



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

Part III: Evaluation of 10 Rooftop PV Plants in Pune

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List of abbreviations

AC	Alternating Current
BOS	Balance of System
CAPEX	Capital Expenditures
COD	Commercial Operation Date
DC	Direct Current
DIF	Diffuse Horizontal Irradiance [Wh/m ²]
EL	Electroluminescence
EOW	End of Warranty
EPC	Engineering Procurement and Construction
FAC	Final Acceptance Commissioning
GHI	Global horizontal irradiation [Wh/m ²]
Isc	Short-circuit current
IR	Infrared
IV	Irradiation / Voltage
KVA	Kilo-Volt-Ampere
LCOE	Levelized Cost of Energy
LID	Light Induced Degradation
LTA	Lender's Technical Advisor
LV	Low Voltage
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracker
OE	Owner's Engineer
OPEX	Operating Expense
O&M	Operations and Maintenance
PAC	Provisional Acceptance Commissioning
PCU	Power Central Unit
PID	Potential Induced Degradation
POA	Plane of the Array
PPA	Power Purchase Agreement
PR	Performance Ratio
PV	Photovoltaic
STC	Standard Test Conditions
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 preselected 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), 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 GSES¹, and thanks to the support of private developers, SECI² and the Distribution Companies, 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 combination of (i) limited O&M, (ii) near shadings, (iii) high module degradation rates and (iv) module product defects. Higher module degradation rates and limited O&M (heavy soiling) stand out in this group, followed by near shading and mechanical damage of the modules. According to the observations and measurements conducted by PI Berlin during the site assessments, the identified findings can contribute individually to losses at the system level between 2% and 20%. The absence of O&M contracts stating (a) clear procedures for preventive and corrective maintenance, (b) reaction times and (c) 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 5 concrete revamping and repowering measures that, depending on the state of each PV plant, may lead to a performance boost between 5% and 30%. Additionally, PI Berlin has identified 10 prevention mechanisms to ensure the revenue and reduce the exposure to adverse technical, management, or environmental risks. These technical and commercial de-risking measures for the next generation projects, are based on international standards, best practices and PI Berlin's criteria beyond the norms.

¹ Global Sustainable Energy Solutions India

² Solar Energy Council of India

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. With this in mind, India's cumulative solar rooftop photovoltaic installations reached ca. 4.4 GW at the end of 2019 [Mercom]. 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 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 third set of 10 rooftop PV plants, located in Pune, Maharashtra.

3. About PI Berlin

The Photovoltaik-Institut Berlin is a leading technical advisor, risk manager and quality assurance provider for PV power plants and equipment. With its experienced team of researchers, scientists and engineers, PI Berlin offers a wide range of design, testing and evaluation services with a focus on the risk management and quality assurance of PV equipment and complex PV power plants. PI Berlin has already supported 11 GW of PV power plants worldwide, with over 245 audits conducted on over 115 manufacturers producing more than 67 GW of PV equipment annually.

PI Berlin has an IEC 17025 accredited test laboratory at its Berlin location for evaluating the performance, reliability and durability of solar modules. Another test laboratory is located

in Suzhou, China. Modules are tested according to strict criteria that meet or exceed IEC standards.

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 available DISCOM's shall be selected
2. PV plants with different nominal capacities shall be selected (50 kW to 1000 kW)
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

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. Additionally, in preparation of the second visit, PI Berlin arranged a SOP³ to introduce the expected on-site activities in order to expedite the access. In parallel, GIZ approached 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 that have direct impact on the performance, such as (i) module cleaning, (ii) PV module degradation, (iii) shading situation and (iv) inverter unavailability or poor maintenance. Safety issues, without a direct impact on the performance, were also documented.

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

³ Standard Operating Procedure

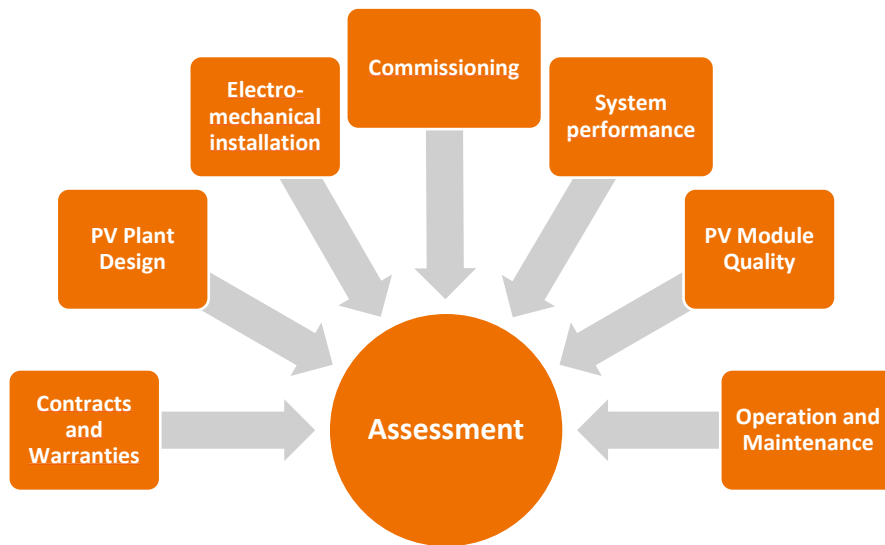


Figure 1: Scope of the evaluation

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 performance drop has been, as far as possible, coupled to an estimated energy loss and 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) simulations using PVsyst software. 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

Pune district is one of the most industrialized regions in India which is one of the reasons why it was a suitable candidate to continue with the study. The selected sites under the scope of the project 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 ⁴
III.1	119.68	1095 kWh/kWp
III.2	57.6	1403 kWh/kWp
III.3	51.2	1052 kWh/kWp
III.4	120	N/A kWh/kWp
III.5	110	996 kWh/kWp
III.6	50	N/A kWh/kWp
III.7	70.4	1251 kWh/kWp
III.8	120	1408 kWh/kWp
III.9	499.2	1292 kWh/kWp
III.10	268.8	928 kWh/kWp

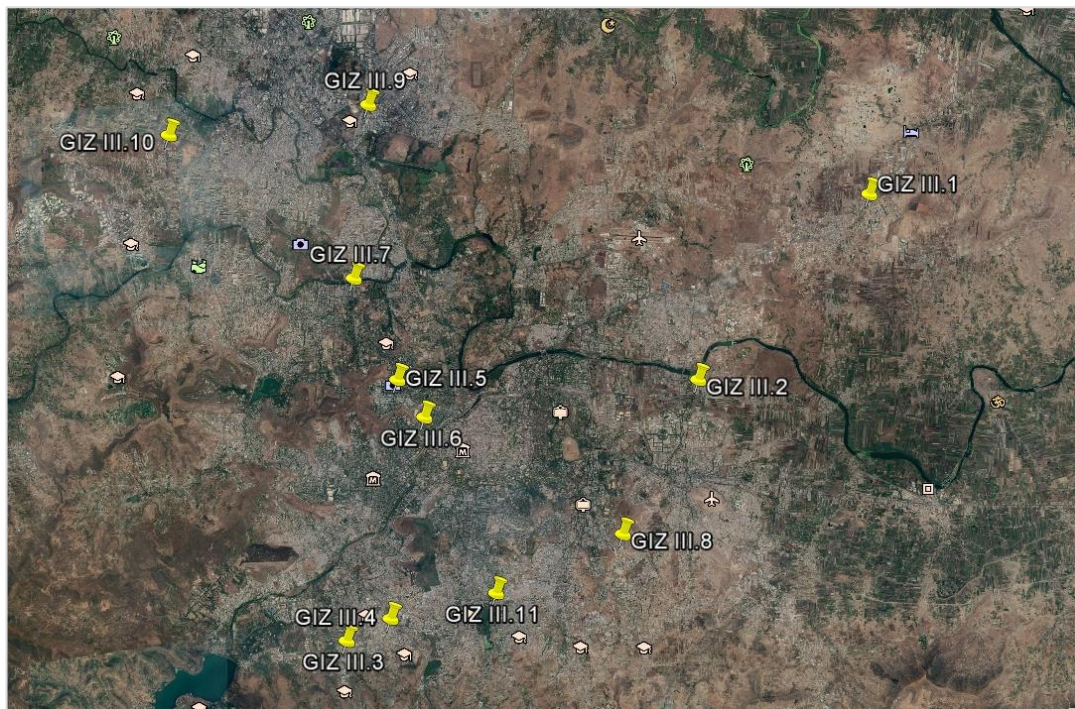


Figure 2: Sites within the Pune area

⁴ N/A - Information not provided by developer or customer.

Climate characteristics: Pune

The prevailing climate here is known as a local steppe climate. During the year, there is little rainfall and the temperature here averages 25.0 °C. The average annual rainfall is 763 mm and the driest month is January. There is nearly zero precipitation in January and most precipitation falls in July, with an average of 211 mm. With an average of 29.6 °C May is the warmest month and December the coldest with an average temperature of 21.1 °C [source: climate-data.org].

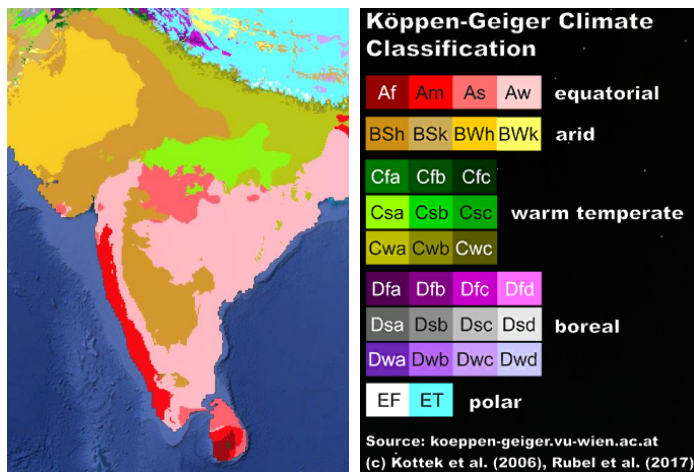


Figure 3: Köppen-Geiger climate classification map for India (1980-2016) [17]

The average Global Horizontal Irradiation (GHI) in the region is 1938 kWh/m² [source: SolarGIS].

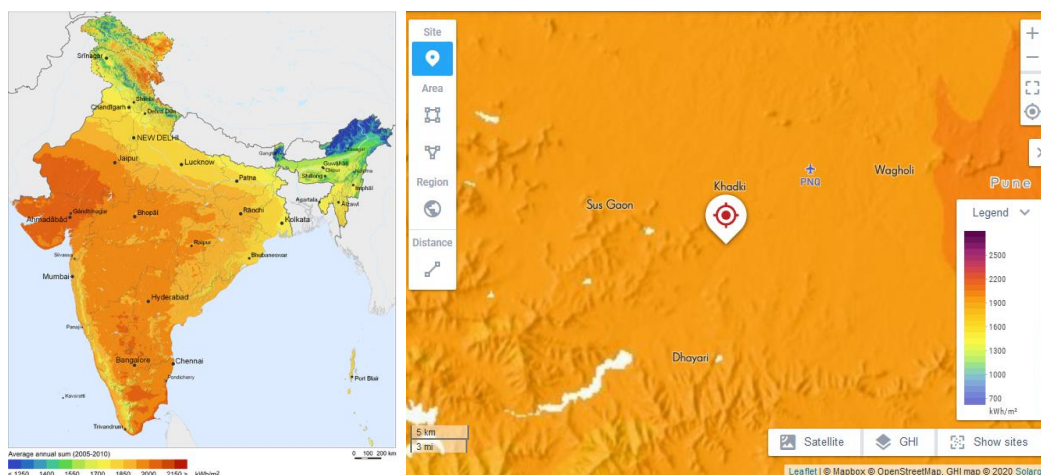


Figure 4: Global horizontal irradiation map of India [source: SolarGIS] (left); Global horizontal irradiation map of Pune, Maharashtra [source: SolarGIS]

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.

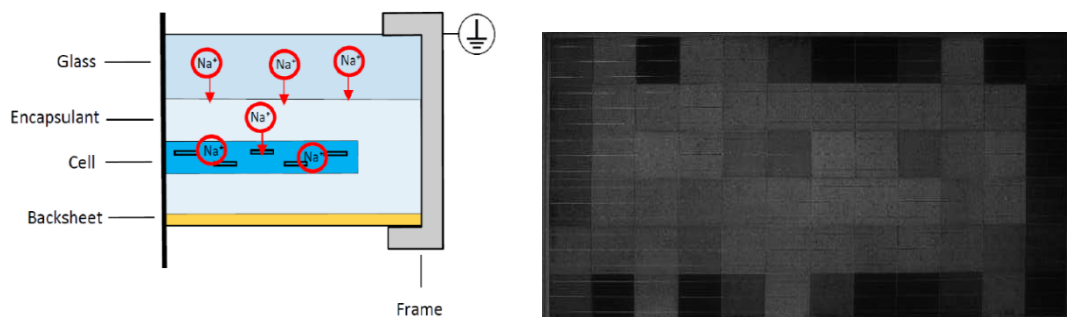


Figure 5: p-n junction damage (left) and typical PID pattern (right) [source: PI Berlin]

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 [1]. 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 [5], [14]. The snail trails appear typically as branched trails across the cells and are a clear sign of hidden cell damages [15], [18].



Figure 6: 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].

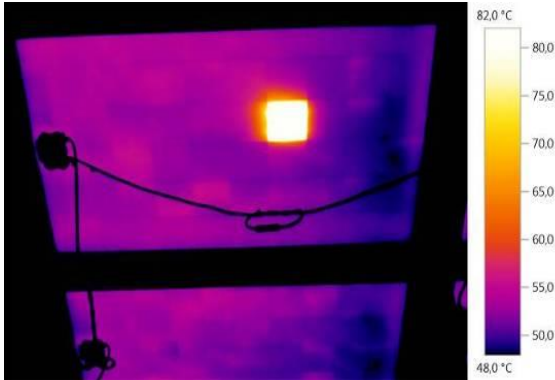


Figure 7: PV Module affected by a hot spot [source: PI Berlin]

6. 4. Inactive Cell Strings

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 [1].

