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

Part II: Evaluation of 10 Rooftop PV Plants in Delhi & Andaman and Nicobar Islands

Report Number: 201802070_II_V2
Berlin, 09.07.2019

Customer

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
B 5/2, 1st Floor, Safdarjung Enclave
New Delhi 110 029, India

Consultant

PI Photovoltaik-Institut Berlin AG
Wrangelstraße 100
10997 Berlin
Germany

Contact Person

Joerg Gaebler
+91-11-4949 5353 Ext. 2176
joerg.gaebler@giz.de

Contact Person

Asier Ukar Naberan
+49 30 814 52 64 – 402
ukar@pi-berlin.com

Report details

Report number	201802070_II_V2	Order date	01.11.2018
Proposal number	1231554	Delivery date	09.07.2019

Customer Information

Customer	Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH	Street address	B 5/2, 1st Floor, Safdarjung Enclave
Responsible person	Joerg Gaebler	City / State	New Delhi
Phone number	+91-11-4949 5353	Zip code	110 029
E-Mail	joerg.gaebler@giz.de	Country	India

Consultant Information

Consultant	PI Photovoltaik-Institut Berlin AG	Street address	Wrangelstraße, 100
Responsible engineers	Asier Ukar Naberan (PM) Patricio Sánchez M. Sc. (PE)	City / State	Berlin
Phone number	+49 30 814 52 64 – 402	Zip code	10997
E-mail	ukar@pi-berlin.com	Country	Germany

Signatures

Created	i. A. [signature] **Asier Ukar Naberan** Senior Consultant	**Revised**	i. A. [signature] **Steven Xuereb** Director of Sales and Project Delivery

Document History

Version	Date	Comments
V1	02.07.2019	First release to Customer
V2	09.07.2019	Second release to Customer: Site details removed

Index

List of abbreviations

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

1. Executive Summary

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

In cooperation with GIZ and PI Berlin's local partner Global Sustainable Energy Solutions India (GSES), and thanks to the support of private developers, SECI and the Distribution Companies BRPL, BYPL and TPDDL, the access to the 10 roofs was secured. The results of the evaluation of each of the PV plants presented in this study show that the low performance of the inspected PV plants is caused by a mix of (i) heavy soiling, (ii) near shading and (iii) high module degradation rates. Module degradation caused by PID and 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 8% and 25%. The absence of O&M contracts stating clear procedures for the corrective maintenance plan, the reaction times and the contractual availability values, is a factor that also contributes decisively to lowering the PV plant's output.

One of the goals of the project is that future O&M contractors and developers can benefit from the knowledge and conclusions drawn from the evaluation of the PV plants presented in this study. In this sense, PI Berlin suggests 5 concrete revamping and repowering measures that, depending on the state of each PV plant, may lead to a performance boost between 6% and 39%. PI Berlin has identified 10 prevention mechanisms that include technical and commercial recommendations to ensure the revenues for the next generation projects.

2. Introduction and Background

The Government of India is aiming for an exponential increase in the installation of renewable energy systems in the country including 100 GW capacity of solar power by 2022 out of which 40 GW is targeted on rooftops. In July 2018, the cumulative installed capacity of grid-connected rooftop photovoltaic systems was around 1,300 MW. 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 second set of 10 rooftop PV plants, half of them located in the greater Delhi and the rest in Andaman and Nicobar Islands.

3. About PI Berlin

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

4. Description of the Inspection Methodology

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

Preparation Phase

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

1. An equal number of roofs from all DISCOM´s shall be selected
2. PV plants with different nominal capacities shall be selected (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 SOP[1] 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 with direct impact in 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 be documented.

