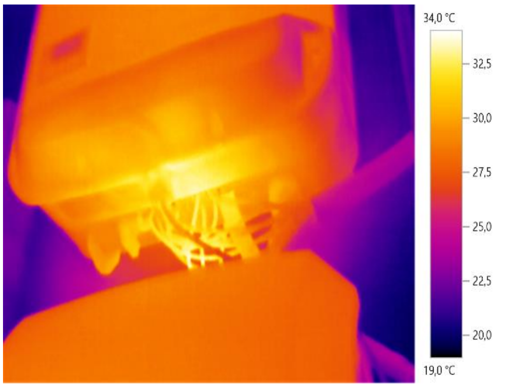

Figure 70: Hot DC cables at the inverter entrance

6

PV plant: ***I.6***

Nominal capacity: ***40 kWp***

Average specific yield since COD (2016): ***600 kWh/kWp***

***Abstract**: The PV plant shows design failures such as the disregard of the inter-row and near shadings, inverter tripping and a strong deviation towards SW that reduces significantly the amount of the solar resource. It is recommended to (i) shorten the strings to mitigate the tripping and shading effects (ii) change the module tilt to 15°, increase the cleaning frequency based on a previous study the adjust the needs to the dry and wet season, and (iii) increase the albedo using white gravel and sticking reflective materials to the walls and shading objects. The estimated production boost caused by the retrofitting actions lies between 13% and 16%.*

PV Plant's health

Main Findings

- The near shading effects were not considered during the design phase and are the main issue of this system. The modules were installed surrounded by walls, antennas and building structures that induce hotspots and inactivity of individual cell strings.

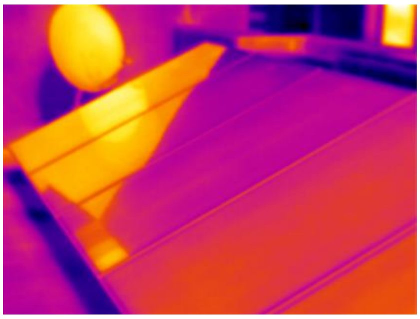

Figure 71: Near shadings on the module surface

- In the area of the system where two module rows are installed, the inter-row losses are significantly high.
- The modules have been installed with an azimuth deviation of 60° towards South West.

Figure 72: Deviation from true South

- Moderate soiling was detected on site.
- The strong azimuth deviation leads to an irradiation loss of around 7%.

Impact on Performance

- The near shading lead to irradiation losses on the module surface of around 8%

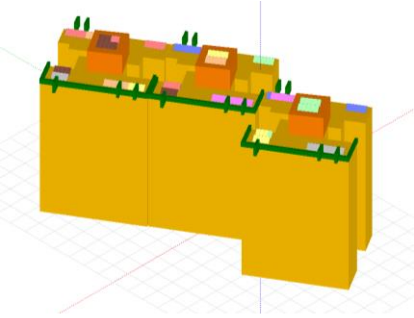

Figure 73: 3D scene

- Soiling measurements were conducted measuring both the short circuit current and nominal power before and after cleaning at irradiations higher than 900 W/m². The estimated soiling factor is in the range 1 – 4%.

Figure 74: Cleaning prior to IV curve tracing

- The inverter configuration generates constant tripping losses due to the high amount of modules connected in series.

Proposed Solutions

- The cleaning cycles shall be increased and defined based on a soiling study that adjusts the cleaning needs to each season.
- It is recommended to shorten the strings in order to reduce the tripping and mitigate the impact of the near shading losses. A DC/DC converter at the inverter input may be needed. This could represent a 2-3% performance boost.
- The walls close to the shaded areas shall be covered with reflective material and the ground re-painted in order to increase the albedo effect. A performance boost of at least 5% is expected.

Figure 75: Area marked with reflective coating

- A modification of the tilt angle to 15° would increase the irradiation on the module surface by at least 1.5%.

Estimated energy boost after conducting the suggested retrofitting actions: 13% to 16%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 0.8 ₹/Wp, 1.5 ₹/Wp/a

Picture Gallery

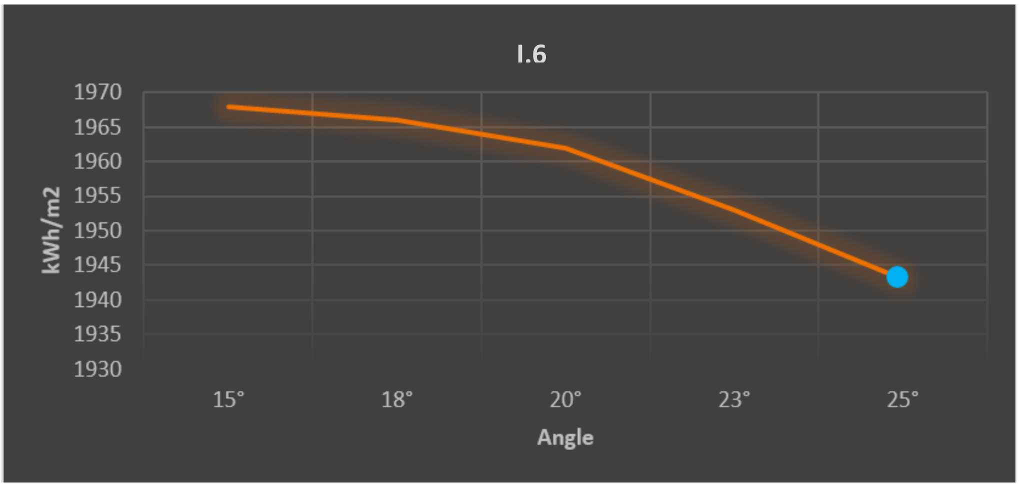

Figure 76: Irradiation increase vs. module tilt

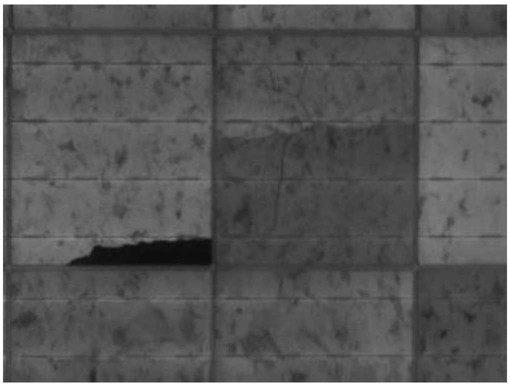

Figure 77: Cell cracks

Figure 78: Tilt measurements

Figure 79: Near shading on the module surface (VI)

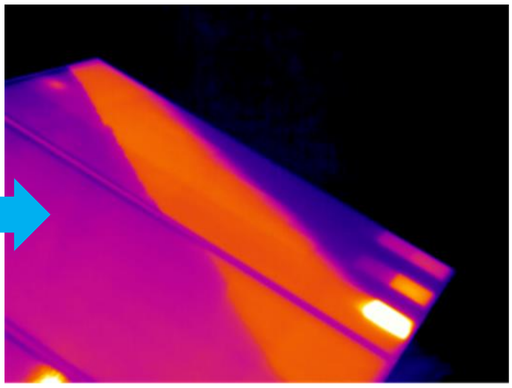

Figure 80: Near shading on the module surface (IR)

Figure 81: Near shading on the module surface (VI)

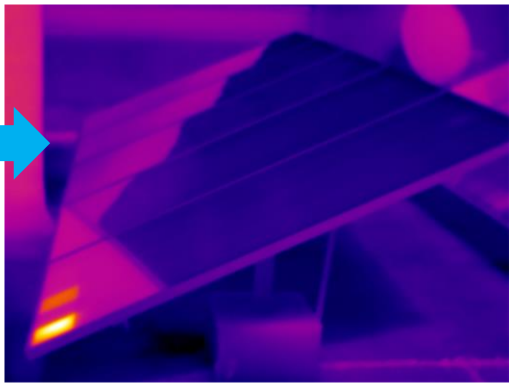

Figure 82: Near shading on the module surface (IR)

7

PV plant: ***I.7***

Nominal capacity: ***70 kWp***

Average specific yield since COD (2018): ***465 kWh/kWp***

***Abstract**: The PV plant shows high levels of soiling caused by bird droppings and a significant amount of inactive cells strings partially induced by soiling. During the assessment installation failures of the DC cabling were detected as well module damages and near shading. It is recommended to (i) change the module tilt to 15°, (ii) increase the cleaning frequency to three times per month, (iii) increase the albedo using white gravel, (iv) relocate the shading objects and (v) replace modules with performance drops beyond manufacturer´s guarantees. The estimated production boost caused by the retrofitting actions lies between 14% and 18%.*

PV Plant's health

Main Findings

- Heavy soiling caused by bird droppings has been detected. A large amount of birds coming from the nearby wasteland, gather on the rooftop system every day.