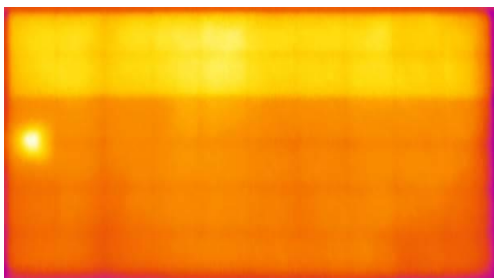


Figure 8: PV Module with an inactive cell string [source: PI Berlin]

6. 5. 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.

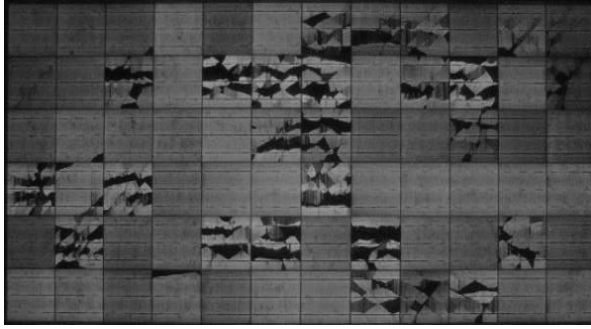


Figure 9: PV Module showing cracks and microcracks [source: PI Berlin]

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).

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: III.1

Nominal capacity: 120 kWp

Average specific yield since COD (January 2018): 1095 kWh/kWp

Abstract: The PV plant is affected by significant soiling due to city pollution and several warm cells likely due to near shadings. Additionally, isolation and safety issues cannot be excluded due to the presence of backsheet scratches and open J-boxes. It is recommended to (i) increase the cleaning frequency (i.e., modules disregarded), (ii) evaluation of the module J-box attachment, (iii) module string rearrangement based on the level of mechanical damage and (iv) weather station/irradiation sensor installation to better monitor the plant's KPIs. The estimated production boost expected by the retrofitting actions lies between 10% and 18%.

PV Plant's health



Main Findings

- During the module sample selection, the first modules selected exposed a detached J-box likely due to overtightened DC cables.
- The module installation on the East side of the system was performed gluing the clamps to the floor, hampering O&M.
- The spacing between modules and ground does not allow for an efficient convection.
- No weather station has been installed. Furthermore, the Performance Ratio is not tracked.

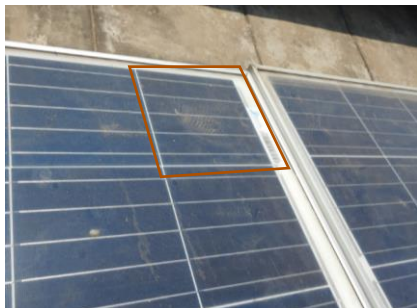


Figure 10: Shoe footprints

- Foot prints, likely from walking on top of the modules, were spotted throughout the plant.

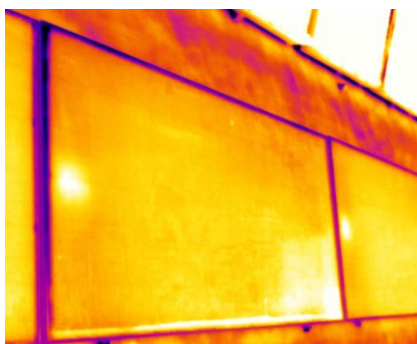


Figure 11: IR inspection of the soiling conditions

- Electroluminescence imaging revealed a considerable number of parallel and micro cracks.

Impact on Performance

- Based on on-site measurements, soiling losses represent on average of 7.5%.
- The losses due to near shadings could represent 6% less irradiance loss, based on a representative simulation.

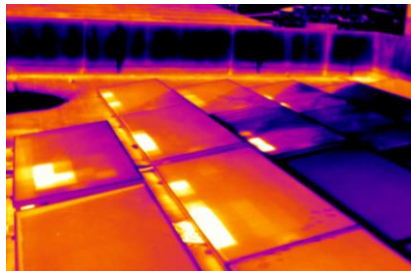


Figure 12: Soiling on the bottom cell string

- Although the soiling induces a shading in the bottom cell string, the landscape orientation reduces the impact of the current reduction.



Figure 13: Soft soiling on landscape modules

- 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.

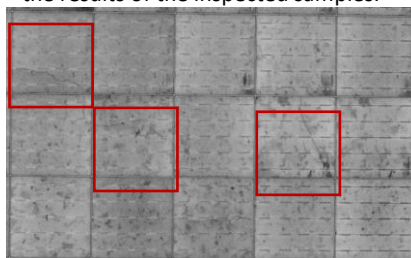


Figure 14: Example of module with cracks

Proposed Solutions

- In order to guarantee module long-term reliability and safety, the module J-boxes shall be assessed. Modules with open or detached J-boxes shall be replaced.
- Modules with a large amount of cracks shall be grouped in the same string or at least assigned to one MPPT. The grouping shall be conducted based on an infrared inspection with high irradiation levels and after cleaning activities.
- The manual cleaning cycles shall be implemented and scheduled based on the results of a soiling study that adjusts the cleaning needs to each season.



Figure 15: Better cleaning cycles required

- The integrity of the mounting structure shall be reinforced to allow a proper O&M.
- A weather station, or at least an irradiation sensor shall be installed on-site to obtain reliable information, i.e., for the PV plant Performance Ratio calculation.

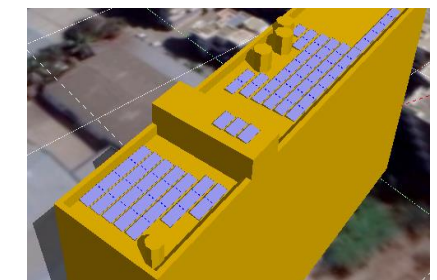


Figure 16: PVsyst 3D scene

Estimated energy boost after conducting the suggested retrofitting actions: 10% to 18%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 1.1 ₹/Wp, 0.4₹/Wp/a

Picture Gallery



Figure 17: Fixed tilt rooftop West building



Figure 18: General view of the system (East rooftop)



Figure 19: Detached J-box



Figure 20: Mounting arrangement



Figure 21: Preparation for soiling measurements



Figure 22: Evidence of crawling on the modules



Figure 23: Module disregarded from O&M scope



Figure 24: Module cable management

2

PV plant: III.2

Nominal capacity: 57.6 kWp

Average specific yield since COD (June 2018): 1403 kWh/kWp

Abstract: The PV plant considers most of the relevant international norms, standards and industry best practices regarding electromechanical installation. However, the PV system is affected by soiling from construction works and residues from the hard water used for cleaning the modules. Furthermore, the module power performance is significantly lower than the expected values. It is recommended to (i) increase cleaning cycles (filtered/soft water), (ii) reinstallation of the temperature sensor and (iii) module power measurements from a larger module sample (and comparison with manufacturer warranties). The estimated production boost expected by the retrofitting actions lies between 3-5%.

PV Plant's health



Main Findings

- The azimuth deviation from the optimum (South) represents a 2% loss.
- The high concentration of dust on top of the modules is likely originated in the construction site next to the system.
- Additionally, the water used for cleaning the modules leaves a gray residue that intensifies the soiling in the long term.
- On the module where the irradiation sensor is located, there is evidence that a cell temperature sensor was previously attached and the surface not cleaned.



Figure 25: Temperature sensor missing

- Although the infrared inspection did not reveal warm cables, the minimum bending radius was partially disregarded when the cables were forced to fit in the structure.



Figure 26: Bending radius partially respected

- Array V_{mpp} at 65°C might be lower than the inverter minimum operating voltage (summer), which leads to undervoltage losses.

Impact on Performance

- Soiling losses in the selected section at Florida State were calculated in 4.7% on average.
- The simulation did not reveal shading losses caused by the overhead cables.
- The lack of calibration of the irradiation sensor will not directly affect the performance of the system. However, the accurate recording of the onsite irradiation will provide confidence to the plant's KPIs.



Figure 27: Non-calibrated irradiation sensor

- A reduced sample of EL imaging did not reveal a significant amount of cracks or any other module failure types.

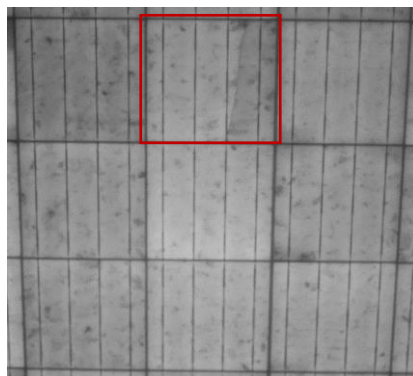


Figure 28: Sample from the EL imaging

- It is recommended to perform a yearly thermographic inspection to the modules at high irradiances to track the evolution of the cracks.

Proposed Solutions

- Manual cleaning shall be implemented and scheduled based on the results of a soiling study that adjusts the cleaning needs to each season.



Figure 29: IV Curve & soiling measurements

- IV curve measurements from a larger module sample should be performed to validate the current power performance of the modules against the manufacturer warranties.

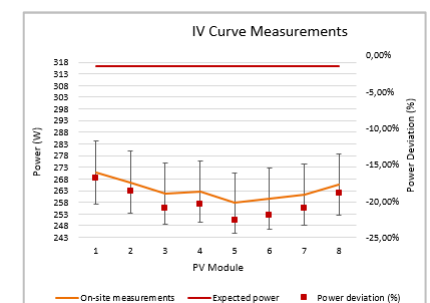


Figure 30: Onsite power measurements

- The average module under-performance is ca. 12% (accounting for a 4.7% soiling losses).



Figure 31: PVsyst 3D scene

Estimated energy boost after conducting the suggested retrofitting actions: 3% to 5%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 0.3 ₹/Wp, 0.5 ₹/Wp/a

Picture Gallery



Figure 32: View of the North section of the system



Figure 33: Infrared inspection of the modules



Figure 34: Preparation for soiling measurement

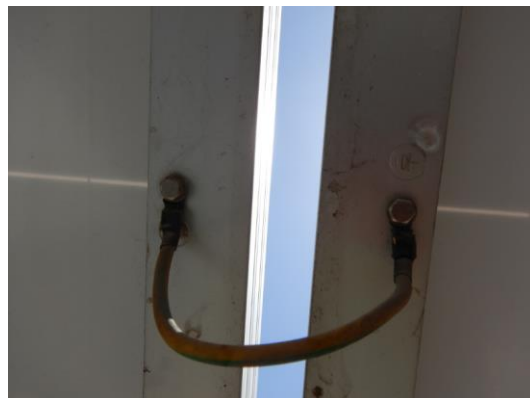


Figure 35: System equipotential bonding



Figure 36: Strings properly labeled



Figure 37: Inverter sealant glands and labeling



Figure 38: Protective tubes properly sealed



Figure 39: Cables casting shading on the modules

3

PV plant: III.3

Nominal capacity: 51.2 kWp

Average specific yield since COD (February 2018): 1052 kWh/kWp

Abstract: The PV plant shows inhomogeneous amount of soiling. There is evidence of both partially open and connectors with abnormal temperatures. Furthermore, the installed modules are hotspot sensitive. It is recommended to (i) increase the cleaning frequency with an appropriate cleaning method, (ii) install an irradiation sensor (iii) continuous cleaning of the inverter-fan filters, (iv) replacement of warm module connectors and (v) yearly thermography inspection of the modules. The estimated production boost expected by the retrofitting actions lies between 5 -10%.

PV Plant's health



Main Findings

- The thermography (IR) inspection revealed MC4 connectors with abnormal temperatures.

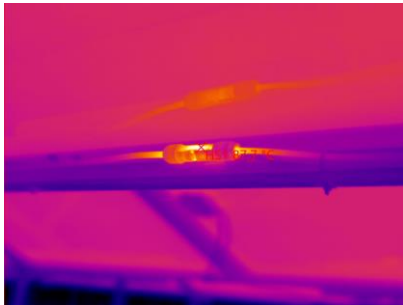


Figure 40: Warm MC4 connector

- The inverter fan filters (outlets) are partially blocked, leading to a higher risk of inverter shut down.
- Since there is no weather station installed on-site, the performance ratio is not monitored.
- A small amount of connectors were not tightly closed.
- Module cables are in contact with sharp edges and bolts from the mounting structure.
- Global irradiation on collector plane can be improved (1%), and near shading losses reduced (-1.6%), at the optimal angle of 10°. However, cleaning cycles might need to be improved.

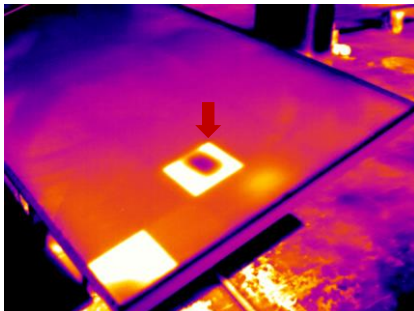


Figure 41: Modules are hotspot sensitive

- The modules are hotspot sensitive. This defect could compromise the long-term reliability of the modules.

Impact on Performance

- Based on the interrow spacing, the simulation estimates near shading losses of ca. 3% on system level.
- Electroluminescence imaging did not reveal significant or severe cracks in the selected module sample.