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

[1] Standard Operating Procedure

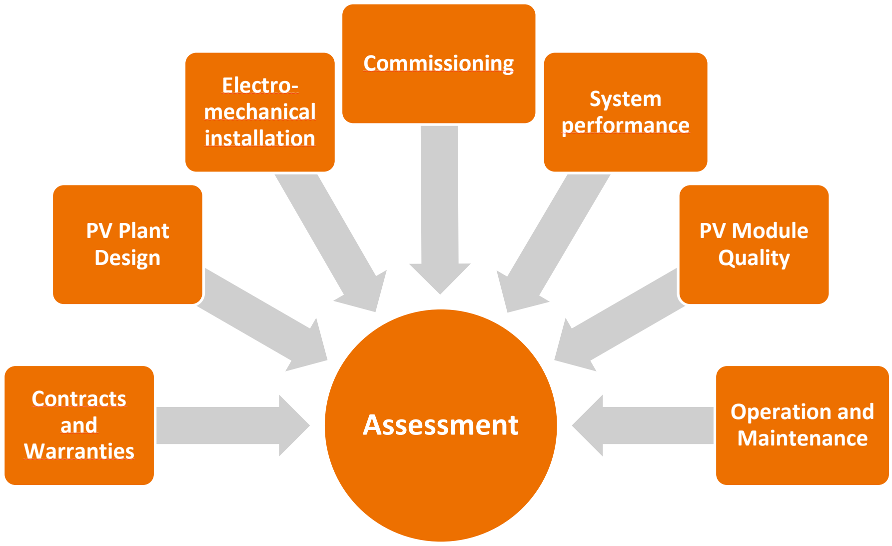

Figure 1: Scope of the evaluation

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) simulation exercises with PV SYST. The results achieved by PI Berlin will provide answers to the following questions:

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

5. List of the Selected Sites

The selected sited analyzed in this study are shown in the following table. Five of the sites are located within the greater Delhi area, while the other five in Andaman and Nicobar Islands.

Table 2: List and location of the selected sites

PV Plant	Installed capacity (kWp)	Average specific yield since COD
II.1	48.8	718 kWh/kWp
II.2	71.5	696 kWh/kWp
II.3	69.87	536 kWh/kWp
II.4	50.7	524 kWh/kWp
II.5	63.375	375 kWh/kWp
II.6	27.9	417 kWh/kWp
II.7	55.8	896 kWh/kWp
II.8	58.28	783 kWh/kWp
II.9	429.04	1233 kWh/kWp
II.10	89.28	1173 kWh/kWp