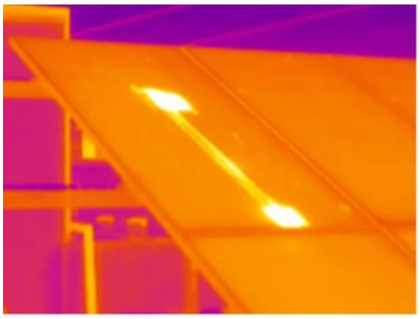

Figure 83: Hotspots induced by bird drops

- The near shadings were ignored during the design phase of this system.
- A significant amount of modules with inactive cell strings were detected. This effect is mainly caused by shading and heavy soiling.
- Scratches at the backside were detected posing safety risks and increasing the risk of inverter disconnection due to loss of insulation.
- The installed irradiation sensor is from a different technology, and has a different tilt angle. The module temperature sensor is not properly fixed.
- A significant of connectors showed overheating due to improper installation.

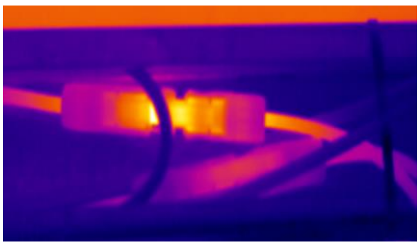

Figure 84: Hot connectors

Impact on Performance

- Soiling measurements were conducted measuring both the short circuit current and nominal power before and after cleaning at irradiations higher than 800W/m². The estimated soiling factor is in the range of 8 – 9%.

Figure 85: Cleaning prior to IV curve tracing

- Modules with inactive cell strings underperform 33% to 66% depending on the amount of affected strings. The extrapolation of the inspected sample to the whole system leads to a loss of 5% on system level.

Proposed Solutions

- The cleaning cycles shall be increased and defined based on a soiling study that adjusts the cleaning needs to each season.
- Spikes against birds shall be installed at the upper edge of the modules.
- The irradiation sensor should be properly reinstalled and it should be of the same technology as the modules.

Figure 86: Irradiation sensor wrongly installed

- The modification of the tilt angle to 15° leads to a performance boost of around 2.2%.
- Increasing the albedo from 0.2 to 0.6 by covering the ground with white gravel leads to an increase of the irradiation on tilted surface of approximately 2%.

Figure 87: 3D scene

Estimated energy boost after conducting the suggested retrofitting actions: 14% to 18%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 0.2 ₹/Wp, 1.2 ₹/Wp/a

Picture Gallery

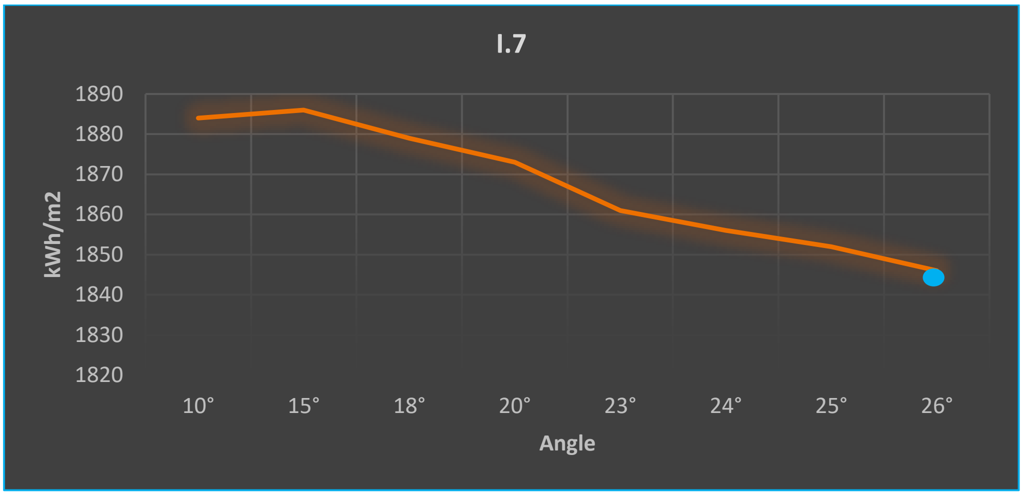

Figure 88: Irradiation increase vs. module tilt

Figure 89: Panorama picture

Figure 90: Scratched backsheet

Figure 91: IV curve tracing

Figure 92: Bird drops on the module surface

Figure 93: Near shading on the module surface (VI)

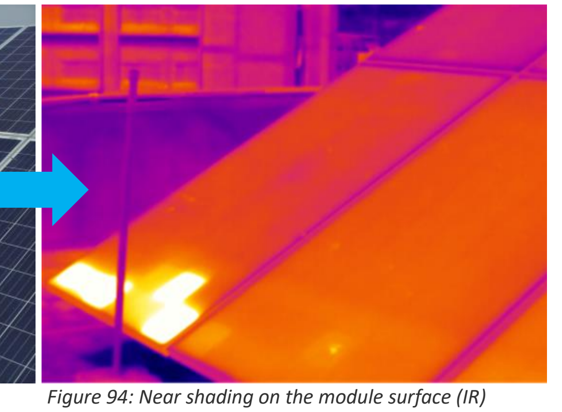

Figure 94: Near shading on the module surface (IR)

8

PV plant: ***I.8***

Nominal capacity: ***150 kWp***

Average specific yield since COD (2018): ***775 kWh/kWp***

***Abstract**: The PV plant shows many cracks at the cell level caused by bad handling, high levels of soiling caused by debris and a strong deviation towards SE that reduces significantly the amount of the solar resource. It is recommended to (i) increase the cleaning frequency to at least three times per month, (ii) increase the albedo using white gravel and (iii) replace modules with product defects and (iv) conduct a resort the modules and strings with individual MPPT assignments according to the level of mechanical damage. The estimated production boost caused by the retrofitting actions lies between 11% and 14%.*

PV Plant's health

Main Findings

- The electroluminescence inspection revealed branched cracks in the modules caused by improper handling during installation and maintenance.

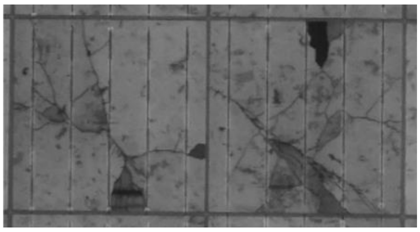

Figure 95: Cell cracks

- Heavy soiling caused mainly by debris was detected.

Figure 96: Bird drops on the module surface

- PV modules of different technologies were mixed in the same string.
- The irradiation sensor was installed at the wrong tilt and was significantly soiled at the time of the visit.
- The PV plant has a strong deviation from South.

Impact on Performance

- The amount and type of cracks is likely to induce a performance loss of around 3%.
- Scratches on the module backsheet were detected posing safety risks and increasing the risk of inverter disconnection due to loss of insulation.
- Soiling measurements were conducted measuring both the short circuit current and nominal power before and after cleaning at irradiations higher than 750W/m². The estimated soiling factor is in the range of 6% - 8%.

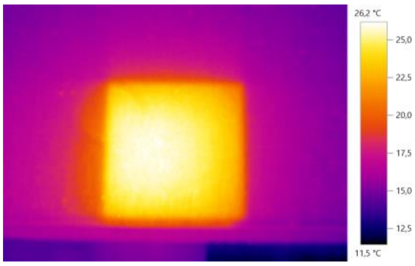

Figure 97: Hot spot

- The deviation of the modules towards South-East leads to an estimated performance loss of around 2.5%.

Proposed Solutions

- Modules with heavy cracks shall be grouped in the same string or at least assigned to one MPPT. The grouping will be conducted based on infrared inspection with high irradiation levels and after cleaning. These modules with cracks will be grouped in strings with same MPPT.
- Strings mixing two different technologies shall be rearranged in order to ensure that they are composed only by one technology type.
- The cleaning cycles shall be increased and defined based on a soiling study that adjusts the cleaning needs to each season. Cleaning once a month during the dry season is not enough.
- The irradiation sensor shall be cleaned and installed at the correct tilt.
- Increasing the albedo from 0.2 to 0.5 by covering the ground with white gravel leads to an increase of the irradiation on tilted surface of at least 1.5%.