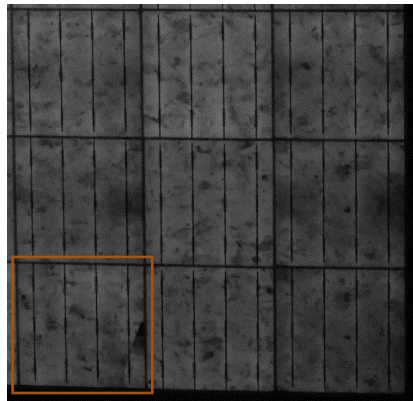


Figure 42: No significant cracks (EL imaging)

- Soiling measurements were conducted via short circuit current reduction and nominal power before and after cleaning. The estimated soiling loss averages 3%.
- The device used for cleaning the modules (mop), does not achieve a homogenous cleaning.

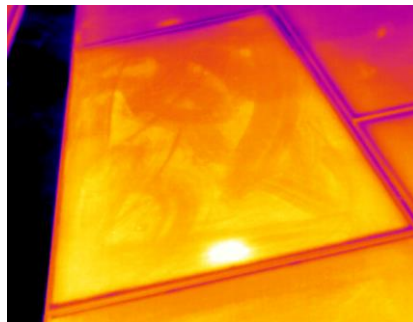


Figure 43: IR inspection of soiling conditions

Proposed Solutions

- A weather station, or at least an irradiation sensor on the module plane, shall be installed so that the performance of the system can be properly determined.
- Manual cleaning cycles shall be increased based on the results of a soiling study that adjusts the cleaning needs to each season.



Figure 44: Recalculation of cleaning cycles

- Thermography (IR) inspection shall be performed to find out the amount of connectors with abnormal temperatures, followed by their suitable replacement.
- Thermography (IR) inspection of the modules shall be performed annually to monitor the evolution of the warm cells and hotspots.
- The outlets of the inverter fan shall be continuously clean (part of the O&M) to avoid inverter overheating.

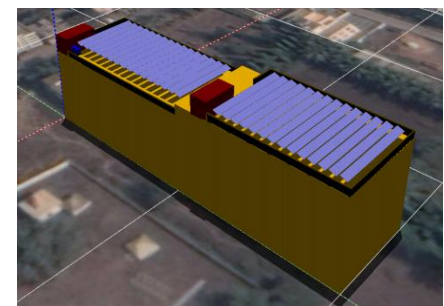


Figure 45: PVsyst 3D scene

Estimated energy boost after conducting the suggested retrofitting actions: 5% to 10%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 1.9 ₹/Wp, 0.5 ₹/Wp/a

Picture Gallery



Figure 46: General view of the system



Figure 47: Solar cable type used for string cabling



Figure 48: Module mounting structure and pitch



Figure 49: Water piping for cleaning activities

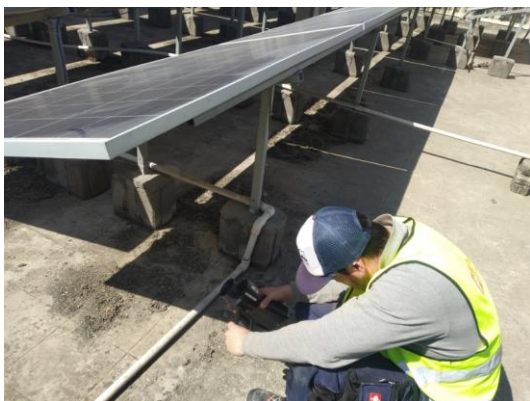


Figure 50: IR inspection of module J-boxes



Figure 51: Coating thickness measurement of galvanization



Figure 52: Inverter fan filters (outlet) partially blocked



Figure 53: On-site electroluminescence imaging

4

PV plant: III.4

Nominal capacity: 120.64 kWp

Average specific yield since COD (2017): N/A kWh/kWp

Abstract: The PV plant, from the safety perspective, presents a defective module attachment. Although a few hotspots, likely due to heavy pollution were spotted (IR), the sample of PV modules did not reveal major cracks or isolated parts. It is recommended to (i) increase cleaning frequency (removing hard-soiling), (ii) cable fixing with UV protection (iii) continuous cleaning of the inverter-fan filters and (iv) install a weather station or at least an irradiation sensor on the module plane to quantify and monitor the Performance Ratio. The estimated production boost expected by the retrofitting actions lies between 10% and 13%.

PV Plant's health



Main Findings

- No weather station has been installed and the Performance Ratio is not tracked.
- The filters of the inverters should be cleaned.
- Open fastening screws were observed on the fixing clamps.



Figure 54: Open fastening screws

- Missing cable ties, hence the module cables and connectors were loosely hanging.



Figure 55: Loose cables

- Some parts of the cables are exposed to UV radiation. Pipes conveying cables are brittle and some parts have already broken.
- Some of the module cables are fixed exceeding the minimum bending radius.

Impact on Performance

- Soiling measurements were conducted measuring both the short circuit current and nominal power before and after cleaning. The estimated soiling loss is on average 8%.
- The four random electroluminescence samples showed no mechanical damage or signs of aging of the modules.

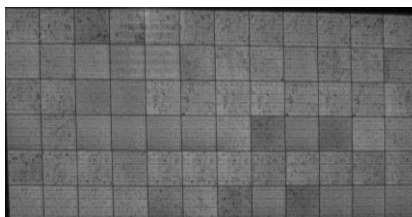


Figure 56: Electroluminescence samples

- Heavy partial pollution creates hotspots. These not only lower the yield but also make the modules age faster.

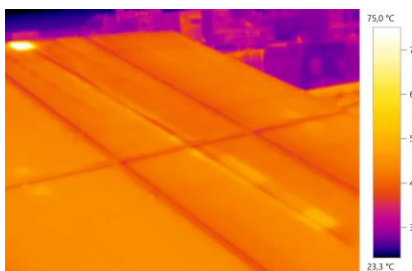


Figure 57: Hotspots created by pollution

Proposed Solutions

- A weather station, or at least an irradiation sensor on the module plane, shall be installed so that the performance of the system can be properly determined.
- Due to the high air pollution in Pune, it is advisable to clean the modules even more regularly.
- The loose hanging cables should be fixed and the bending radii checked.
- Fixing the fastening clamps is essential to ensure the safety of the system.
- The simulation of the system showed a shading loss of 2.7%.



Figure 58: 3D scene in PVsyst

Estimated energy boost after conducting the suggested retrofitting actions: 10% to 13%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 0.2 ₹/Wp, 0.2 ₹/Wp/a

Picture Gallery



Figure 59: Missing cable ties



Figure 60: Broken cable ducts



Figure 61: Inverter



Figure 62: Unsealed seals



Figure 63: General overview main building



Figure 64: General overview



Figure 65: Missing cable ties



Figure 66: Cables exposed to UV radiation

5

PV plant: III.5

Nominal capacity: 110 kWp

Average specific yield since COD (October 2017): 996 kWh/kWp

Abstract: The PV plant is affected by soiling due to city pollution and near shadings caused by surrounding structures. The infrared inspection revealed hotspots induced by different types of shadings. Electroluminescence imaging did not reveal important cracks but exposed a few backsheet scratches. It is recommended to (i) adjust the DC/AC ratio, (ii) shading objects and module relocation and (iii) further monitoring of the module failure types (hotspots, label detachment, browning). The estimated production boost caused by the retrofitting actions lies between 10% and 12%.

PV Plant's health



Main Findings

- Although the cleaning activities were performed the day before the inspection, a few modules were discovered to still have significant amounts of dust.
- Near shadings effects are caused by shading structures, overhead cables and cooling equipment were visible.



Figure 67: Near shadings disregarded

- In the DC distribution box II, some cable terminals of the negative pole are burned, likely due to a faulty contact.
- Inverter 3 is slightly oversized, leading to overload losses of approximately 3%.
- The limited access to the southeast section of the plant is likely the reason why there are footprints on the first module of the table. This will likely induce cell damages and hotspots.

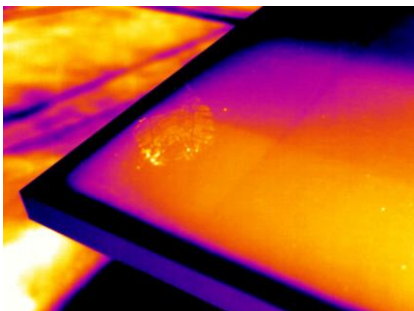


Figure 68: IR inspection of shoe footprints

- Through visual inspection, browning on the module, backsheet degradation and advance corrosion in the grounding cables (distribution box), among other failure types were exposed.

Impact on Performance

- Electroluminescence imaging did not reveal a significant amount of cracks. However, module backsheet scratches could lead to safety hazards and increased risk of inverter disconnection due to loss of insulation.
- A soiling loss of 5.9% was determined from IV curve measurements of a sample module before and after cleaning.
- The near shadings are responsible for an irradiation reduction on the tilted plane of approx. 1.5% at the system level.



Figure 69: Hotspots likely induced by shading

- Advanced corrosion in the grounding cables might reduce the effectiveness of the insulation.

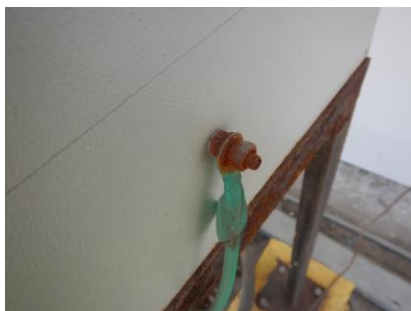


Figure 70: Advance corrosion in grounding cables

Proposed Solutions

- The module most affected by the shades from the shading structure can be easily relocate. This will reduce the impact of the shadings on the whole string. Furthermore, after the relocation, modules with hotspots (>100°C) shall be monitored to assess the damage and their possible replacement.
- Grounding cabling shall be replaced to guarantee a proper grounding throughout the system.
- 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 might not suffice.



Figure 71: Soiling measurements

- A weather station, or at least an irradiation sensor shall be installed on-site to obtain reliable information, i.e., for the plant performance ratio calculation.

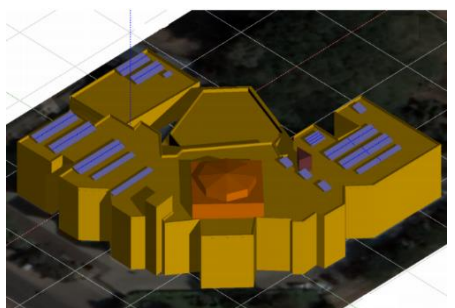


Figure 72: 3D model of the system

Estimated energy boost after conducting the suggested retrofitting actions: 10% to 12%

Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 1.5 ₹/Wp, 0.1 ₹/Wp/a

Picture Gallery



Figure 73: General view of the system



Figure 74: Modules with label detachment issues



Figure 75: Mounting structure



Figure 76: Browning effect on RFID tag



Figure 77: BS degradation due to hotspot



Figure 78: Combiner box with open glands

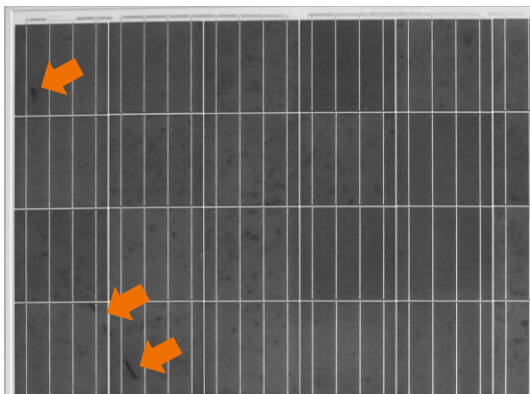


Figure 79: Scratch in backsheet (EL imaging)

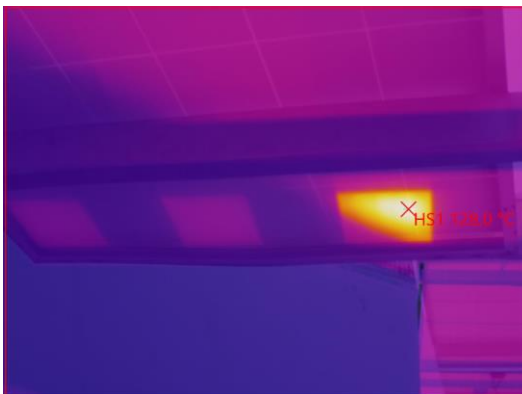


Figure 80: Hotspots likely induced by shading

6

PV plant: III.6

Nominal capacity: 300 kWp

Average specific yield since COD (2017): N/A kWh/kWp

Abstract: The PV plant is likely affected by an early stage of PID. Electroluminescence imaging did not reveal significant mechanical damages. Hotspots induced by heavy soiling were discovered through IR inspection. Regarding safety requirements, the mounting structure hangs beyond the roof edge (it shall consider DIN 1055). It is recommended to (i) clean all the modules including those with difficult access, (ii) validation that all strings and module connectors are closed (iii) implement anti-PID measures. The estimated production boost expected by the retrofitting actions lies between 10% and 15%.

PV Plant's health



Main Findings

- No weather station has been installed and the Performance Ratio is not tracked.
- The PV system is built with an overhang of up to 2 meters over the roof edge. Static safety is therefore not guaranteed.



Figure 81: Overhanging modules

- The module fasteners cannot be opened, which makes maintenance impossible.
- Open module plugs lead to not producing strings. This could be measured on the inverter.



Figure 82: Open connectors

- Some parts of the cables are exposed to UV radiation. Pipes conveying cables are brittle and some parts have already broken.
- Several shading problems were found caused by roof structures.

Impact on Performance

- Soiling measurements were conducted before and after cleaning. The estimated soiling loss is on average 3.5%. However, the measured modules were much cleaner than modules that are more difficult to access.
- Heavy partial pollution creates hotspots. These not only lower the yield but also make the modules age faster.