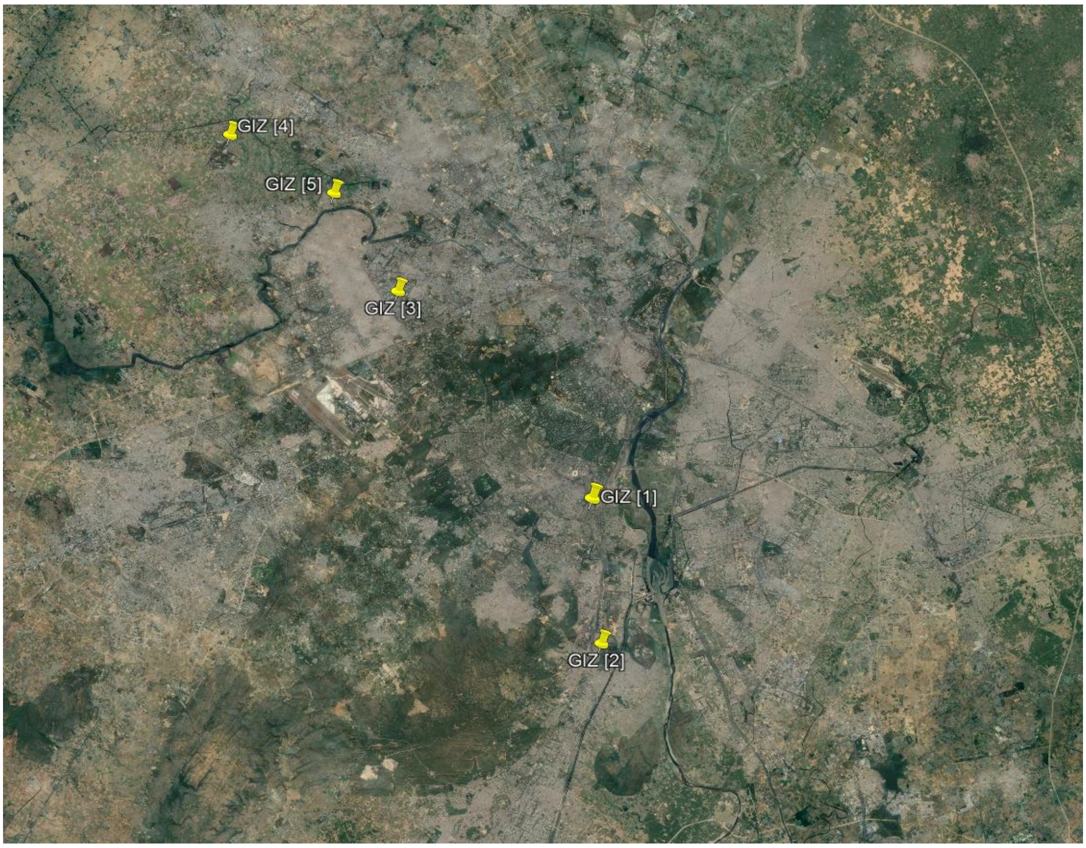

Figure 2: Sites within the greater Delhi area

Figure 3: Sites on the Andaman and Nicobar Islands

Climate characteristics: New Delhi

The prevailing climate here is known as a local steppe climate. During the year, there is little rainfall and the temperature here averages 25.2 °C. The average annual rainfall is 693 mm and the driest month is April. There is 3 mm of precipitation in April and most precipitation falls in August, with an average of 246 mm. With an average of 34.3 °C, June is the warmest month and January the coldest with an average temperature of 14.2 °C. The precipitation varies 243 mm between the driest month and the wettest month. The average temperatures vary during the year by 20.1 °C [source: climate-data.org]. The Global Horizontal Irradiation (GHI) is approximately 1,700 kWh/m² [source: SolarGIS].

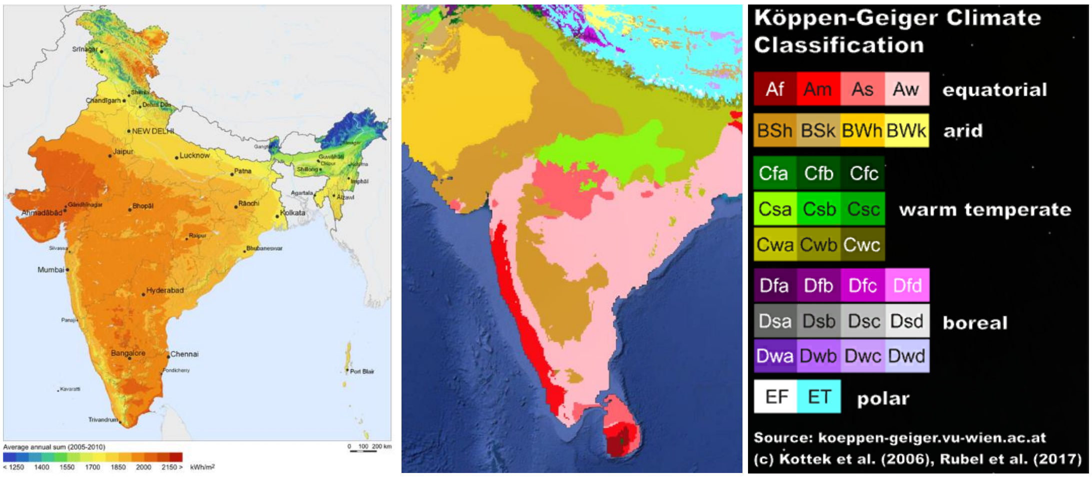

Figure 4: Global horizontal irradiation map of India [source: SolarGIS] (left); Köppen-Geiger climate classification map for India (1980-2016) [17] (middle and right)

Climate characteristics: Port Blair, Andaman and Nicobar Islands

The prevailing climate here is tropical climate, classified as Am by Köppen-Geiger classification. Throughout the year there is a significant amount of rainfall. The average annual rainfall is 3068 mm and the driest month is March. There is 20 mm of precipitation in March and most precipitation falls in June, with an average of 513 mm. The precipitation varies 493 mm between the driest month and the wettest month. With an average of 27.9 °C, April is the warmest month and January the coldest with an average temperature of 25.8 °C. The average temperatures vary during the year by 2.1 °C [source: climate-data.org]. The Global Horizontal Irradiation (GHI) is approximately 1,831 kWh/m² [source: SolarGIS].