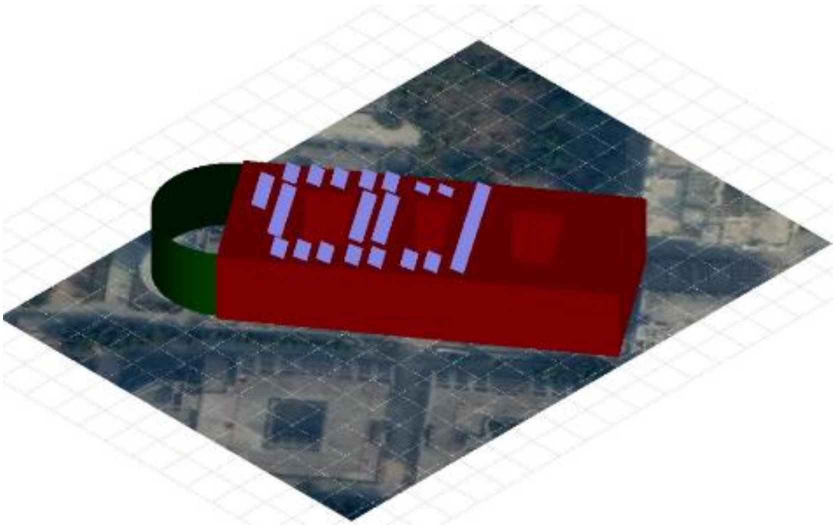

Figure 98: 3D scene

Estimated energy boost after conducting the suggested retrofitting actions: 11% to 14%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 1.2 ₹/Wp, 1.3 ₹/Wp/a

Picture Gallery

Figure 99: Panorama picture

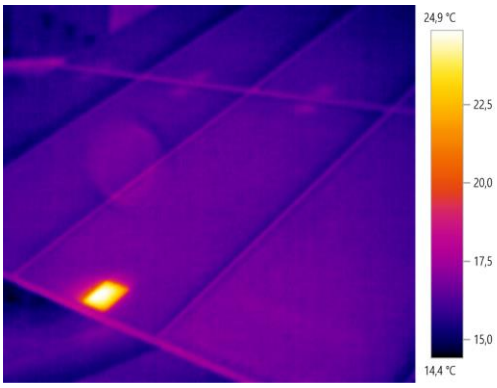

Figure 100: Hot spot

Figure 101: Backsheet damage

Figure 102: Measurements of the coating thickness

Figure 103: Debris around and below the modules

Figure 104: Dirty irradiation sensor

Figure 105: Mixing of poly and mono c-Si modules

9

PV plant: ***I.9***

Nominal capacity: ***120 kWp***

Average specific yield since COD (2017): ***800 kWh/kWp***

Abstract*: The PV plant has a strong deviation towards SW that reduces significantly the amount of the solar resource. The irradiation on the module surface is also reduced by shading objects like trees. Modules with product defects such as unsealed frames and open junction boxes were detected. The modules are very hotspot sensitive. It is recommended to (i) increase the cleaning frequency to at least three times per month, (ii) increase the albedo using white gravel, (iii) replace modules with product defects, (iv) reduce the tilt angle by 2° and (iv) trim the trees in the South part. The estimated production boost caused by the retrofitting actions lies between 5% and 8%.*

PV Plant's health

Main Findings

- The PV modules have a strong orientation towards South-West (220°).
- High presence of near shading objects and E-W shading caused by different mounting table heights.
- A significant level of soiling was detected. The soiling is mainly caused by the presence of birds and nearby vegetation.
- The irradiation sensor was installed at the wrong tilt and was significantly soiled.

Figure 106: Inaccurate fixing of the sensors

- The installed modules are very hotspot sensitive. The interrow shading leads to the development of hotspots at the lower module rows. The tree located South of the plant shades the PV surface created also hotspots. This was evidenced during the infrared inspection.

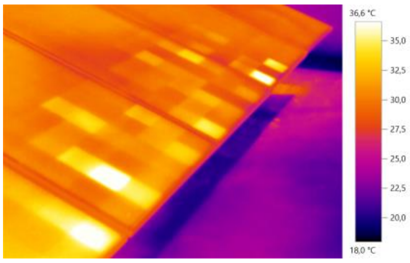

Figure 107: Hot spots caused by near shading

Impact on Performance

- Soiling measurements were conducted measuring both the short circuit current and nominal power before and after cleaning at irradiations close to 900W/m².The estimated soiling factor is in the range of 6%.

Figure 108: Bird presence at site

- The deviation of the PV plant towards South-East leads to an irradiation loss towards the optimum of around 7%.

Proposed Solutions

- The cleaning cycles shall be increased and defined based on a soiling study that adjusts the cleaning needs to each season. Cleaning once a month during the dry season is not enough.
- The tree in the south-east corner should be trimmed
- The irradiation sensor shall be cleaned and installed at the correct tilt.
- Increasing the albedo from 0.2 to 0.5 by covering the ground with white gravel leads to an increase of the irradiation on tilted surface of at least 1.3%.

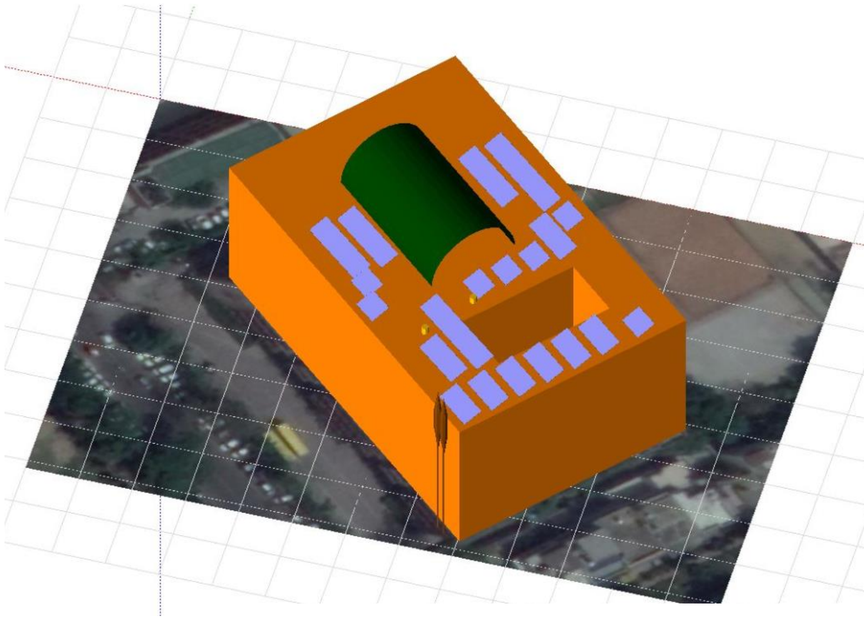

Figure 109: 3D scene

Estimated energy boost after conducting the suggested retrofitting actions: 5% to 8%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 0 ₹/Wp, 1.3 ₹/Wp/a

Picture Gallery

Figure 110: Open connectors

Figure 111: Unsealed module frame

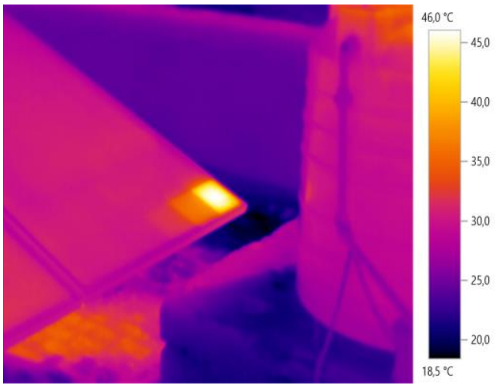

Figure 112: Hotspot caused by near shadings

Figure 113: Junction box without lid

Figure 12: Near shading on the module surface (VI)