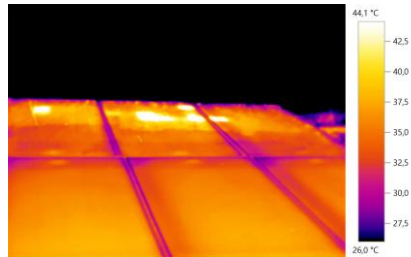


Figure 83: Hotspots created by pollution

- Since the modules cannot be removed, only one electroluminescence sample could be taken. This showed no mechanical damage.

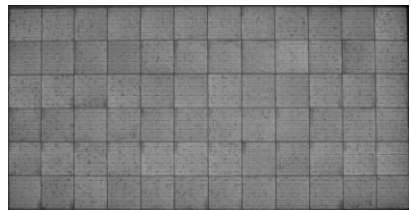


Figure 84: Electroluminescence samples

- To the negative side of the string, the modules may show first signs of PID.

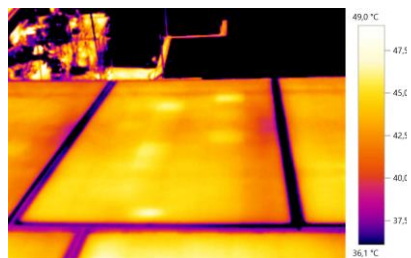


Figure 85: First signs of PID

Proposed Solutions

- The design should be checked for static stability.
- A weather station, or at least an irradiation sensor on the module plane, shall be installed so that the performance of the system can be properly determined.
- All strings should be checked for closed module plugs since the measured power loss in the examined subsystem was 37%.
- The modules should be cleaned regularly.
- The loose hanging cables should be fixed and the bending radii checked.
- An anti-PID measure, such as anti-PID box, shall be implemented in order to stop or reverse the degradation.

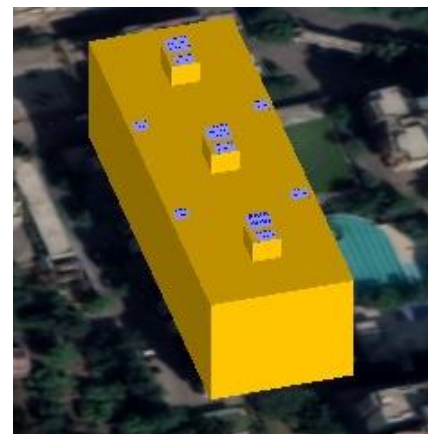


Figure 86: 3D Scene in PVsyst

Estimated energy boost after conducting the suggested retrofitting actions: 10% to 15%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 0.14 ₹/Wp, 0.1 ₹/Wp/a

Picture Gallery



Figure 87: Partial pollution



Figure 88: General overview



Figure 89: Dirty modules in hard-to-reach areas



Figure 90: Loose cable

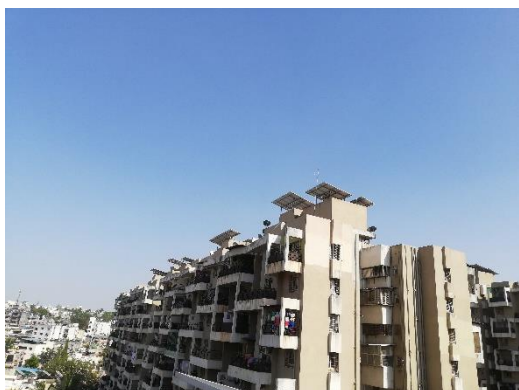


Figure 91: General overview



Figure 92: Dirty modules in hard-to-reach areas

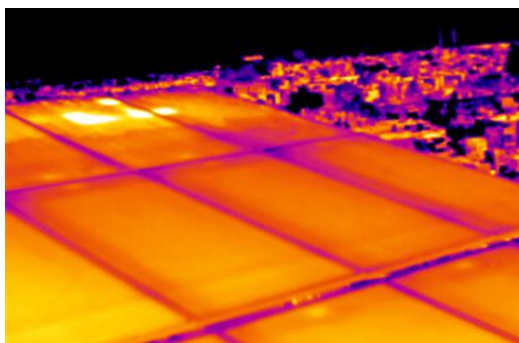


Figure 93: Hotspots created by pollution



Figure 94: Fuse box not properly fixed

7

PV plant: III.7

Nominal capacity: **20.2 kWp (70.4 kWp)**

Average specific yield since COD (December 2017): **1251 kWh/kWp**

Abstract: The PV plant shows significant levels of soiling caused by city pollution, modules with an important amount of warm cells and a variety of crack types. Furthermore, the modules showed substantial underperformance and affection by product defects. It is recommended to (i) increase cleaning cycles, (ii) conduct a string reengineering with individual MPPT assignments, based on IR inspection, (iii) replacement of modules exceeding the manufacturer's guaranteed performance drop and (iv) replacement of modules with defective J-boxes. The estimated production boost caused by the retrofiting actions lies between 15% and 30%.

PV Plant's health



Main Findings

- Electroluminescence analysis revealed a variety of module failure types, both from manufacturing defects, as well as from handling and installation practices.
- The last modules at the West and East sides of the tables are affected by shadings from the position of the wall and from antennas.

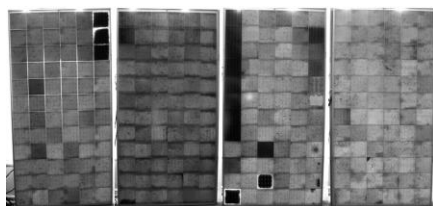


Figure 95: Sample from EL failure modes

- An important amount of warm cells were spotted via thermographic inspection.

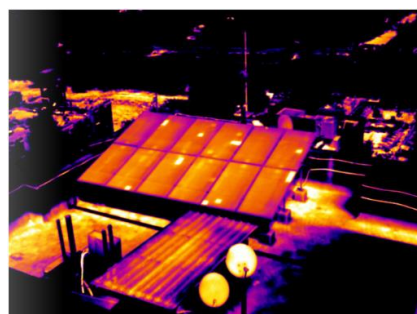


Figure 96: Modules with warm cells (full cells)

- The modules present different types of J-box failure types, e.g., overheated, open or missing lid.
- String cables damaged by, or in contact with sharp edges were spotted.
- From the module samples, the on-site IV curve measurements indicated that the power performance lies 25% and 19%, beneath the minimum expected value (according to label values and natural degradations), for full cell and HC cell, respectively.

Impact on Performance

- Soiling losses were determined based on the measurements on-site to be 4.2%, on average.
- The new modules installed early this year (Half-cut cells) showed a significantly lower performance via on-site IV curve measurements.

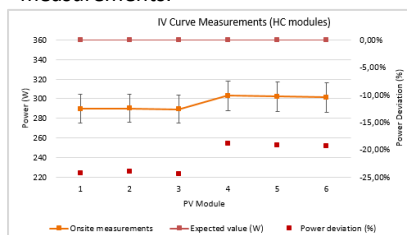


Figure 97: Onsite power measurements (HC cell)

- Although half-cut cell modules have been recently installed, the cells already have an abnormal thermal behavior.

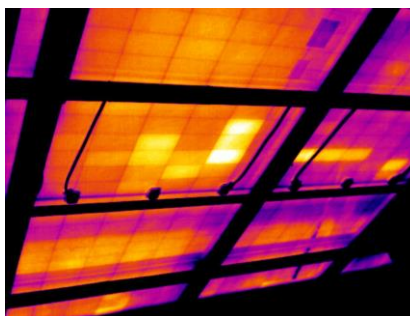


Figure 98: Modules with HC warm cells

- The amount and type of cracks found during electroluminescence inspection is likely to induce a drop of the nominal power of around 8-10%.

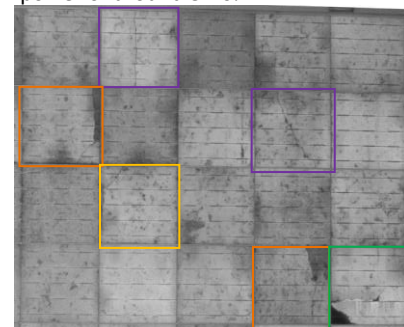


Figure 99: Variety of cracks discovered via EL

Proposed Solutions

- A weather station, or at least an irradiation sensor shall be installed on-site to obtain reliable information, i.e., for the plant performance ratio calculation.
- Modules with multiple cracks shall be regrouped in the same string, or at least assigned to one MPPT. The grouping shall be conducted based on infrared inspection with high irradiation levels and after cleaning activities.
- 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.
- 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.

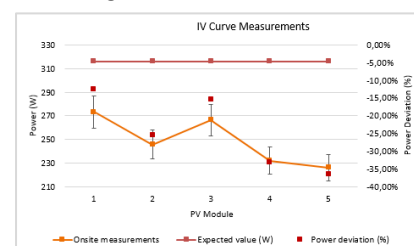


Figure 100: Onsite power measurements (full cell)

- Modules with any defect on the J-box shall be immediate replaced (safety, operation and reliability issues).



Figure 101: 3D model constructed in PVsyst

Estimated energy boost after conducting the suggested retrofiting actions: 15% to 30%

Estimated costs of proposed retrofiting actions (CAPEX, OPEX): 2.9 ₹/Wp, 0.4 ₹/Wp/a

Picture Gallery



Figure 102: General view of the system (full cells)



Figure 103: HC Modules system recently added



Figure 104: Module with open Jbox lid (VI)

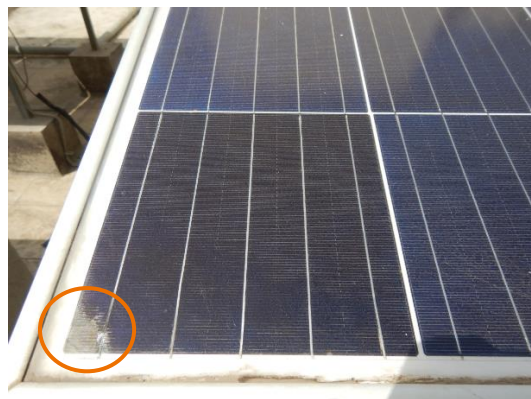


Figure 105: Module corrosion/delamination



Figure 106: Overheated J-box (likely blown diode)



Figure 107: Open and loose J-boxes



Figure 108: Blocked drainage



Figure 109: String cables in contact with sharp edges

8

PV plant: **III.8**

Nominal capacity: **120 kWp**

Average specific yield since COD (January 2018): **1048 kWh/kWp**

Abstract: The PV plant was installed in an unstable mounting structure. From the safety perspective, the mounting structure should be reinforced. The module sample displayed a few microcracks through electroluminescence. Hotspots, likely induced by heavy soiling, were discovered through thermographic inspection. It is recommended to (i) improve cleaning cycles, for every module in the system (ii) IR inspection of cables and connectors for hotspots and (iii) install a weather station or at least an irradiation sensor on the module plane. The estimated production boost expected by the retrofitting actions lies between 15% and 20%.

PV Plant's health



Main Findings

- No weather station has been installed and the Performance Ratio is not tracked.
- The mounting structure is made up of many small beams. This endangers the stability of the system.



Figure 110: Unstable mounting structure

- The filters of the inverter have been found dirty.
- Some modules are affected by local shading. These cause hotspots and burned cells.



Figure 111: Partial shading

- Some parts of the cables are exposed to UV radiation and the bending radii have not been observed.
- Several shading problems were found caused by roof structures.
- Some of the strings measured had lower outputs.

Impact on Performance

- Soiling measurements were conducted before and after cleaning. The estimated soiling loss is on average 14.1%. Two levels of pollution were measured. The highest losses were 26.1%.
- Heavy partial pollution creates hotspots. Some modules were extremely dirty.

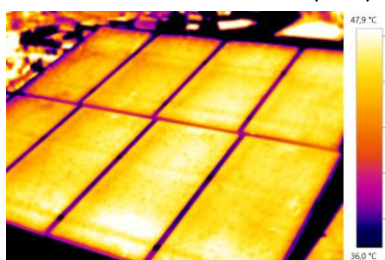


Figure 112: Hotspots created by pollution

- According to the amount of cracks discovered via EL imaging, the system is not expected to have a large power losses due to inactive areas.

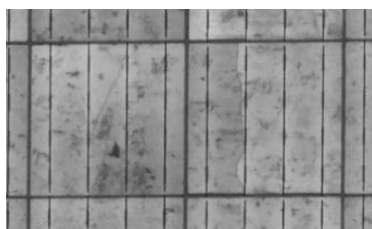


Figure 113: Electroluminescence sample

- Several hot cables were found on the distribution boxes and inverters.



Figure 114: Overheated connector

Proposed Solutions

- The individual beams of the mounting structure should be reinforced.
- A weather station, or at least an irradiation sensor on the module plane, shall be installed so that the performance of the system can be properly determined.
- The cables and plugs should be checked for temperature and functionality.
- The modules should be cleaned regularly.
- The loose hanging cables should be fixed and the bending radii checked.
- The causes of the local shadings should be removed.
- The filters of the inverter should be cleaned.