Figure 5: Global horizontal irradiation map of Andaman and Nicobar Islands [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.

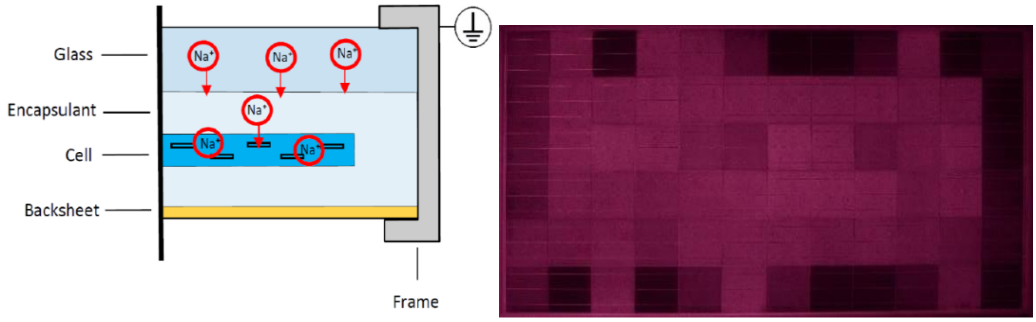

Figure 6: p-n junction damage (left) and typical PID pattern (right) [source: PI Berlin]

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

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

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

6. 2. Snail Trails

It is defined as a grey/black discoloration of the silver paste of the front metallization of screen-printed solar cells. In the PV module the effect looks like a snail trail on the front glass of the module and is visible to the human eye. The discoloration occurs along invisible cell cracks. The discoloration typically occurs 3 months to 1 year after installation of the PV modules. During the summer and in hot climates snail trails occur faster [9]. The area of the snail trail discoloration along the silver finger of the front side cell metallization shows nanometer-sized silver particles in the EVA above the silver finger. These silver particles cause the discoloration [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 7: 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].

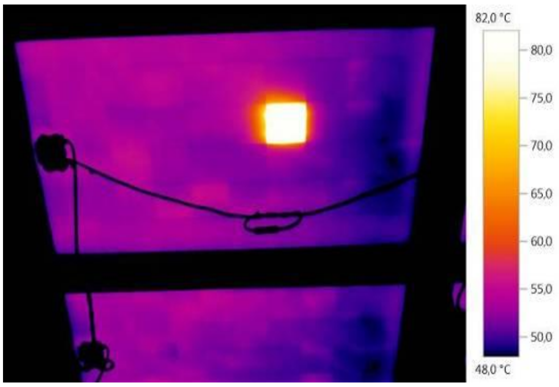

Figure 8: PV Module affected by a hot spot [source: PI Berlin]

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 [9].

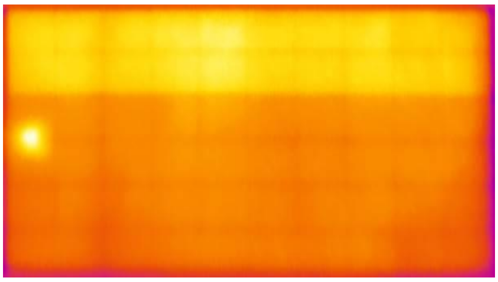

Figure 9: PV Module with an inactive cell string [source: PI Berlin]

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.