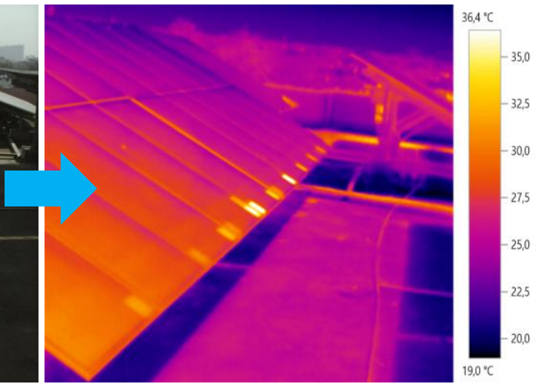

Figure 13: Near shading on the module surface (IR)

Figure 114: Near shading on the module surface (VI)

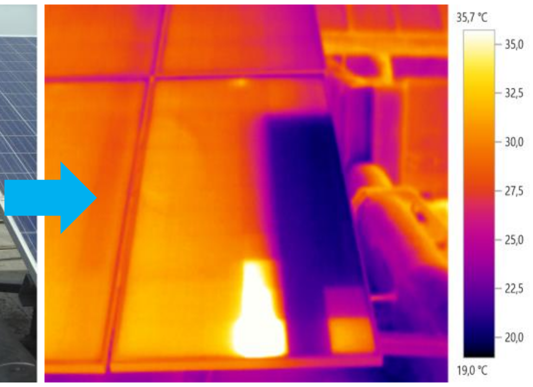

Figure 115: Near shading on the module surface (IR)

10

PV plant: ***I.10***

Nominal capacity: ***60 kWp***

Average specific yield since COD (2011): ***730 kWh/kWp***

Abstract*: The PV plant shows high levels of soiling, inconsistent tilts of the seasonal trackers, severe mechanical damages at the cell level, product defects at the module level and installation failures mainly of the DC cabling. The infrared inspection showed also hotspots induced by cracks and soiling. It is recommended to (i) increase the cleaning frequency to at least three times per month, (ii) homogenize the module tilt, (iii) relocate the shading objects and (iv) conduct a resorting of the modules according to the level of mechanical damage. The estimated production boost caused by the retrofitting actions lies between 14% and 19%.*

PV Plant's health

Main Findings

- Heavy soiling caused by bird droppings and the nearby industrial area has been detected.

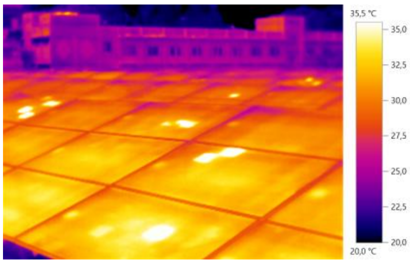

Figure 116: Soiling induced hotspots

- The PV tables showed inconsistent tilts at the time of the visit. The mounting structure has a seasonal tracking system but the tilt is not kept consistent.
- Due to the difficult access to the roof it is likely that the modules suffered mechanical stress during transport, handling and installation. The electroluminescence inspection revealed a big number of cracks in the analyzed modules. This was evidenced by the large number of snail trails detected.

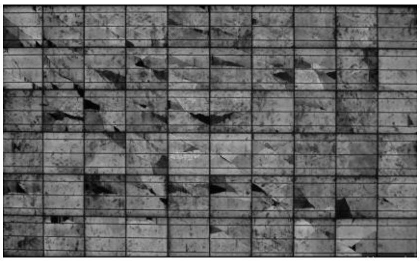

Figure 117: Cell cracks

- Product and installation failures at the module level were detected, such as hot cables at the junction box entry, inaccurate soldering or loose connectors.
- Hotspots induced by soiling, near shading and cracks were detected.
- The installed irradiation sensor is from a different technology, and has a different tilt angle.

Impact on Performance

- Soiling measurements were conducted measuring both the short circuit current and nominal power before and after cleaning at irradiations close to 900 W/m². The estimated soiling factor is in the range 7– 10%.
- The amount and type of cracks found during the electroluminescence inspection is likely to induce a drop of the nominal power of around 8-10%. Many cracks are evidenced with clearly visible snail trails.

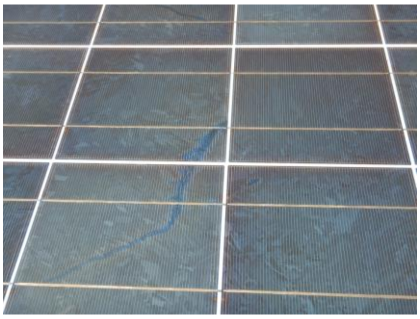

Figure 118: Snail trails

- The inconsistency of the module tilt leads to a mismatch loss of approximately 3%.

Figure 119: Inconsistent module tilt

Proposed Solutions

- Spikes against birds shall be installed at the upper edge of the modules.
- The cleaning cycles shall be increased and defined based on a soiling study that adjusts the cleaning needs to each season. Cleaning once a month during the dry season is not enough.
- The tilt and shading angles throughout the system shall be homogenized.
- Modules with heavy cracks shall be grouped in the same string or at least assigned to one MPPT. The grouping will be conducted based on infrared inspection with high irradiation levels and after cleaning.
- All modules with faulty connectors shall be replaced.
- The lighting pole shall be relocated in order to avoid shadings on the North-West part.
- The irradiation sensor should be properly reinstalled and it should be of the same technology as the modules.
- Increasing the albedo from 0.2 to 0.5 by covering the ground with white gravel leads to an increase of the irradiation on the tilted surface of at least 1.7%.

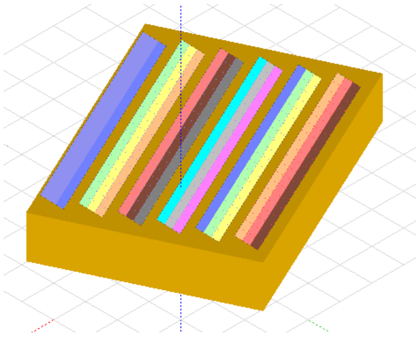

Figure 120: 3D scene

Estimated energy boost after conducting the suggested retrofitting actions: 14% to 19%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 2.7 ₹/Wp, 1.3 ₹/Wp/a

Picture Gallery

Figure 121: Dirty irradiation sensor

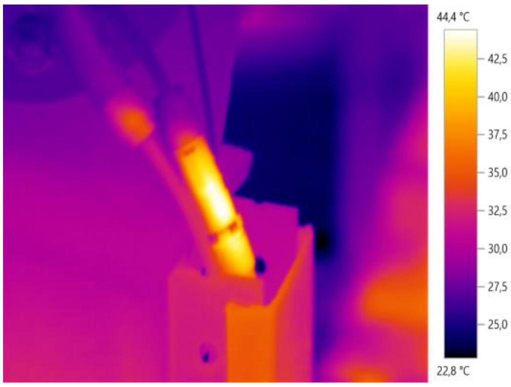

Figure 122: Hot connectors

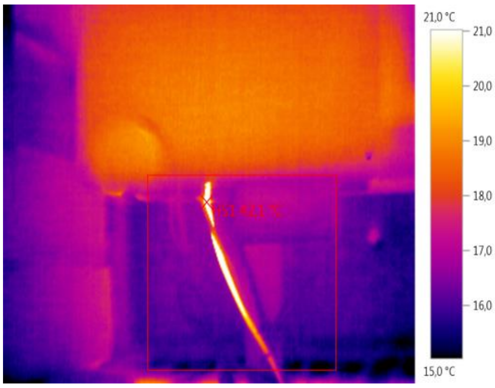

Figure 123: Hot DC cable at the inverter entrance

Figure 124: Cleaning prior to IV curve tracing

Figure 125: Difficult access during installation

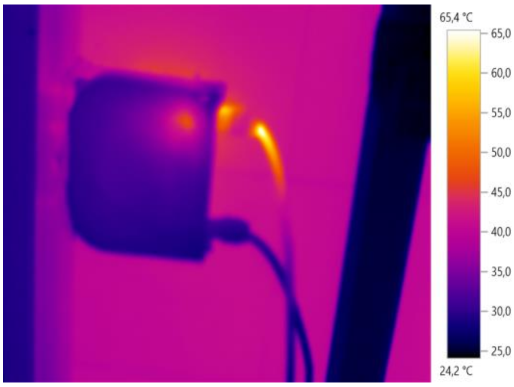

Figure 126: Hot cable at the junction box entrance

Figure 127: Burned cell (VI)

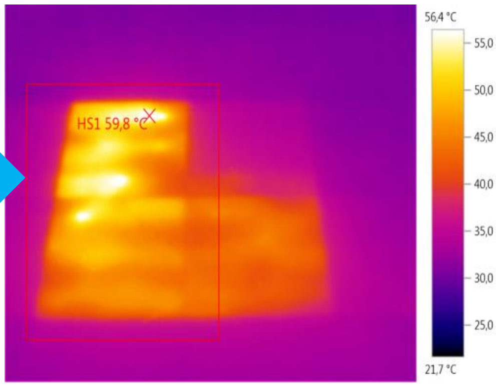

Figure 128: Burned cell (IR)

8. Lessons Learned and Outlook for the Next Generation Projects

The results of the evaluation of each of the 10 PV plants exposed in the previous section, will be used in this chapter to shed some light on three fundamental questions.