Figure 115: 3D scene in PVsyst

Estimated energy boost after conducting the suggested retrofitting actions: 15% to 20%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 0.8 ₹/Wp, 0.2 ₹/Wp/a

Picture Gallery



Figure 116: Heavily soiled modules



Figure 117: Heavily soiled modules

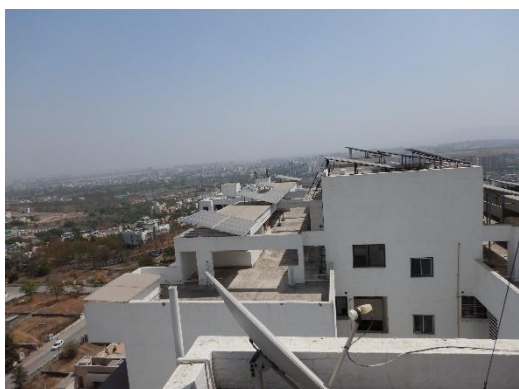


Figure 118: General overview



Figure 119: Bending radius too small



Figure 120: Inverter and Combiner Box



Figure 121: Burnt cells due to hot spot

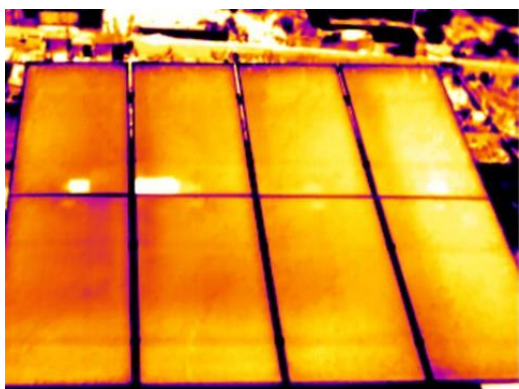


Figure 122: Hotspots created by pollution



Figure 123: Improperly routed cables

9

PV plant: III.9

Nominal capacity: **225 kWp (499.2 kWp)**

Average specific yield since COD (April 2018): **1292 kWh/kWp**

Abstract: The PV plant is affected by moderate soiling due to city pollution, near and microshading. Infrared inspection revealed warm cables, different electrical and temperature anomalies within the modules. Electroluminescence imaging exposed different module mechanical damages. It is recommended to (i) improve cleaning activities, (ii) replace modules exceeding the manufacturer's guaranteed performance drop, (iii) conduct a string reengineering with individual MPPT assignments, based on EL imaging or IR inspection and (iv) replace modules with inactive cell strings. The estimated production boost caused by the retrofitting actions lies between 15% and 20%.

PV Plant's health



Main Findings

- The remaining pillar beams (from the building) induce microshading on several modules.

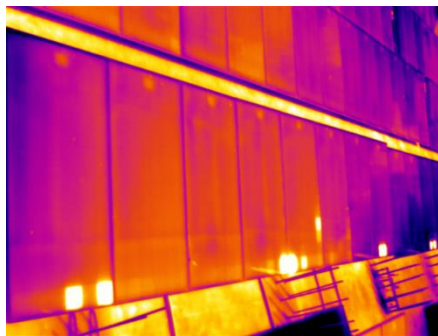


Figure 124: Microshading from pillar beams

- The mounting system includes *power snap fastening & grounding clips*. Although the installation time is reduced, O&M activities are limited since individual modules, from inside of the table, cannot be removed.
- Through IR inspection, a handful of modules with inactive cell strings were spotted.
- Moving between module rows is usually done by crossing over the tables, i.e., walking on the modules. Thus, mechanical stress is inevitable (cracks and broken cells). The cracks could also have been initiated during handling and installation.
- Cabling installation failures at string level, such as hot cables at the inverter inputs, inaccurate soldering or loose connectors, were detected.

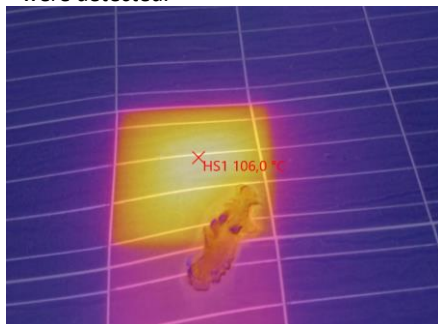


Figure 125: Hotspot induced by foreign objects

Impact on Performance

- Soiling measurements were conducted via short circuit current reduction and nominal power, before and after cleaning, with irradiances higher than 1000 W/m². The estimated soiling factor is in the range of 4-6.2%.
- Due to near objects and microshading, the simulation estimates near shading losses of ca. 4.3% on system level.

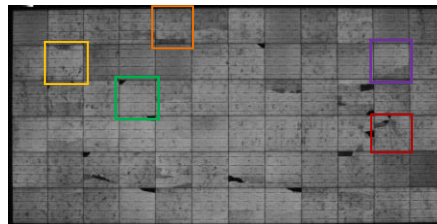


Figure 126: Mechanical damage on modules

- Based on the crack distribution and type found during the electroluminescence inspection, the module nominal power could be reduced by 4-8%. Furthermore, these types of cracks could eventually lead to inactive areas and higher power loss in the midterm.
- Modules with inactive cell strings could 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 string level.

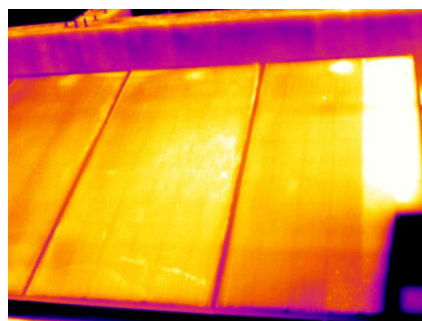


Figure 127: Module with inactive cell strings

Proposed Solutions

- The remaining pillar beams shall be cut or bent to avoid microshading.
- A weather station, or at least an irradiation sensor on the module plane (GTI), shall be installed so that the performance ratio of the system can be properly calculated.
- Manual cleaning shall be implemented and scheduled based on the results of a soiling study that adjusts the cleaning needs to each season.
- Modules with similar amount of cracks shall be re-grouped in the same string or at least assigned to one MPPT. The grouping will be conducted, ideally based on EL imaging, otherwise through IR inspection with high irradiation levels and after cleaning activities.

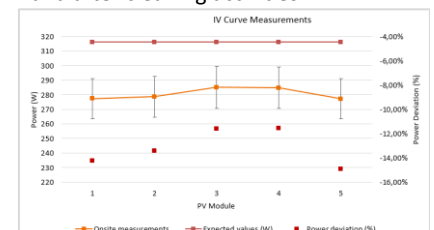


Figure 128: Onsite power measurements

- Modules underperforming above the warranty conditions shall be replaced. If the replacement is not possible, the modules shall be re-grouped in power classes within the same string and assigned to individual MPPT in combination with the amount and type of cracks.

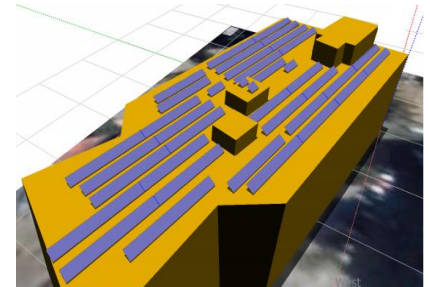


Figure 129: 3D model constructed in PVsyst

Estimated energy boost after conducting the suggested retrofitting actions: 15% to 20%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 0.9 ₹/Wp, 0.2 ₹/Wp/a

Picture Gallery



Figure 130: General view of the system (East building)



Figure 131: Personnel walking on the modules



Figure 132: General view of the system (West building)



Figure 133: Clamps (easy to install/difficult to replace)

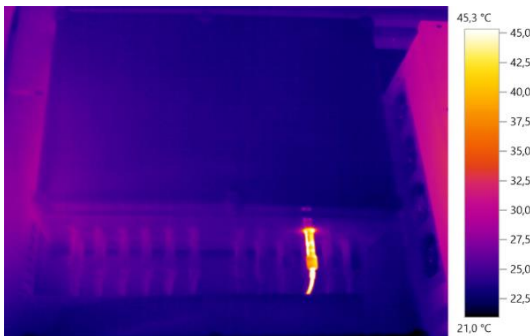


Figure 134: Warm string cable in the inverter input



Figure 135: Module comparison from cleaning activities



Figure 136: Lightning arrester



Figure 137: Warm string cables in the combiner box

10

PV plant: III.10

Nominal capacity: 260.8 kWp (318.7 kWp)

Average specific yield since COD (March 2019): 928 kWh/kWp

Abstract: The PV plant is heavily affected by soiling. Furthermore, near and microshading, are likely responsible for hotspots discovered via thermographic inspection. A considerable amount of microcracks and isolated parts were discovered through the electroluminescence sample. PID was found to be in a fairly advanced stage and some of the modules are extremely dirty. It is recommended to (i) Improve O&M activities (ii) implement anti-PID solutions (iii) install a irradiation sensor and (iv) restringing of the modules from the shaded areas. The estimated production boost expected by the retrofitting actions lies between 15% and 24%.

PV Plant's health



Main Findings

- No weather station has been installed and the Performance Ratio is not tracked.
- The system is heavily affected by shading from the building structure and surrounding components.



Figure 138: Shading on module

- The complicated clamping system makes maintenance of the modules almost impossible.
- The back sheet shows signs of aging in the form of cracks.



Figure 139: Cracks in the back sheet

- Some parts of the cables are exposed to UV radiation and the bending radii have not been observed.
- Some of the strings measured had lower outputs caused by shading.
- Some areas of the plant were extremely dirty.
- Several hot cables were found on the distribution boxes and inverters.

Impact on Performance

- Soiling measurements were conducted before and after cleaning. The estimated soiling loss is on average 10.6%. The measurements were carried out on the less polluted modules. Higher losses are to be expected in other areas of the plant.
- Heavy partial pollution creates hotspots. Some modules were extremely dirty.

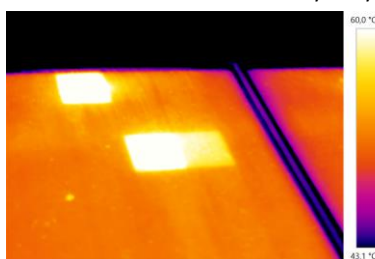


Figure 140: Hotspots induced by pollution

- PID presence was detected via IR and EL inspection. The impact at the system level is estimated to be around 10%.

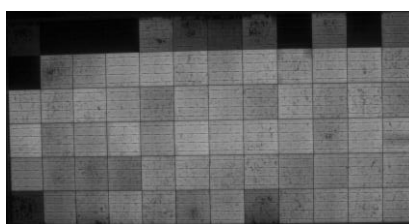


Figure 141: PID presence via EL

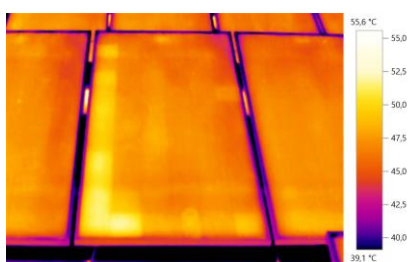


Figure 142: PID presence IR

Proposed Solutions

- A restringing of the modules from the shaded areas should be conducted in the following way: modules with similar shading conditions should be installed in the same string or at least assigned to individual MPPTs.
- A weather station, or at least an irradiation sensor on the module plane, shall be installed so that the performance of the system can be properly determined.
- Anti-PID measures should be implemented in order to stop or reverse the 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 MPPTs.
- The modules should be cleaned regularly.
- The broken modules should be replaced with new modules.
- The simulation of the system showed a shading loss of 3.5%. This value refers to the part of the system with fewer shading problems.

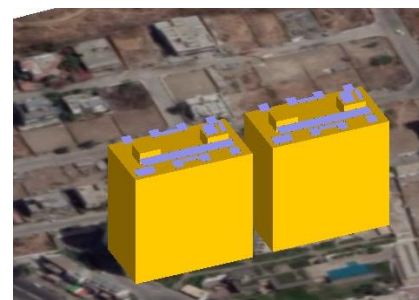


Figure 143: 3D scene in PVsyst

Estimated energy boost after conducting the suggested retrofitting actions: 15% to 24%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 1.3 ₹/Wp, 0.4 ₹/Wp/a

Picture Gallery



Figure 144: Hot connectors

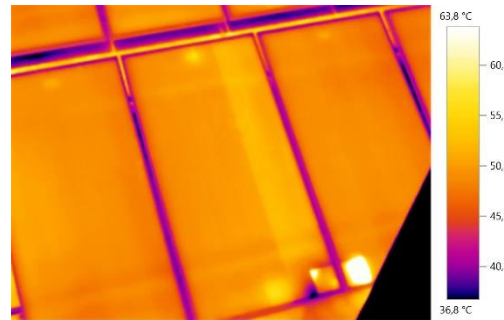


Figure 145: Module effected by shading (diode)



Figure 146: Shading



Figure 147: Dirty modules



Figure 148: Unfavorable clamping system



Figure 149: General view

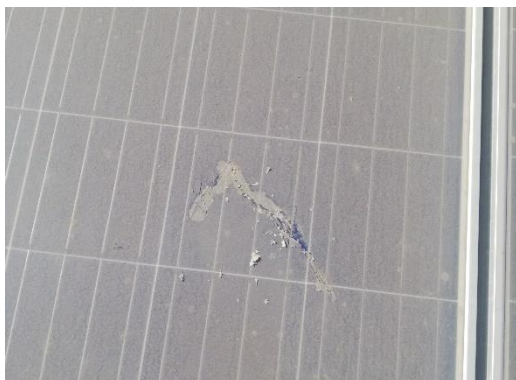


Figure 150: Layer of accumulated dust



Figure 151: Shading on module

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 findings detected on-site having a negative impact on the performance of the analyzed PV plants. The number attached to each bar shows in how many PV plants each finding was present.