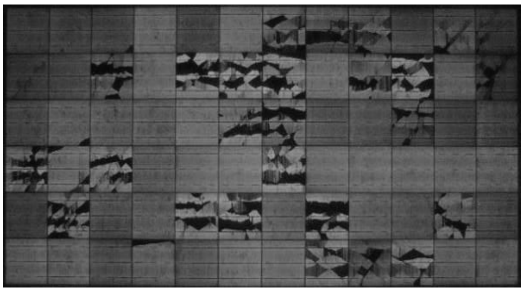

Figure 10: PV Module showing cracks and microcracks [source: PI Berlin]

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: ***II.1***

Nominal capacity: ***48.8 kWp***

Average specific yield since COD (October 2016): ***718 kWh/kWp***

Abstract: *The actual module tilt angle is deviated from the optimal angle of 10° leading to an estimated loss of 2.8%. From the safety perspective, the inverter does not include an overvoltage protection and isolation losses can't be excluded due to the presence of scratches at the backsheet. The modules are hotspot sensitive and heavily affected by PID. It is recommended to: (i) reduce the module by at least 5°, (ii) implement an anti-PID solution and (iii) restring the system so that modules with similar tilt and azimuth are grouped together. The estimated production boost expected by the retrofitting actions lies between 20% and 25%.*

PV Plant's health

Main Findings

- No weather station has been installed and the Performance Ratio is not tracked.
- The actual module tilt angles (7° and 25°), were found to be deviated from the optimal angle of 10°.
- Scratches were observed on the back side of some modules.

Figure 13: Scratch on the back sheet

- Some connectors were found to be not tightly closed.

Figure 14: Connector not tightly closed

- Cable ties broke hence the module cables and connectors were loosely hanging.
- Some parts of the cables are exposed to UV radiation. Pipes conveying cables are brittle and some parts have already broken.
- There is no overvoltage protection in the inverter room.
- PID presence was confirmed via IR and EL inspections.

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 0.8%.
- The amount and type of cracks found in the selected modules during the electroluminescence inspection, reduce the nominal power of the PV plant by ca. 3%. This statement is based on the extrapolation of the results of the sample measurements.

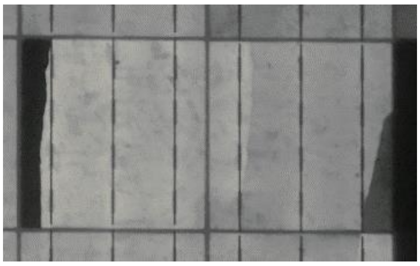

Figure 15: Examples of cracks

- PID causes power losses close to 15% on system level. The degradation is in a fairly advanced stage.

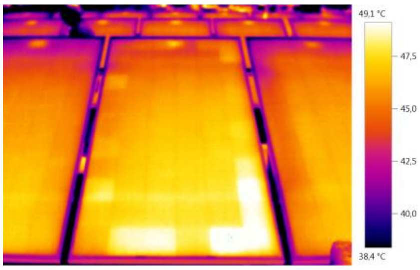

Figure 16: PID affected module

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.
- The adjustment of the tilt angle towards the optimal angle could result in ca. 2.8% increase in the effective irradiation on the module plane.

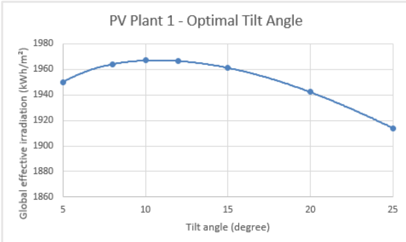

Figure 17: Effective irradiation vs. tilt

- An anti-PID measure, such as anti-PID box, shall 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 MPPT.
- The modules with the same tilt and azimuth shall be grouped in strings with the same MPPT.

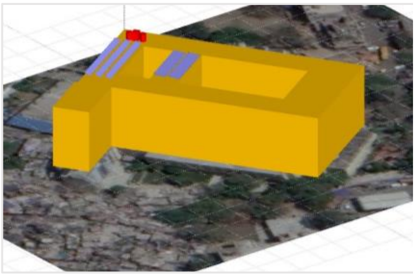

Figure 18: 3D scene in PVsyst

Estimated energy boost after conducting the suggested retrofitting actions: 20% to 25%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 1.3 ₹/Wp, 0.8 ₹/Wp/a