8. 1. Which findings arise more often and which have the highest impact on the performance?

The following chart shows the top 10 findings detected on site having a negative impact on the performance of the analysed PV plants. The number attached to each bar shows in how many PV plants each finding was present.

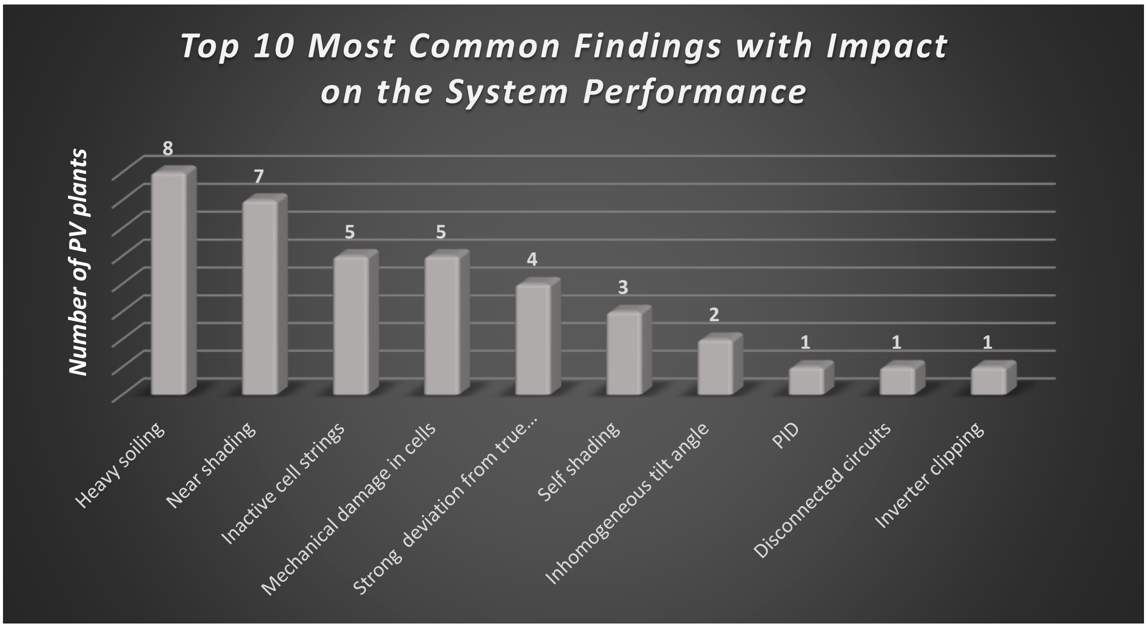

Figure 129: Chart showing in how many PV plants each finding is present (sample: 10 plants)

It can be seen how *heavy soling* and *near shading*, two findings linked to the design constraints of the site, appear in almost all PV plants, while *inactive cell strings* and *mechanical damages in cells*, both related to the electromechanical integrity of the modules, are present in at least half of them. The findings *strong deviation from true South*, *self-shading* and the *inconsistent tilt angle* belong to the third level, and all of them are related to an inadequate design of the PV plants. Finally, *Potential Induced Degradation (PID)*, *disconnected circuits* and *inverter clipping* represent a mix of findings related to (i) an inadequate design of the electrical architecture of the DC part, (ii) failures in the installation and (iii) unexpected module degradation mechanisms.

The results show that the low performance of the inspected PV plants is caused by a mix of (i) disregarded on site design constraints, (ii) poor installation practices, (iii) inaccurate DC design and (iv) module failures.

Another aspect that also contributes to the loss of energy production is an operation and maintenance plan below market standards. Specifically, the lack of spare parts on site coupled with high reaction times, are two aspects that directly result in loss of availability and therefore in a drop of the yield. Only one of the PV plants had spare parts on site and in most of them there was no written agreement setting the contractual reaction times.

The absence of O&M contracts stating clear procedures for the corrective maintenance plan, the reaction times and the contractual availability values, is a factor that also contributes decisively to lowering the PV plant's output.

In regards to the extremely low specific yields recorded in some of the PV plants, it is important to consider that although in some of them less nominal power was installed than initially planned, the calculation of the specific yield is carried out with the latter. This undoubtedly leads to unfairly low performance indicators. The following graph shows which of the 10 findings shown previously has the highest impact on the performance of the inspected PV plants. The graph also indicates the maximum energy loss values associated to each of these findings.[1]

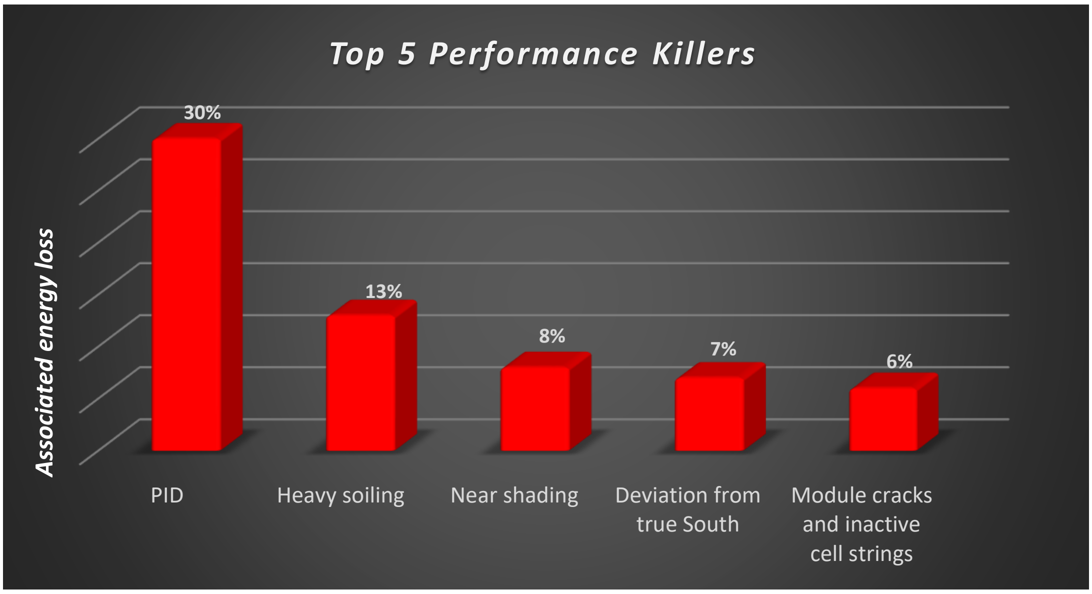

Figure 130: Top 5 findings with the highest performance impact on the inspected PV plants

The graph above shows how an advanced stage of *Potential Induced Degradation (PID)* can lead to a loss of global production at the PV plant level of more than 30%. It is important to bear in mind that this degradation detected in the PV plant number 3 has been reached in only three years[2]. This rapid degradation is explained by the high PID sensitivity of the PV used modules and the typical hot and humidity conditions in the region, all of which are

[1] *These values have been calculated by PI Berlin through (i) estimates based on PI Berlin's long-term experience, (ii) 3D simulation, (ii) processing of data obtained directly on site by means of special equipment.*
[2] *The PV plant was connected to the grid in 2016.*

aspects that contribute to a fast development of this phenomenon. The presence of bird droppings, debris or pollution, result in soiling losses of up to 13% in some of the PV plants. In this regard, it is important to bear in mind that the PV plants visited by PI Berlin underwent a natural cleaning a few days before by means of a heavy rainstorm and hail that likely removed much of the accumulated dirt on the modules. The values measured on site by PI Berlin can therefore be greatly exceeded in the dry season.