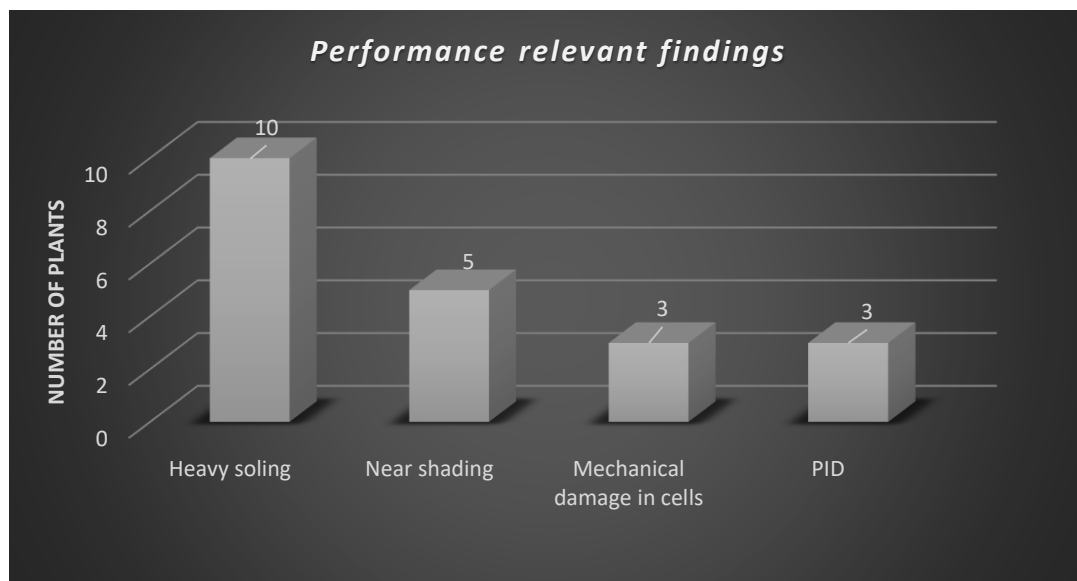


Figure 152: Summary of PV plant and findings (sample: 10 plants)

It can be seen how, once again, heavy soiling and near shading appear in nearly every PV plant. The Potential Induced Degradation (PID) is a finding associated to unexpected module degradation mechanisms caused by a combination of (i) negative potential, (ii) high temperatures and (iii) high humidity rates. PID is a defect that can be prevented taking the appropriate measures during the design phase. Furthermore, mechanical damages in cells, which is related to the electromechanical integrity of the modules, is a fault also discovered on a large number of sites. The source of this failure mode is likely improper module handling and installation during the installation and operation phase⁵.



The low performance of the inspected PV plants is caused by a combination of (i) heavy soiling, (ii) near shading and (iii) high module degradation rates (cracks and underperformance)

⁵ Walking on the modules largely contributes to the appearance of cell damages

Another aspect that also contributes to the loss of energy production is an operation and maintenance plan below market standards. Specifically, the lack of adequate cleaning activities and spare parts on site (coupled with high reaction times), are two aspects that directly result in loss of performance and availability, and therefore, underperformance. None of the PV plants had a proper weather station and 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, the Performance Ratio monitoring and the contractual availability values, is a key factor that contributes decisively to lowering the PV plant's output.

In regard to underperforming systems, modules with power performance considerably below the expected values⁶ were discovered in a significant number of PV plants. This issue shall be further addressed and, when applicable, clarified with the installer or the module manufacturing, according to the specific installation contract. The following graph shows highest impacts on the performance from the aforementioned findings of the inspected PV plants. The graph also indicates the maximum energy loss values associated to each of these findings.⁷

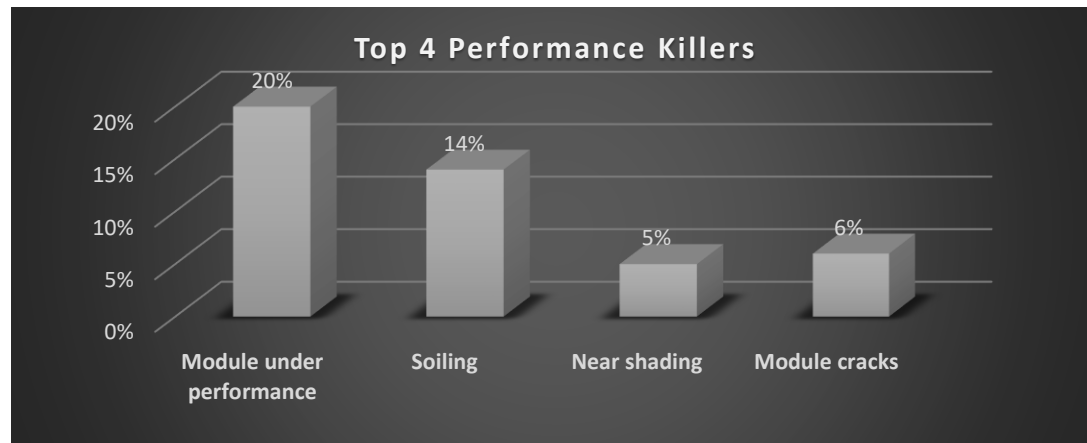


Figure 153: Top 4 findings with the highest performance impact on the inspected PV plants

As shown in the graph, underperforming modules (with potentially advanced stage of Potential Induced Degradation) could lead to a yield loss of 20% at the PV plant level. In some of the examined plants, this degradation value has been reached in two years. This rapid degradation could be explained by the high PID sensitivity of the PV cells in the installed modules, in combination with the typical hot and humidity conditions. The presence of bird droppings, debris or pollution, results in soiling losses close to 26% for some of the systems.

⁶ The power is corrected taking into account the light induced degradation and yearly natural degradation, according to the years in operation, from flash-lists (when available) or label values.

⁷ These values have been calculated by PI Berlin through (i) estimates based on PI Berlin's long-term experience, (ii) 3D simulation, (iii) processing of data obtained directly on site by means of special equipment.

In this regard, it is important to bear in mind that some PV plants visited by PI Berlin underwent cleaning activities a few days before the inspection. Hence, the values measured on-site by PI Berlin can therefore be greatly exceeded if cleaning activities are disregarded, particularly during the dry season.

According to PI Berlin calculations, the global losses at the PV plant level caused by underperforming modules (likely PID effect) could exceed 20%, while the losses associated with soiling can widely reach 25% in the dry season.

The losses caused by near shading are estimated in some of the inspected PV plants at around 6%. Although only a small amount of plants were affected, these losses are difficult to avoid since they are a consequence of near buildings and vegetation. This matter shall be properly addressed during the design phase, since after the installation, only mitigation actions can be implemented. Furthermore, shading losses caused by trees can only be reduced in case the trimming is allowed by the authorities. Finally, the losses associated with mechanical damage of cells can reduce the production of some PV plants by around 8% according to PI Berlin's estimations.

In some of the inspected PV plants, the losses caused by near shadings could exceed 6%, 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 also by up to 6%.

Worldwide, PV manufacturers have developed advanced production and inspection techniques to ensure that the "dispatched modules" have a limited amount of product failures, such as microcracks. Moreover, PI Berlin' long-term experience in the matter indicates that most of the *mechanical stress induced cracks* occur during handling and module installation, as well as during O&M activities. However, the assessment of cracks in operating PV modules is not an easy task since the crack distribution will not certainly lead to a homogenous power degradation. Additionally, since the warranties⁸ offered by the installation company are limited to the product and do not include workmanship, the module damages from mishandling during the installation remain contractually uncovered.

⁸ In some cases, the EPC warranty has also expired without a Final Acceptance Test or proper commissioning.

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

It would be fair to mention that the quality of the Pune sites, in general, was slightly better than the previous plants evaluated within this project. Nevertheless, the former plants also exposed some of the most common failure modes, not only in the Indian market, but worldwide. 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:

- i Improvement of module cleaning frequency.** The source of soiling in most of the inspected PV plants is either bird droppings, city pollution, debris or a combination of all three. In order to figure out what the optimum cleaning interval is, the output of clean⁹ 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.
- i 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 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 shall 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.
- i 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 will 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.

⁹ The clean strings are used as a benchmark and will be cleaned every day.

-
- i 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.

 - i Increase of the albedo factor.** A possible alternative to extra-boosting the yield is to paint the surface with light colors, cover the ground with white gravel and/or 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 plane of array. Glaring of neighboring 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 30%.
These actions do not require large investments in the OPEX.

Besides the retrofitting actions suggested to increase the energy generation, any necessary improvements to operate the PV plants in a safe environment shall also be carried out.

-
- ! These safety improvements shall be conducted regardless how high the estimated performance boost is¹⁰.**
-

¹⁰ An example of this is the installation of a safety lifeline (when applicable) or the replacement of damaged cables and modules (from broken J-box or glass).

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 partially solved 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. An energy yield assessment shall be conducted during the development phase. That said, it shall consider all shading objects that might 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. Where near shadings seem to pose a significant impact in the energy production, module strings shall be sized with less modules and they shall be grouped accordingly. Near 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 optimal solution.
5. All PV plants shall be *commissioned* before handover, according to the industrial best practices. These practices shall include, besides all safety tests specified 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 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 shall be tailor made to the needs of each individual PV plant.¹¹
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 activities, as well as the *pass and fail* criteria for handover, with its associated penalties.¹²
10. Each PV plant shall include a weather station with at least (i) one irradiation sensor on the tilted plane (GTI), (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, at least, every 2 years. It shall be kept clean and at the right tilt, in order to ensure an accurate and representative PR calculation.

¹¹ This recommendation may be difficult to implement for small rooftop systems

¹² This recommendation may be difficult to implement for small rooftop systems

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Annex I – IV Curve Tracing Results

Site	Module No.	Meas. No.	Pmax (P)	Voc (V)	Vmpp (V)	Imp (A)	Isc (A)	Irr. (W/m²)	Module Temp. (°C)	FF	Status	Isc (A)	Irradiation (W/m²)	EL Pic. No.	ΔP from Min. Expected
1	1	29	272,8	44,6	36,1	7,6	8,1	962,0	63,0	75,0	Dirty	8,2	960,0	00030	-11,5%
1	1	30	274,4	44,6	36,2	7,6	8,2	962,0	63,0	75,0	Dirty				-11,0%
1	1	31	273,3	44,6	36,1	7,6	8,2	965,0	63,0	75,0	Dirty				-11,3%
1	1	32	293,3	45,2	36,3	8,1	8,6	981,0	60,0	75,0	Clean	8,9	982,0		-4,8%
1	1	33	294,3	45,2	36,3	8,1	8,7	979,0	60,0	75,0	Clean				-4,5%
1	1	34	294,2	45,1	36,3	8,1	8,7	977,0	60,0	75,0	Clean				-4,5%
2	2	126	271,1	43,9	35,3	7,7	8,2	1042,0	53,0	76,0	Dirty				-14,2%
2	2	127	270,0	43,9	35,2	7,7	8,2	1042,0	53,0	75,0	Dirty				-14,6%
2	2	128	270,6	44,0	35,8	7,6	8,2	1041,0	53,0	75,0	Dirty				-14,4%
2	3	129	267,0	43,6	35,2	7,6	8,1	1031,0	53,0	76,0	Dirty				-15,5%
2	3	130	266,5	43,6	35,1	7,6	8,1	1029,0	53,0	76,0	Dirty				-15,7%
2	3	131	266,4	43,6	35,1	7,6	8,1	1028,0	53,0	76,0	Dirty				-15,7%
2	4	132	261,4	43,1	34,3	7,6	8,1	1016,0	53,0	75,0	Dirty				-17,3%
2	4	133	262,1	43,1	34,5	7,6	8,1	1025,0	53,0	75,0	Dirty				-17,1%
2	4	134	261,2	43,0	35,0	7,5	8,1	1022,0	53,0	75,0	Dirty				-17,4%
2	5	135	262,4	43,1	34,7	7,6	8,1	1028,0	53,0	75,0	Dirty				-17,0%
2	5	136	262,7	43,3	34,7	7,6	8,1	1028,0	53,0	75,0	Dirty				-16,9%
2	5	137	262,5	43,3	34,7	7,6	8,1	1030,0	53,0	75,0	Dirty				-17,0%
2	6	138	257,9	43,3	34,3	7,5	8,0	1029,0	53,0	75,0	Dirty			00080	-18,4%
2	6	139	257,7	43,2	34,8	7,4	8,0	1030,0	53,0	75,0	Dirty				-18,5%
2	6	140	257,5	43,2	34,9	7,4	7,9	1034,0	53,0	75,0	Dirty				-18,6%
2	7	141	259,9	43,3	35,0	7,4	8,0	1027,0	53,0	76,0	Dirty				-17,8%
2	7	142	259,1	43,2	34,9	7,4	7,9	1027,0	53,0	76,0	Dirty				-18,0%
2	7	143	259,9	43,2	34,9	7,5	8,0	1025,0	53,0	76,0	Dirty				-17,8%
2	8	144	261,1	43,6	35,2	7,4	7,9	1031,0	53,0	76,0	Dirty				-17,4%
2	8	145	261,4	43,6	35,3	7,4	7,9	1032,0	53,0	76,0	Dirty				-17,3%
2	8	146	261,8	43,6	35,3	7,4	7,9	1031,0	53,0	76,0	Dirty				-17,2%
2	9	147	264,8	43,9	35,4	7,5	7,9	1024,0	53,0	76,0	Dirty				-16,3%
2	9	148	266,1	44,0	35,6	7,5	8,0	1024,0	53,0	76,0	Dirty				-15,8%
2	9	149	265,9	44,0	35,5	7,5	8,0	1022,0	53,0	76,0	Dirty				-15,9%
2	2	150	282,0	44,4	35,8	7,9	8,4	995,0	53,0	76,0	Clean				-10,8%
2	2	151	283,3	44,6	36,0	7,9	8,4	999,0	53,0	76,0	Clean				-10,4%
2	2	152	282,2	44,5	36,7	7,7	8,4	1004,0	53,0	76,0	Clean				-10,7%
2	3	153	280,7	44,4	35,7	7,9	8,3	997,0	53,0	76,0	Clean				-11,2%
2	3	154	279,0	44,3	35,7	7,8	8,3	1003,0	53,0	76,0	Clean				-11,8%
2	3	155	280,2	44,3	35,8	7,8	8,3	1001,0	53,0	76,0	Clean				-11,4%
2	4	156	275,8	44,0	35,4	7,8	8,3	1004,0	53,0	76,0	Clean				-12,8%
2	4	157	275,8	44,0	35,7	7,7	8,3	995,0	53,0	76,0	Clean				-12,8%
2	4	158	274,8	43,8	35,0	7,9	8,3	992,0	53,0	76,0	Clean				-13,1%
2	5	159	275,5	43,8	35,5	7,8	8,3	986,0	53,0	76,0	Clean				-12,9%
2	5	160	274,8	43,8	35,3	7,8	8,3	983,0	53,0	76,0	Clean				-13,1%
2	5	161	275,1	43,8	35,2	7,8	8,3	979,0	53,0	76,0	Clean				-13,0%
2	6	162	272,5	43,8	35,6	7,7	8,2	979,0	53,0	76,0	Clean				-13,8%
2	6	163	272,0	43,8	35,0	7,8	8,2	980,0	53,0	76,0	Clean				-14,0%
2	6	164	271,8	43,8	35,5	7,7	8,2	979,0	53,0	75,0	Clean				-14,0%
2	7	165	273,1	43,8	35,6	7,7	8,3	977,0	53,0	76,0	Clean				-13,6%
2	7	166	272,9	43,8	35,6	7,7	8,2	978,0	53,0	76,0	Clean				-13,7%
2	7	167	272,3	43,7	35,0	7,8	8,2	978,0	53,0	76,0	Clean				-13,9%
2	8	168	272,2	43,7	35,3	7,7	8,2	969,0	53,0	76,0	Clean				-13,9%
2	8	169	272,2	43,7	35,2	7,7	8,2	967,0	53,0	76,0	Clean				-13,9%
2	8	170	271,9	43,7	35,2	7,7	8,2	964,0	53,0	76,0	Clean				-14,0%