Picture Gallery

Figure 19: Access to the roof

Figure 20: General view of the system

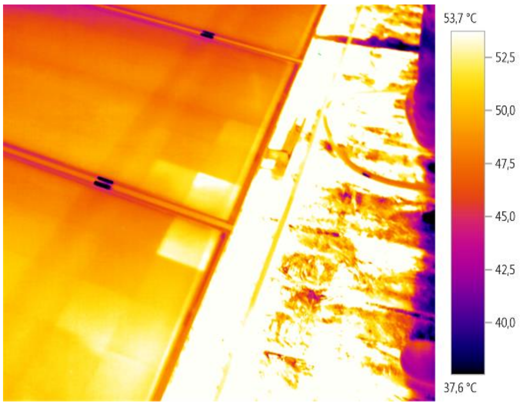

Figure 21: Crack induced hot spots

Figure 22: View of the rear part

Figure 23: Foundation of the mounting structure

Figure 24: Cleaning of the modules

Figure 25: Connections at the inverter

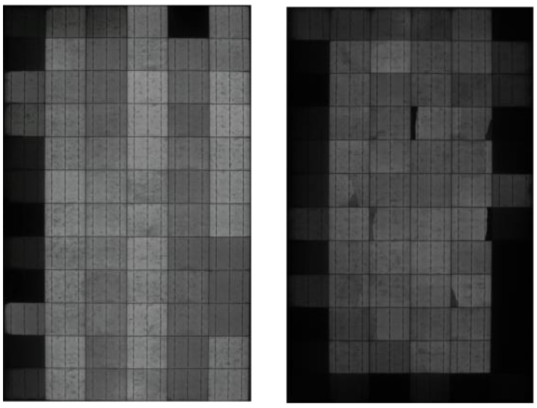

Figure 26: PID affected modules

2

*PV plant: **II.2***

*Nominal capacity: **71.5 kWp***

*Average specific yield since COD (February 2018): **696 kWh/kWp***

***Abstract**: The PV plant is affected by significant soiling caused by concrete splattered on the modules. 10% of the modules were found with broken glass. PID was found to be in a fairly advanced stage and several DC cables showed evidence of monkey bites. The new buildings erected on the west part of the system induce a significant amount of shading during the afternoon. It is recommended to: (i) replace every broken module, (ii) increase the cleaning cycles, (iii) rearrange the strings based on shading categories and (iv) implement anti-PID solutions. The estimated production boost expected by the retrofitting actions lies between 26% and 32%.*

PV Plant's health

Main Findings

- The module connectors show damages since they were opened with improper tools.
- A loose connection of the module connectors has caused burning.
- A significant number of modules show mechanical damages on the front glass.
- Some fuses in the combiner boxes have burned.
- Cables damaged by monkey bites were observed.

Figure 27: Monkey bites

- There is no weather station, and hence no PR monitoring.
- The PV plant is partly surrounded by buildings which cast shadows onto the modules.
- PID presence was detected via IR and EL inspection.

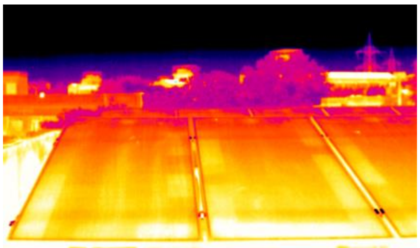

Figure 28: PID modules

Impact on Performance

- Some parts of the PV plant are heavily soiled (soiling loss determination was not possible due to bad weather). The loss is estimated to be >10% based on past experiences.

Figure 29: Soiling on the modules

- The significant number of broken modules could lead to a performance loss of at least 7% at the system level.
- Based on the simulation, the shading losses due to the surrounding buildings is ca. 4.8%.
- PID was found to be in a fairly advanced stage. This could result in a performance loss of as high as 10% at the system level, based on PI Berlin experiences (on-site measurement was not possible).

Figure 30: Broken module

Proposed Solutions

- The broken modules shall be replaced with new modules.
- The cleaning cycles shall be increased based on the results of a soiling study that adjusts the cleaning needs to each season.
- 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.
- A restringing of the modules from the shaded areas shall be conducted in the following way: modules with similar shading conditions shall be installed in the same string or at least assigned to individual MPPTs.
- Anti-PID measures shall 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.
- Covering the ground with white gravel or white paint increases the albedo factor to 0.5, leading to performance boost of approximately 1%.