According to PI Berlin calculations, the global losses at the PV plant level caused by *PID* exceed 30% in 3 years, while the losses associated with soling can widely exceed 13% in the dry season.

The losses caused by *near shading* and *strong deviation from true South* are estimated in some of the inspected PV plants at around 8% and 7% respectively. These losses are difficult to mitigate since they are due to design constraints which should have been properly addressed during the design phase. Finally, the losses associated with (i) *mechanical damage of cells* and (ii) *inactive cell strings* induced by soiling, shading or cracks, can reduce the production of some PV plants by 6% respectively.

In some of the inspected PV plants, the losses caused by *near shading* and *deviation from true South* exceed 8% and 7% respectively, according to PI Berlin's estimations. In PV plants with severe *mechanical damage* at the module level, the nominal power of the PV plant can be reduced by up to 6%.

These losses are in some cases due to the mishandling of the modules during the installation and O&M phase, and in others due to product failures. Only in the case of the latter, can cooperation of the manufacturer in relation to the supply of replacement modules be expected. Since the warranties offered by the installation company are limited to the product and do not include workmanship, the damages resulting from mishandling during installation remain uncovered.

8. 2. Which retrofitting solutions can be implemented to boost the energy production of the inspected PV plants?

PI Berlin suggests 5 retrofitting actions to partially mitigate the negative consequences of the findings described in the previous section. The most important actions associated to these retrofitting actions are described below:

Re-sorting of modules and strings. A re-sorting of the modules shall be conducted in those cases where the present configuration leads to significant mismatch at inverter level or to low output currents of some strings due to the low performance of individual modules. Modules affected by inactive cell strings and/or heavy cracks with isolated cell sections that induce hotspots, shall be grouped in the same strings. In those cases where the output voltage of low performing strings affects significantly the string voltage, “good” and “bad” strings will be assigned to different MPP trackers. The distinction between good and bad strings and between damaged and not damaged modules can be conducted with a multimeter and an infrared camera respectively. The infrared inspection shall be conducted after cleaning and at irradiation values higher than 800W/m².

Increasing of the module cleaning frequency. The source of soiling in most of the inspected PV plants is either bird droppings, pollution, debris or a combination of all three. In order to figure out what the optimum cleaning interval is, the output of clean[3] and dirty strings shall be compared for at least 3 months. As soon as the difference in the output leads to a loss of revenue that offsets the cleaning costs of the whole plant, a cleaning visit will be needed. This study will be performed separately for the dry and rainy season, as natural cleaning comes into place in the rainy months. Cleaning becomes particularly relevant in those plants where the modules are mounted with very flat angles.

Module replacement. The replacement of the modules should only be carried out if the cost of the components is borne by the manufacturer. This case can only occur (i) if the manufacturer still exists, (ii) if the reasons why the replacement is required are due to product defects or a loss of performance higher than the guaranteed values, and (iii) if the warranties are still active. The manufacturer's warranties do not cover damages caused by bad handling or improper installation and poor O&M practices.

[3] *The clean strings are used as a benchmark and will be cleaned every day.*

Shorten module strings. In situations where the near shadings seriously affect the energy generation of the modules, it is recommended to shorten the strings by reducing the number of modules connected in series. The strings will be grouped by MPPTs at the inverter level to reduce as much as possible the voltage mismatch. DC/DC converters may be necessary at the inverter input in cases where the minimum MPP voltage is not reached under operating conditions.

Increase of the albedo factor. It is recommended to cover or paint the ground with white gravel or light colours and stick reflective materials to the walls and shading objects surrounding the PV modules. These measures aim at increasing the overall albedo factor to 0.5 and thus, the amount of kWh/m² reaching the PV module surface. Glaring of neighbouring buildings shall be avoided.

Depending on the status of each PV plant, and as long as the future O&M contractor has sufficient personnel and budget, all or only some of the abovementioned measures can be applied. In any case, the measures proposed by PI Berlin do not imply huge investments and can be implemented with a reasonable budget. The measures suggested by PI Berlin must be complemented with a reinforcement of the commercial conditions in the O&M contracts, mainly in regards to (i) the reduction of the reaction times and (ii) the storage of spare parts needed to commit to the said reaction times.

PI Berlin suggests 5 retrofitting actions that depending on the status of each PV plant may lead to a performance boost between 5% and 50%. These actions do not require large investments in the OPEX.

Besides the retrofitting actions needed to increase the energy generation, any necessary improvements to operate the PV plants in a safe environment shall also be carried out. These improvements shall be conducted regardless how high the estimated performance boost is.

8. 3. Which mechanisms are needed to avoid underperformance and to ensure the revenues in the next generation projects?

Problems caused by wrong decisions taken during the design phase can only be solved partially during the operational phase. Therefore, preventive measures shall be applied in order to save costs and time at later stages. PI Berlin makes the following suggestions based on the issues and findings detected during the assessment of the 10 PV plants:

1. The energy yield assessment conducted during the development phase shall consider all shading objects that have an impact on the system performance. This

will help to avoid overestimations of the yearly output and an inaccurate modelling of the cash flows.

2. The module strings shall be sized with less modules in those cases where the near shadings have a significant impact in the energy production. Shading losses higher than 5% shall be avoided.
3. Self-shading between rows shall be kept as low as possible. Lower tilt angles help achieving this goal.
4. The PV plants shall not deviate more than 30° from true South. Aligning the PV plant´s layout to the orientation of the building is not always the best solution.
5. All PV plants shall be commissioned before handover according to the industrial best practices. These practices shall include besides all safety tests stated in the IEC 62446, a PR test of at least 5 days and an infrared inspection of 100% of the PV modules, inverters and cables. The reliability of the SCADA system and the weather station shall be evaluated as well.
6. In case of lack of experience, the installation and O&M teams shall be trained to avoid damages on the PV modules during their daily activities.
7. The O&M contracts shall include clear indications on the expected reaction times, intervention plan during corrective maintenance, preventive maintenance plan, spare part management, reporting, contractual availability values and SCADA visualization. These topics will be tailor made to the needs of each individual PV plant.[4]
8. The module cleaning frequency shall be adjusted after the first year based on the methodology described in chapter 8.2.
9. The EPC contract shall include dedicated sections describing the best practices for installation and commissioning practices as well as the pass and fail criteria for handover with its associated penalties.[5]
10. Each PV plant shall include a weather station with at least (i) one irradiation sensor on the tilted plane, (ii) one ambient temperature sensor and (iii) one module temperature sensor. All sensors shall be properly installed according to the manufacturer’s requirements. The irradiation sensor shall be calibrated every 2 years, kept clean and installed at the right tilt, in order to ensure an accurate and representative PR calculation

[4] *This recommendation may be difficult to implement for small rooftop systems*

[5] *This recommendation may be difficult to implement for small rooftop systems*

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[18] Assessment of Photovoltaic Module Failures in the Field; Report IEA-PVPS T13-09:2017; International Energy Agency;