Site	Module No.	Meas. No.	Pmax (P)	Voc (V)	Vmpp (V)	Imp (A)	Isc (A)	Irr. (W/m²)	Module Temp. (°C)	FF	Status	Isc (A)	Irradiation (W/m²)	EL Pic. No.	ΔP from Min. Expected
2	9	171	275,3	43,9	35,7	7,7	8,3	971,0	53,0	76,0	Clean				-12,9%
2	9	172	274,2	43,9	35,5	7,7	8,2	970,0	53,0	76,0	Clean				-13,3%
2	9	173	274,5	43,9	35,5	7,7	8,3	966,0	53,0	76,0	Clean				-13,2%
3	1	35	274,1	44,9	35,6	7,7	8,3	958,0	52,0	74,0	Dirty	8,2	950,0		-13,5%
3	1	36	274,5	44,9	35,6	7,7	8,3	954,0	52,0	74,0	Dirty				-13,4%
3	1	37	275,9	44,8	36,4	7,6	8,3	954,0	52,0	74,0	Dirty				-12,9%
3	1	38	291,3	44,9	36,3	8,0	8,8	1006,0	49,0	74,0	Clean	9,0	986,0		-8,0%
3	1	39	289,9	44,8	35,4	8,2	8,7	1019,0	49,0	74,0	Clean				-8,5%
3	1	40	290,2	44,9	35,9	8,1	8,8	1017,0	49,0	74,0	Clean				-8,4%
3	2	41	281,5	44,5	35,6	7,9	8,7	989,0	51,0	73,0	Dirty			00037	-11,2%
3	2	42	278,5	44,5	35,6	7,8	8,6	1000,0	51,0	73,0	Dirty				-12,1%
3	2	43	279,4	44,6	35,3	7,9	8,6	1008,0	51,0	73,0	Dirty				-11,8%
3	3	44	282,7	44,5	35,5	8,0	8,5	982,0	51,0	75,0	Dirty			00035	-10,8%
3	3	45	283,5	44,6	35,7	7,9	8,5	988,0	51,0	75,0	Dirty				-10,5%
3	4	46	279,6	44,4	35,6	7,9	8,5	995,0	51,0	74,0	Dirty			00037	-11,7%
3	4	47	278,4	44,5	35,5	7,8	8,5	997,0	51,0	73,0	Dirty				-12,1%
3	4	48	278,4	44,4	35,0	8,0	8,6	1001,0	51,0	73,0	Dirty				-12,1%
3	2	49	284,9	44,3	35,4	8,1	8,7	1012,0	51,0	74,0	Clean				-10,1%
3	2	50	285,6	44,3	35,2	8,1	8,8	1028,0	51,0	74,0	Clean				-9,9%
3	2	51	285,2	44,3	35,4	8,1	8,8	1036,0	51,0	73,0	Clean				-10,0%
3	3	52	286,0	44,3	35,0	8,2	8,7	1037,0	51,0	74,0	Clean				-9,7%
3	3	53	285,3	44,3	35,5	8,0	8,6	1040,0	51,0	75,0	Clean				-10,0%
3	4	54	288,8	44,2	35,2	8,2	8,9	1041,0	50,0	74,0	Clean				-8,9%
3	4	55	287,0	44,2	35,3	8,1	8,8	1028,0	50,0	74,0	Clean				-9,4%
3	4	56	287,6	44,3	35,4	8,1	8,9	1028,0	50,0	73,0	Clean				-9,2%
4	1	4	270,2	44,4	35,5	7,6	8,2	1006,0	60,5	74,0	Dirty	8,5	1009,0	5801	-13,4%
4	1	5	270,1	44,6	35,6	7,6	8,2	1009,0	60,5	74,0	Dirty	8,5	1009,0	5801	-13,4%
4	1	6	271,5	44,6	36,2	7,5	8,2	1003,0	60,5	74,0	Dirty	8,5	1009,0	5801	-12,9%
4	2	7	265,4	44,2	35,3	7,5	8,0	998,0	58,5	75,0	Dirty	8,4	1007,0	5800	-15,5%
4	2	8	268,7	44,3	35,5	7,6	8,1	991,0	58,5	75,0	Dirty	8,4	1007,0	5800	-14,1%
4	2	9	269,4	44,4	35,7	7,6	8,1	996,0	58,5	75,0	Dirty	8,4	1007,0	5800	-13,7%
4	3	10	271,7	44,5	35,4	7,7	8,2	1002,0	56,0	74,0	Dirty	8,5	1000,0	5797	-12,8%
4	3	11	270,1	44,4	35,2	7,7	8,2	1002,0	56,0	74,0	Dirty	8,5	1000,0	5797	-13,5%
4	3	12	274,5	44,4	35,3	7,8	8,3	989,0	56,0	75,0	Dirty	8,5	1000,0	5797	-11,6%
4	4	13	265,6	44,5	35,7	7,4	7,9	1035,0	57,4	76,0	Dirty	8,4	989,0	5799	-15,4%
4	4	14	269,3	44,5	35,6	7,6	8,0	1015,0	57,4	76,0	Dirty	8,4	989,0	5799	-13,8%
4	4	15	271,5	44,5	35,8	7,6	8,1	1019,0	57,4	75,0	Dirty	8,4	989,0	5799	-12,9%
4	3	16	293,0	45,1	35,7	8,2	8,7	899,0	53,7	75,0	Clean	7,9	863,0	5797	-4,6%
4	3	17	292,0	45,0	36,0	8,1	8,7	892,0	53,7	75,0	Clean	7,9	863,0	5797	-4,9%
4	3	18	295,1	45,1	36,1	8,2	8,7	864,0	53,7	75,0	Clean	7,9	863,0	5797	-3,8%
4	4	19	288,4	44,8	36,0	8,0	8,8	904,0	53,1	73,0	Clean	8,3	919,0	5799	-6,2%
4	4	20	290,7	44,8	35,6	8,2	8,8	902,0	53,1	73,0	Clean	8,3	919,0	5799	-5,4%
4	4	21	289,9	44,8	35,7	8,1	8,9	910,0	53,1	73,0	Clean	8,3	919,0	5799	-5,7%
5	4	57	251,9	39,7	30,7	8,2	8,8	971,0	59,0	73,0	Dirty	8,8	980,0	00045	-18,8%
5	4	58	249,3	39,7	31,0	8,0	8,7	980,0	59,0	72,0	Dirty				-19,7%
5	4	59	249,2	39,7	31,5	7,9	8,7	975,0	59,0	73,0	Dirty				-19,7%
5	1	60	266,4	42,3	33,6	7,9	8,5	999,0	45,0	74,0	Clean			00042	-14,1%
5	1	61	265,4	42,1	33,6	7,9	8,5	1002,0	45,0	74,0	Clean				-14,5%
5	1	62	263,2	41,9	33,3	7,9	8,5	1001,0	45,0	74,0	Clean				-15,2%
5	5	63	267,7	42,4	33,6	8,0	8,5	994,0	45,0	74,0	Clean			00041	-13,7%
5	5	64	266,6	42,2	33,7	7,9	8,5	1001,0	45,0	74,0	Clean				-14,1%
5	5	65	264,2	41,9	33,6	7,9	8,5	1008,0	46,0	74,0	Clean				-14,8%
5	2	66	260,5	41,5	32,5	8,0	8,5	1000,0	48,0	74,0	Clean			00052	-16,0%
5	2	67	259,5	41,4	33,4	7,8	8,5	995,0	50,0	74,0	Clean				-16,4%

Site	Module No.	Meas. No.	Pmax (P)	Voc (V)	Vmpp (V)	Imp (A)	Isc (A)	Irr. (W/m²)	Module Temp. (°C)	FF	Status	Isc (A)	Irradiation (W/m²)	EL Pic. No.	ΔP from Min. Expected
5	2	68	259,4	41,4	32,8	7,9	8,5	995,0	50,0	74,0	Clean				-16,4%
5	4	69	248,6	40,3	31,7	7,8	8,5	991,0	54,0	73,0	Clean				-19,9%
5	4	70	248,8	40,3	32,0	7,8	8,5	1002,0	54,0	73,0	Clean				-19,8%
5	4	71	246,5	40,1	31,5	7,8	8,4	991,0	55,0	73,0	Clean				-20,6%
6	1	22	287,9	44,3	35,5	8,1	8,7	980,0	50,6	75,0	Dirty	8,9	989,0	-	-7,1%
6	1	23	288,1	44,3	35,5	8,1	8,7	980,0	50,6	75,0	Dirty	8,9	989,0	-	-7,0%
6	1	24	286,5	44,3	35,3	8,1	8,7	980,0	50,6	75,0	Dirty	8,9	989,0	-	-7,6%
6	2	25	288,7	44,8	35,6	8,1	8,6	976,0	54,3	75,0	Dirty	8,8	980,0	-	-6,8%
6	2	26	293,0	45,0	36,0	8,1	8,7	976,0	54,3	75,0	Dirty	8,8	980,0	-	-5,2%
6	2	27	292,8	45,1	36,0	8,1	8,6	976,0	54,3	75,0	Dirty	8,8	980,0	-	-5,3%
6	3	28	283,4	44,3	35,1	8,1	8,7	977,0	51,2	74,0	Dirty	8,8	982,0	-	-8,8%
6	3	29	282,8	44,5	35,6	8,0	8,6	977,0	51,2	74,0	Dirty	8,8	982,0	-	-9,0%
6	3	30	283,7	44,4	35,6	8,0	8,6	977,0	51,2	74,0	Dirty	8,8	982,0	-	-8,7%
6	4	31	282,8	44,3	35,5	8,0	8,6	977,0	51,1	74,0	Dirty	8,5	970,0	-	-9,0%
6	4	32	283,5	44,3	35,0	8,1	8,6	977,0	51,1	74,0	Dirty	8,5	970,0	-	-8,7%
6	4	33	282,0	44,3	35,5	8,0	8,6	977,0	51,1	74,0	Dirty	8,5	970,0	-	-9,3%
6	5	34	288,2	44,4	35,6	8,1	8,7	941,0	53,0	75,0	Dirty	8,1	941,0	5802	-7,0%
6	5	35	287,1	44,3	35,6	8,1	8,6	941,0	53,0	75,0	Dirty	8,1	941,0	5802	-7,4%
6	5	36	288,3	44,4	35,6	8,1	8,7	941,0	53,0	75,0	Dirty	8,1	941,0	5802	-6,9%
6	1	37	295,3	44,4	35,5	8,3	8,9	920,0	51,0	75,0	Clean	8,4	914,0	-	-4,4%
6	1	38	294,9	44,5	35,5	8,3	8,9	920,0	51,0	75,0	Clean	8,4	914,0	-	-4,5%
6	1	39	295,1	44,5	35,6	8,3	8,9	920,0	51,0	75,0	Clean	8,4	914,0	-	-4,5%
6	5	40	300,5	44,8	36,4	8,3	9,0	902,0	48,0	75,0	Clean	7,3	941,0	5802	-2,6%
6	5	41	300,0	44,8	36,1	8,3	9,0	902,0	48,0	75,0	Clean	7,3	941,0	5802	-2,8%
6	5	42	299,5	44,8	36,7	8,2	8,9	902,0	48,0	75,0	Clean	7,3	941,0	5802	-2,9%
7	1	72	289,7	42,1	34,3	8,4	9,2	1021,0	64,0	75,0	Dirty	10,0	1010,0		-19,5%
7	1	73	290,2	42,0	33,7	8,6	9,2	1016,0	64,0	75,0	Dirty				-19,4%
7	1	74	289,2	42,0	34,2	8,5	9,2	1019,0	64,0	75,0	Dirty				-19,7%
7	1	75	302,9	42,7	34,6	8,8	9,4	1050,0	61,0	75,0	Clean	10,4	1047,0		-15,9%
7	1	76	302,0	42,7	35,1	8,6	9,4	1050,0	61,0	75,0	Clean				-16,1%
7	1	77	301,5	42,6	34,8	8,7	9,4	1043,0	61,0	75,0	Clean				-16,2%
7	1	78	273,5	45,6	36,0	7,6	8,2	1047,0	64,0	73,0	Dirty				-13,5%
7	1	79	273,2	45,7	36,0	7,6	8,2	1048,0	64,0	73,0	Dirty				-13,6%
7	1	80	272,2	45,6	35,9	7,6	8,2	1048,0	64,0	73,0	Dirty				-13,9%
7	2	81	245,6	43,9	33,5	7,3	8,0	1036,0	64,0	70,0	Dirty			00055	-22,3%
7	2	82	246,2	43,9	33,5	7,4	8,1	1035,0	64,0	70,0	Dirty				-22,1%
7	2	83	246,0	43,9	33,5	7,3	8,0	1037,0	64,0	70,0	Dirty				-22,2%
7	3	84	267,0	44,4	35,6	7,5	8,1	1041,0	63,0	74,0	Dirty			00064	-15,6%
7	3	85	266,3	44,4	35,6	7,5	8,1	1044,0	63,0	74,0	Dirty				-15,8%
7	3	86	267,2	44,4	35,6	7,5	8,1	1039,0	63,0	74,0	Dirty				-15,5%
7	4	87	231,9	44,3	31,8	7,3	8,0	1043,0	63,0	66,0	Dirty			00055	-26,6%
7	4	88	232,0	44,3	31,3	7,4	8,0	1044,0	63,0	66,0	Dirty				-26,6%
7	4	89	232,2	44,4	32,3	7,2	7,9	1041,0	63,0	66,0	Dirty				-26,6%
7	5	90	225,7	43,7	33,5	6,7	7,8	1034,0	60,0	66,0	Dirty			00059	-28,6%
7	5	91	226,2	43,8	33,4	6,8	7,8	1026,0	60,0	66,0	Dirty				-28,5%
7	5	92	227,7	43,9	33,6	6,8	7,9	1028,0	61,0	66,0	Dirty				-28,0%
7	1	93	278,8	45,9	36,3	7,7	8,3	1042,0	60,0	73,0	Clean				-11,8%
7	1	94	279,2	45,9	36,1	7,7	8,4	1036,0	60,0	73,0	Clean				-11,7%
7	1	95	279,4	45,9	36,2	7,7	8,3	1036,0	61,0	73,0	Clean				-11,6%
8	1	43	195,5	44,3	24,6	7,9	8,5	1002,0	54,8	52,0	Dirty	7,9	1010,0	5805	-58,7%
8	1	44	196,9	44,4	24,8	8,0	8,5	1002,0	54,8	52,0	Dirty	7,9	1010,0	5805	-57,5%
8	1	45	197,0	44,4	24,3	8,1	8,5	1002,0	54,8	52,0	Dirty	7,9	1010,0	5805	-57,4%
8	2	46	277,0	44,4	35,5	7,8	8,3	1013,0	57,1	75,0	Dirty	7,8	1012,0	5806	-11,9%
8	2	47	276,4	44,3	35,5	7,8	8,3	1013,0	57,1	75,0	Dirty	7,8	1012,0	5806	-12,2%