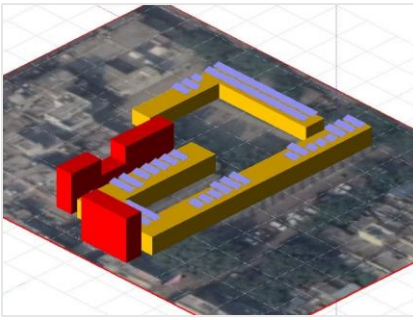

Figure 31: 3D scene

Estimated energy boost after conducting the suggested retrofitting actions: 27% to 33%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 1.2 ₹/Wp, 0.4 ₹/Wp/a

Picture Gallery

Figure 32: View of part of the system

Figure 33: View of part of the system

Figure 34: Buildings near the system

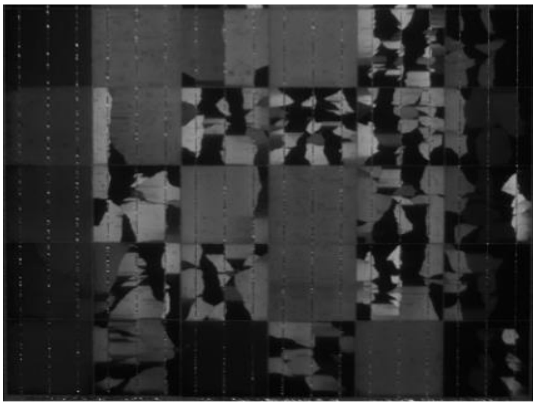

Figure 35: Module affected by glass breakage

Figure 36: Module glass breakage

Figure 37: Burned fuses

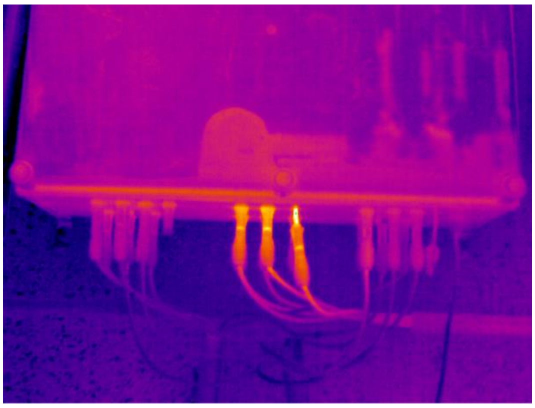

Figure 38: Connections with abnormal temperature

Figure 39: Trees causing shading

3

PV plant: ***II.3***

Nominal capacity: ***69.87 kWp***

Average specific yield since COD (December 2017): ***536 kWh/kWp***

Abstract*: The PV plant is affected by significant soiling due to pollution, near shadings caused by surrounding trees in the south and west part of the system and advanced PID degradation. It is recommended to: (i) increase the cleaning frequency, (ii) rearrange the strings based on the shading categories incase trimming is not allowed, (iii) implement an anti-PID box solution and (iv) install an irradiation sensor on the tilted plane that enables the calculation and monitoring of the Performance Ratio. The estimated production boost expected by the retrofitting actions lies between 16% and 20%.*

PV Plant's health

Main Findings

- Burned AC cables were reported a couple of times, as well as AC switches, leading to significant availability losses.
- There is no weather station, and hence no PR monitoring.
- Some of the module cables are fixed exceeding the minimum bending radius.

Figure 40: Small bending radius

- Tubes protecting cables are not robust and some have already broken.

Figure 41: Broken tube (UV exposed)

- Near shading is caused by nearby trees.
- PID presence was detected via IR and EL inspections.

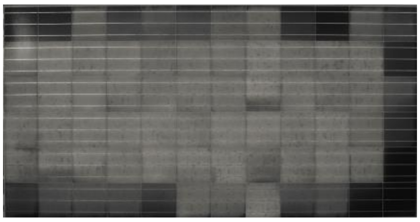

Figure 42: EL image of a PID module

Impact on Performance

- A soiling loss of 7.4% was determined from IV curve measurements of a module before and after cleaning.