Annex I – IV Curve Tracing Results

	Pmax	Voc	Vmpp	Impp	Isc	Irrad.	Modul Temp.	FF		Isc (A)	Irradiation (W/m²)	EL	STC Δ
1	237,54	41,01	32,5	7,31	8,13	794	47	71	Dirty	6,42	777	5501-5503	6,04%
2	236,2	41,01	32,29	7,32	8,09	793	47	71	Dirty	6,42	777		
3	234,81	40,94	32,14	7,31	7,91	792	47	73	Dirty	6,42	777		
13	251,4	41,54	32,86	7,65	8,45	741	48	72	Clean	6,52	780		
4	243,94	41,16	33,49	7,28	7,94	770	47	75	Dirty			5505	5,19%
5	248	41,17	32,55	7,62	8,11	751	47	74	Dirty				
6	245,7	41,15	33,45	7,35	7,88	737	46	76	Dirty				
7	271,24	42,16	33,74	8,04	8,57	723	40	75	Clean				
8	257,83	41,99	34,06	7,57	8,15	755	44	75	Clean				
9	259,1	41,92	33,41	7,76	8,2	735	44	75	Clean				
10	242,2	41,09	32,94	7,35	7,89	716	46	75	Dirty	5,92	724		7,44%
11	260,8	41,95	33,6	7,76	8,31	730	46	75	Clean	6,76	724		
12	261,7	41,87	33,53	7,81	8,38	724	40	75	Clean	6,76	724		
14	204,3	40,27	29,39	6,95	7,69	707	44	66	Dirty	4,9	600	5497-5498	12,39%
15	233,2	41,93	31,13	7,49	8,14	753	34	68	Clean	6,2	760		
16	255,7	43,29	34,52	7,41	7,82	773	29	76	Dirty	6,05	772		1,62%
17	257,53	41,92	33,69	7,64	8,07	711	38	76	Clean	5,9	710		
18	259,9	41,78	34,33	7,57	8,06	708	38	77	Clean				
19	100,29	31,48	18,44	5,44	7,57	861	38	42	Dirty	7,38	890	5500	7,20%
20	98,92	31,43	19,29	5,13	7,38	856	47	43	Dirty				
21	107,97	31,59	18,63	5,8	8,12	753	39	42	Clean	7	800		
22	106,6	31,87	18,94	5,63	7,89	795	39	42	Clean				
23	92,53	31,43	19,32	4,79	6,89	916	48	43	Dirty	8,13	979		3,98%
24	108,8	34,55	21,55	5,05	6,97	998	48	45	Dirty				
25	114,01	34,83	21,12	5,4	7,38	999	40	44	Clean	8,67	7013		
26	113,4	34,62	21,33	5,31	7,43	988	40	44	Clean				
27	80,37	29,54	17,05	4,71	6,86	861	46	40	Dirty	6,25	800		7,73%
28	87,53	30,34	17,82	4,91	7,06	928	38	41	Clean	6,86	800		
29	87,1	29,98	17,15	5,08	7,19	883	38	40	Clean				
30	101,9	33,83	20,94	4,87	7,2	833	46	42	Dirty	6,84	828		12,55%
31	116,5	34,91	22,56	5,17	7,6	905	37	44	Clean	7,37	830		
32	116,21	34,86	22,53	5,16	7,6	928	37	44	Clean				
33	226	39,01	33,75	6,7	7,82	528	35	74					
34	227,2	38,86	33,64	6,76	7,98	508	35	73					
35	293,73	45,11	37,2	7,9	8,35	989	42	78	Dirty	8,21	940		0,73%
36	292,5	45,06	36,71	7,97	8,33	977	42	78	Dirty				
42	294,7	45,26	36,95	7,98	8,41	890	39	77	Clean	7,95	904		
43	294,82	45,23	36,94	7,98	8,45	899	39	77	Clean				
38	285,1	45,29	36,9	7,73	8,09	1009	41	78	Dirty	8,4	1000	5567	-0,85%
39	284,7	45,21	36,9	7,71	8,12	1012	41	78	Dirty			5567	
40	283,6	45,07	36,23	7,83	8,16	962	38	77	Clean	8,14	970	5567	
41	282,7	45,05	36,15	7,82	8,12	971	38	77	Clean			5567	
44	299	45,53	36,9	8,1	8,57	824	39	77	Dirty	7,11	810	5570-5572	4,10%
45	293,63	45,39	36,86	7,97	8,23	796	39	79	Dirty			5570-5572	
46	311,8	46,35	37,92	8,22	8,62	902	39	78	Clean	8,4	955	5570-5572	
47	301,55	45,97	37,84	7,97	8,41	959	38	78	Clean			5570-5572	
48	292,4	45,34	37,06	7,89	8,48	755	55	76	Dirty	7,56	851		4,93%
52	307,6	45,32	37,05	8,3	8,78	760	43	77	Clean	7,86	858		
49	287,7	45,01	36,88	7,8	8,06	824	52	79	Dirty	7,3	871		4,03%
53	299,8	45,05	36,88	8,13	8,5	726	43	78	Clean	7,6	870		
50	291,1	45,12	36,72	7,93	8,44	842	54	76	Dirty	7,79	860		4,39%
55	304,5	45,16	36,61	8,32	8,88	830	44	76	Clean	7,75	850		
51	281,1	44,61	36,67	7,67	8,14	814	51	77	Dirty	7,2	856		4,60%
54	294,6	45,11	37,27	7,91	8,28	746	44	79	Clean	7,4	856		
56	283,1	44,49	35,93	7,88	8,4	971	44	76	Dirty	8,2	941	5592-5595	3,13%
59	292,2	44,67	36,01	8,12	8,64	974	40	76	Clean	8,72	987		
57	277,8	44,44	35,78	7,77	8,23	919	45	76	Dirty	7,34	831	5597	6,17%

	Pmax	Voc	Vmpp	Impp	Isc	Irrad.	Modul Temp.	FF		Isc (A)	Irradiation (W/m²)	EL	STC Δ
60	296,1	44,95	36,53	8,11	8,62	972	44	76	Clean	8,82	985		
58	277,8	44,31	35,96	7,73	8,31	969	45	75	Dirty	8,5	960	5599	5,15%
61	292,9	44,73	36,16	8,1	8,64	965	44	76	Clean	8,72	982		
63	293,4	44,83	35,7	8,22	8,71	1000	43	75	Clean	8,76	986	5605-5607	8,68
64	295,5	44,81	36,33	8,13	8,74	951	43	75	Clean	8,6	985	5601-5604	8,75
65	158,7	34,17	25,97	6,11	6,63	948	42	70	Dirty	6,27	914		-0,83%
71	157,4	34,94	28,86	5,45	6,86	811	42	66	Clean	6,5	904		
66	148	34,75	26,37	5,61	6,5	861	42	66	Dirty	6,27	907		7,38%
72	159,8	35	26,72	5,98	6,93	833	43	66	Clean	6,2	875		
67	154,9	34,84	27,15	5,71	6,53	819	42	68	Dirty	6,24	923		9,63%
70	171,4	35,01	27,05	6,34	7,09	848	40	69	Clean	6,34	872		
68	154,6	34,61	27,05	5,71	6,37	970	43	70	Dirty	6,27	928		9,98%
69	171,7	35,3	27,2	6,31	6,87	833	43	71	Clean	6,1	852		

Annex II – Documentation required from the Rooftop Owners

	Required Documents	Description	Available yes	Available no	Comments Owner
1	**GENERAL ASPECTS**				
1.1	Customer name				
2	**RELEVANT DOCUMENTS DURING THE DEVELOPMENT PHASE**				
2.1	Yield assesment				
3	CONTRACTS				
3.1	O&M contract				
3.2	EPC contract				
4	**COMPONENTS**				
4.1	PV Module				
4.1.1	Amount of modules				
4.1.2	Datasheet				
4.1.3	Warranty documentation				
4.1.4	Flash-lists				
4.2	Mounting structure				
4.2.1	Technical description				
4.2.2	Sectional drawings of the module-tables/structure				
4.3	Inverter				
4.3.1	Amount of inverters				
4.3.2	Warranty documentation				
4.3.3	Datasheet				
4.4	Combiner boxes				
4.4.1	Drawings				
4.4.1	Datasheets				
4.5	Monitoring system (SCADA)				
4.5.1	Remote access to SCADA system				
4.5.2	Datasheets of the weather sensors				
5	**DESIGN**				
5.1	Exact module and inverter location (if possible as CAD drawings as well)				
5.2	Location of combiner boxes in the field				
5.3	Number of strings				
5.4	Single line diagram				
6	**INSTALLATION**				
6.1	Installation date and grid connection date				
6.2	Location of the installed sensors				
6.3	As-built layout				
7	**COMMISSIONING**				
7.1	Commissioning protocols				
8	**PERFORMANCE**				
8.1	Internal or external reports				
8.2	Irradiation and temperature data on hourly basis since COD				
9	**O&M**				
9.1	Monthly operating reports or any other information collected since COD regarding the operational status of the plant				
9.2	Procedures for verifying correct system operation				
9.3	Preventive maintenance checklists				
9.4	Cleaning procedure				