Site	Module No.	Meas. No.	Pmax (P)	Voc (V)	Vmpp (V)	Imp (A)	Isc (A)	Irr. (W/m²)	Module Temp. (°C)	FF	Status	Isc (A)	Irradiation (W/m²)	EL Pic. No.	ΔP from Min. Expected
8	2	48	276,2	44,3	35,5	7,8	8,3	1013,0	57,1	75,0	Dirty	7,8	1012,0	5806	-12,3%
8	3	49	231,7	44,2	36,5	6,4	6,8	941,0	49,6	78,0	Dirty	6,7	957,0	5807	-33,8%
8	3	50	232,7	44,2	36,5	6,4	6,8	941,0	49,6	78,0	Dirty	6,7	957,0	5807	-33,2%
8	3	51	233,8	44,3	36,6	6,4	6,8	941,0	49,6	78,0	Dirty	6,7	957,0	5807	-32,6%
8	4	52	230,5	43,8	36,5	6,3	7,1	962,0	55,0	74,0	Dirty	8,2	957,0	5804	-34,6%
8	4	53	229,2	43,7	36,5	6,3	7,1	962,0	55,0	74,0	Dirty	8,2	957,0	5804	-35,3%
8	4	54	228,7	43,7	36,4	6,3	7,1	962,0	55,0	74,0	Clean	8,2	957,0	5804	-35,6%
8	1	55	204,2	44,7	25,2	8,1	8,8	925,0	56,3	52,0	Clean	8,0	904,0	5805	-51,8%
8	1	56	203,2	44,7	25,1	8,1	8,9	925,0	56,3	51,0	Clean	8,0	904,0	5805	-52,6%
8	1	57	202,7	44,7	25,1	8,1	8,8	925,0	56,3	51,0	Clean	8,0	904,0	5805	-53,0%
8	2	58	291,7	44,8	36,0	8,1	8,7	908,0	57,0	75,0	Clean	8,2	899,0	5806	-6,3%
8	2	59	287,2	44,7	36,9	7,8	8,6	908,0	57,0	75,0	Clean	8,2	899,0	5806	-8,0%
8	2	60	290,1	44,7	35,8	8,1	8,6	908,0	57,0	75,0	Clean	8,2	899,0	5806	-6,9%
8	3	61	284,9	44,6	35,9	7,9	8,6	784,0	56,3	75,0	Clean	-	-	5807	-8,9%
8	3	62	283,8	44,6	35,7	7,9	8,5	784,0	56,3	75,0	Clean	-	-	5807	-9,3%
8	3	63	282,3	44,5	35,8	7,9	8,5	784,0	56,3	75,0	Clean	-	-	5807	-9,9%
8	4	64	287,8	44,4	36,2	8,0	8,6	750,0	51,2	76,0	Clean	-	-	5804	-7,7%
8	4	65	290,7	44,3	35,6	8,2	8,7	750,0	51,2	75,0	Clean	-	-	5804	-6,7%
8	4	66	289,7	44,3	36,1	8,0	8,7	750,0	51,2	75,0	Clean	-	-	5804	-9,4%
9	96	96	274,2	44,3	35,6	7,7	8,3	1058,0	57,0	74,0	Dirty			00069	-13,3%
9	97	97	275,2	44,3	35,5	7,8	8,3	1048,0	57,0	74,0	Dirty				-12,9%
9	98	98	277,5	44,3	35,4	7,8	8,4	1036,0	57,0	74,0	Dirty				-12,2%
9	99	99	275,4	44,3	35,8	7,7	8,3	1039,0	57,0	75,0	Dirty			00067	-12,9%
9	100	100	275,1	44,3	35,4	7,8	8,3	1043,0	57,0	75,0	Dirty				-13,0%
9	101	101	273,7	44,3	35,9	7,6	8,2	1045,0	57,0	75,0	Dirty				-13,4%
9	102	102	275,9	44,3	35,6	7,8	8,3	1055,0	53,0	75,0	Dirty				-12,7%
9	103	103	272,5	44,1	35,4	7,7	8,2	1064,0	52,0	75,0	Dirty				-13,8%
9	104	104	273,2	44,2	35,4	7,7	8,2	1061,0	52,0	75,0	Dirty				-13,6%
9	105	105	272,2	44,1	35,2	7,7	8,2	1075,0	54,0	75,0	Dirty				-13,9%
9	106	106	272,0	44,1	35,1	7,8	8,2	1073,0	54,0	75,0	Dirty				-14,0%
9	107	107	271,7	44,0	35,2	7,7	8,2	1078,0	54,0	75,0	Dirty				-14,1%
9	108	108	261,3	44,2	35,9	7,3	7,7	1078,0	55,0	77,0	Dirty				-17,4%
9	109	109	260,5	44,2	35,4	7,4	7,7	1082,0	55,0	77,0	Dirty				-17,6%
9	110	110	261,0	44,2	35,4	7,4	7,7	1083,0	55,0	76,0	Dirty				-17,5%
9	111	111	277,9	44,5	35,4	7,9	8,3	1043,0	50,0	76,0	Clean				-12,1%
9	112	112	277,2	44,4	35,4	7,8	8,3	1049,0	50,0	75,0	Clean				-12,3%
9	113	113	276,2	44,4	35,4	7,8	8,3	1052,0	50,0	76,0	Clean				-12,6%
9	114	114	279,6	44,2	35,1	8,0	8,5	999,0	53,0	74,0	Clean				-11,6%
9	115	115	275,9	44,2	35,6	7,8	8,4	1009,0	53,0	74,0	Clean				-12,7%
9	116	116	276,7	44,2	35,1	7,9	8,4	1009,0	53,0	74,0	Clean				-12,5%
9	117	117	278,4	44,2	35,3	7,9	8,4	1010,0	54,0	75,0	Clean				-11,9%
9	118	118	278,7	44,3	35,3	7,9	8,4	1008,0	54,0	75,0	Clean				-11,8%
9	119	119	278,6	44,2	35,3	7,9	8,4	1008,0	54,0	75,0	Clean				-11,9%
9	120	120	285,6	44,5	35,7	8,0	8,6	1001,0	54,0	75,0	Clean				-9,7%
9	121	121	283,8	44,4	35,6	8,0	8,5	1004,0	54,0	75,0	Clean				-10,2%
9	122	122	285,8	44,5	35,6	8,0	8,6	994,0	54,0	75,0	Clean				-9,6%
9	123	123	284,5	44,3	35,3	8,1	8,5	1013,0	53,0	75,0	Clean				-10,0%
9	124	124	284,9	44,2	35,4	8,1	8,5	1014,0	53,0	76,0	Clean				-9,9%
9	125	125	284,7	44,3	35,3	8,1	8,5	1012,0	53,0	75,0	Clean				-10,0%
10	1	67	196,0	39,8	29,5	6,6	7,5	1053,0	56,0	65,0	Dirty	8,1	1006,0	5813	-58,2%
10	1	68	192,6	39,7	29,7	6,5	7,4	1053,0	56,0	65,0	Dirty	8,1	1006,0	5813	-61,0%
10	1	69	191,1	39,7	29,5	6,5	7,4	1053,0	56,0	65,0	Dirty	8,1	1006,0	5813	-62,2%
10	2	71	225,1	40,8	32,7	6,9	7,6	1005,0	56,0	73,0	Dirty	7,1	1042,0	5812	-37,8%
10	2	72	224,9	40,9	32,7	6,9	7,5	1005,0	56,0	73,0	Dirty	7,1	1042,0	5812	-37,9%

Site	Module No.	Meas. No.	Pmax (P)	Voc (V)	Vmpp (V)	Imp (A)	Isc (A)	Irr. (W/m²)	Module Temp. (°C)	FF	Status	Isc (A)	Irradiation (W/m²)	EL Pic. No.	ΔP from Min. Expected
10	2	73	224,9	40,9	32,7	6,9	7,5	1005,0	56,0	73,0	Dirty	7,1	1042,0	5812	-37,9%
10	3	74	229,5	40,5	32,0	7,2	7,6	967,0	39,0	75,0	Dirty	7,5	982,0	5811	-35,1%
10	3	75	230,5	40,5	32,1	7,2	7,6	964,0	39,0	75,0	Dirty	7,5	982,0	5811	-34,5%
10	3	76	231,0	40,6	32,3	7,2	7,6	972,0	39,0	75,0	Dirty	7,5	982,0	5811	-34,2%
10	4	77	221,8	40,2	32,0	6,9	7,5	976,0	39,0	74,0	Dirty	7,5	985,0	5810	-39,8%
10	4	78	221,6	40,2	32,0	6,9	7,5	976,0	39,0	74,0	Dirty	7,5	985,0	5810	-40,0%
10	4	79	221,9	40,2	32,1	6,9	7,5	978,0	39,0	74,0	Dirty	7,5	985,0	5810	-39,7%
10	2	80	246,6	41,2	33,5	7,4	8,1	910,0	39,0	74,0	Clean	7,6	904,0	5813	-25,7%
10	2	81	247,9	41,2	33,0	7,5	8,2	906,0	39,0	73,0	Clean	7,6	904,0	5813	-25,1%
10	2	82	247,2	41,1	32,9	7,5	8,2	910,0	39,0	73,0	Clean	7,6	904,0	5813	-25,5%
10	1	83	213,4	40,0	30,1	7,1	8,3	907,0	39,0	64,0	Clean	7,5	906,0	5812	-45,3%
10	1	84	213,5	39,9	29,6	7,2	8,3	915,0	39,0	65,0	Clean	7,5	906,0	5812	-45,3%
10	1	85	212,5	39,9	30,0	7,1	8,2	915,0	39,0	65,0	Clean	7,5	906,0	5812	-45,9%

Annex II – Documentation required from the Rooftop Owners

	Required Documents	Description	Available		Comments Owner
			yes	no	
1	GENERAL ASPECTS				
1.1	Customer name				
2	RELEVANT DOCUMENTS DURING THE DEVELOPMENT PHASE				
2.1	Yield assessment				
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					
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					

No.	Item	Interview needed?	Photo needed?	Comments	Photo No.	Note No.
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					
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					
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					

No.	Item	Interview needed?	Photo needed?	Comments	Photo No.	Note No.
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	Curtailement and grid stability					
7.20	Reactive power compensation and power quality requirements					

Annex IV – Measurement Equipment used on Site

I- HT SOLAR-IV [S/N 11110683, calibration date 28.05.2019, tolerance 5%]

II- HT SOLAR-IV [S/N 11011124, calibration date 05.12.2019, tolerance 5%]

HT Solar-IV 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 106: HT SOLAR-IV IV curve tracer [source: pv-engineering]

I- Irradiation sensor HT304N [S/N 14042952, calibration date 02.2019, tolerance <3%]

II- Irradiation sensor HT304N [S/N 14032936, calibration date 01.2019, tolerance <3%]

HT304N 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 137: Duo reference cell [source: PI Berlin]

I- Infrared camera Testo T885 [S/N 02298789, calibration date 01.03.2019, tolerance $<2^\circ$],

II- Infrared camera Testo T885 [S/N 02732076, calibration date 01.03.2019, tolerance $<2^\circ$]

Testo T885 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 138: Infrared camera [source: Testo]

Through 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 139: 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