Annex III – TDD Checklist

No.	Item	Interview needed?	Photo needed?	Comments	Photo No.	Note No.
0	**General**					
0.1	Date of inspection					
0.2	Name and size of the plant					
0.3	Coordinates					
0.4	Commercial Operation Date (COD)					
0.5	Name of the Owner					
0.6	Name of the EPC					
0.7	Name of the O&M company					
1	**Contracts**					
1.1	Warranties of the EPC contract (PAC and FAC)					
1.2	Warranties of the O&M contract					
1.3	Completeness of the PAC in the EPC contract					
1.4	Name of the OE					
1.5	Name of the LTA					
2	**PV Plant Design**					
2.1	DC size					
2.2	AC size					
2.3	DC/AC ratio					
2.4	Level of injection					
2.5	Size of each PCU					
2.6	Module type					
2.7	Module technology					
2.8	Inverter type					
2.9	Pitch					
2.10	Tilt of the modules					
2.11	Mounting structure type					
2.12	Module arrangement					
2.13	Statics					
2.14	Location of the inverters and AC distribution boxes					

No.	Item	Interview needed?	Photo needed?	Comments	Photo No.	Note No.
3	**Electromechanical Installation**					
3.1	**Mounting structure**					
3.1.1	Module fixation					
3.1.2	Labelling of rows					
3.1.3	Rust mounting structure					
3.2	**Combiner box (CB)**					
3.2.1	Sealing of the cable glands					
3.2.2	Cleanliness of the CB					
3.2.3	Overvoltage in the CB					
3.2.4	Labelling of the CB					
3.3	**Cables**					
3.3.1	Cable damage					
3.3.2	Labelling of cables					
3.3.3	Connectors					
3.3.4	Cable fixation					
3.3.5	Bending radius					
3.3.6	Protection of cables against UV					
3.3.7	Sealing of tubes					
3.3.8	Cable pipes					
3.4	**Inverter**					
3.4.1	Overvoltage in the inverter					
3.4.2	Cleanliness of the inverter room					
3.4.3	Cooling					
3.4.4	Status of filters					
3.4.5	Entrance of the communication cable					
3.5	**Grounding**					
3.5.1	Status of the grounding and equipotential bonding system					
3.5.2	Functional grounding					
3.6	**Civil work**					
3.6.1	Status of the roads					

No.	Item	Interview needed?	Photo needed?	Comments	Photo No.	Note No.
3.6.2	Status of the drainage system					
3.7	**Documentation**					
3.7.1	Completeness of the as-built documentation					
3.7.2	Progress reports of the installation phase					
4	**Commissioning**					
4.1	Tests conducted at PAC and FAC?					
4.2	Did anyone witness and validate?					
5	**System Performance**					
5.1	Parallel logging of the irradiation sensors					
5.2	Parallel logging of the temperature sensors					
5.3	Date of calibration of the sensors					
5.4	Weather station status					
5.5	What has been the PR of the plant since grid connection?					
5.6	How is the PR calculated?					
5.7	PR correction					
5.8	Yield assessment					
6	**Module Quality**					
6.1	Visual inspection modules					
6.2	Availability of the flash lists					
6.3	Scratches in back sheet					
6.4	Long term durability certificates of the PV modules and inverters					
6.5	IR analysis					
6.6	EL analysis					
6.7	IV curve tracing					
6.8	Snail trails					
6.9	PID					
7	**Operation & Maintenance**					
7.1	Specific issues reported since COD					

No.	Item	Interview needed?	Photo needed?	Comments	Photo No.	Note No.
7.2	Relevant environmental events					
7.3	Experience of workers in PV					
7.4	Experience of workers in O&M					
7.5	H&S program					
7.6	Allowance to operate MV devices					
7.7	Calculation of the soiling loss					
7.8	Cleaning methodology					
7.9	Vegetation					
7.10	Check the tools and devices used					
7.11	Reporting					
7.12	Reaction times					
7.13	Preventive maintenance					
7.14	Corrective maintenance					
7.15	Availability calculation					
7.16	Responsibility for SCADA					
7.17	SCADA resolution					
7.18	Theft on site					
7.19	Curtailment and grid stability					
7.20	Reactive power compensation and power quality requirements					

Annex IV – Measurement Equipment used on Site

HT SOLAR-IV [S/N **11110683**, calibration date **08.2018**, tolerance **5%**] is a peak power measuring device and IV curve tracer that provides the measurement of the IV curve of photovoltaic modules and strings on site. Measurements of PV array IV characteristics under actual on-site conditions and their extrapolation to Standard Test Conditions (STC) can provide data on power rating, verification of installed array power performance relative to design specification, detection of possible differences between on-site module characteristics and laboratory or factory measurements, and detection of a possible performance degradation of module and arrays with respect to on-site initial data.

Figure 141: HT SOLAR-IV IV curve tracer [source: pv-engineering]

Irradiation sensor Si-13TC-x [S/N **14032936**, calibration date **08.2018**, tolerance **<3%**] is a reference cell for sun irradiation measurements that enables a precise analysis of PV module power or energy yields using measured values from the sensor. It has a double input for connection to mono or multi crystalline modules.

Figure 132: Duo reference cell [source: PI Berlin]

Infrared camera Testo T885 [S/N **02732076,** tolerance **<2°**] enables non-destructive diagnosis of some thermal and electrical failures in PV modules. It provides fast, real-time, two-dimensional infrared (IR) imaging, revealing characteristic features of PV systems. The measurements can be performed during normal operation for individual PV modules as well as large arrays.

Figure 133: Infrared camera [source: Testo]

By means of the **Sony ILCE-7S** camera with a CCD High pass edge filter, **electroluminescence** pictures are taken in the field to reveal failures such as microcracks, PID, failure of diodes or similar, as a complement to the STC-measurement and infrared inspection. EL imaging is particularly suitable for the detection and tracking of crack-related issues, which can occur for example during module transportation or installation.

Figure 134: SONY ILCE-7S with CCD high pass edge filter [source: PI Berlin]

Annex V – Normative References Used for the Study

IEC 61557-4:2007	**Electrical safety in low voltage distribution systems up to 1 000 V a.c. and 1 500 V d.c. – Equipment for testing, measuring or monitoring of protective measures Part 4: Resistance of earth connection and equipotential bonding**
IEC 60664-1:2007	Insulation coordination for equipment within low-voltage systems Part 1: Principles, requirements and tests
IEC 61215:2005	Crystalline silicon terrestrial photovoltaic (PV) modules - Design qualification and type approval
IEC 61730-1&2:2005	Photovoltaic (PV) module safety qualification
IEC 61829:2015	Photovoltaic (PV) array - On-site measurement of current-voltage characteristics
IEC 60364-4-41:2005	Low-voltage electrical installations - Part 4-41: Protection for safety - Protection against electric shock
IEC 60364-4-42:2010	Low-voltage electrical installations - Part 4-42: Protection for safety - Protection against thermal effects
IEC 60364-4-43:2008	Low-voltage electrical installations - Part 4-43: Protection for safety - Protection against overcurrent
IEC 60364-4-46:1981	Electrical installations of buildings. Part 4: Protection for safety. Chapter 46: Isolation and switching
IEC 60364-5-51:2005	Electrical installations of buildings - Part 5-51: Selection and erection of electrical equipment - Common rules
IEC 60364-5-52:2009	Low-voltage electrical installations - Part 5-52: Selection and erection of electrical equipment - Wiring systems
IEC 60364-5-54:2011	Low-voltage electrical installations - Part 5-54: Selection and erection of electrical equipment - Earthing arrangements and protective conductors
IEC 60364-6:2006	Low-voltage electrical installations - Part 6: Verification
IEC 60364-7-712:2011	Electrical installations of buildings - Part 7-712: Requirements for special installations or locations - Solar photovoltaic (PV) power supply systems
IEC 60529 1989+A1:1999+A2:2013	Degrees of protection provided by enclosures (IP Code)
IEC 60068-2-68:1997	Environmental testing - Part 2: Tests; test L: Dust and sand
IEC 60721 1-2:2013	Classification of environmental conditions
IEC 60721 3-4:1995	Classification of environmental conditions - Part 3: Classification of groups of environmental parameters and their severities - Section 4: Stationary use at non-weather protected locations (?)
IEC 61084-1:1991	Cable trunking and ducting systems for electrical installations
IEC 61238-1:2003	Foundation earth electrode - Planning, execution and documentation
IEC 62446:2009	Photovoltaic (PV) systems - Requirements for testing, documentation and maintenance
IEC 62548:2010	Photovoltaic (PV) arrays - Design requirements
UL 1703:2002	Standard for Flat-Plate Photovoltaic Modules and Panels
VDE-AR-E-2283-4:2010-10	Requirements for cables for PV systems
2 PfG 1169/08.2007*	Requirements for cables for use in photovoltaic-systems