Figure 43: Possible source of soiling

- Near shading losses are estimated to be 3.1% at the system level.

Figure 44: Trees cause shading

- PID leads to a performance loss of as high as 26% at the module level based on the measurements conducted on site. The degradation is in a fairly advanced stage. The impact at the system level is estimated to be around 10%,

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.
- The trees surrounding the system shall be trimmed if allowed. Otherwise, a restringing of the modules shall be conducted in the following way: modules with similar shading conditions shall be installed in the same string or at least assigned to one MPPT.
- The cleaning cycles shall be increased based on the results of a soiling study that adjusts the cleaning needs to each season.
- Anti-PID measures shall 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 MPPT.

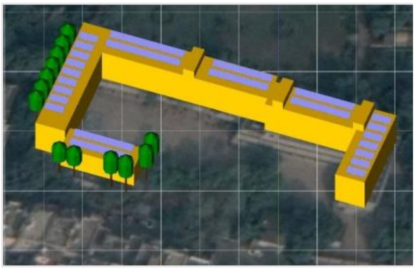

Figure 45: 3D scene

Estimated energy boost after conducting the suggested retrofitting actions: 16% to 20%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 0.7 ₹/Wp, 1.2 ₹/Wp/a

Picture Gallery


Figure 46: View of part of the system


Figure 47: View of part of the system

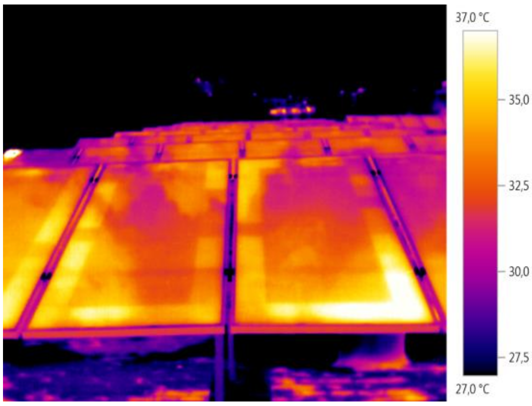

Figure 48: Modules affected by PID


Figure 49: Mounting system fixation


Figure 50: Cable fixation


Figure 51: Broken tube


Figure 52: Warm cells caused by shading from trees, VI (left), IR (right)

4

PV plant: ***II.4***

Nominal capacity: ***50.7 kWp***

Average specific yield since COD (December 2017): ***524 kWh/kWp***

Abstract*: The PV plant shows design failures such as the disregard of the inter-row and near shadings. The modules show signs of soiling due to foliage, hard water and bird drops. Advanced module degradation caused by PID was detected. Some MC4 connectors are overheated due to an increase of the surface resistance. It is recommended to (i) increase the cleaning frequency, (ii) rearrange strings based on the shading categories, (iii) trim regularly the surrounding trees if allowed by the authorities, and (iv) implement anti-PID solutions. The estimated production boost expected by the retrofitting actions lies between 34% and 39%.*

PV Plant's health

Main Findings

- Many areas are heavily shaded by trees.

- There is no weather station, and hence no PR monitoring.
- Some connections were found to be loose leading to an increase of the contact resistance.

Figure 53: Loose connection

- PID presence was detected via IR and EL inspections.

Impact on Performance

- PID loss was determined based on the on-site measurements to be as high as 56%. The degradation has already reached advanced stage.

Figure 55: IR image of PID modules

- Soiling losses were determined based on the measurements on site to be on average 0.5%.
- Based on the simulation, shading losses are estimated to be 15% at the system level.

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.
- The nearby trees shall be trimmed regularly. Otherwise, a restringing of the modules shall be conducted in the following way: modules with similar shading conditions shall be installed in the same string or at least assigned to one MPPT.
- Anti-PID measures shall 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 MPPT.

Figure 54: 3D model constructed in PVsyst

Estimated energy boost after conducting the suggested retrofitting actions: 34% to 39%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 0.9 ₹/Wp, 0.8 ₹/Wp/a

Picture Gallery

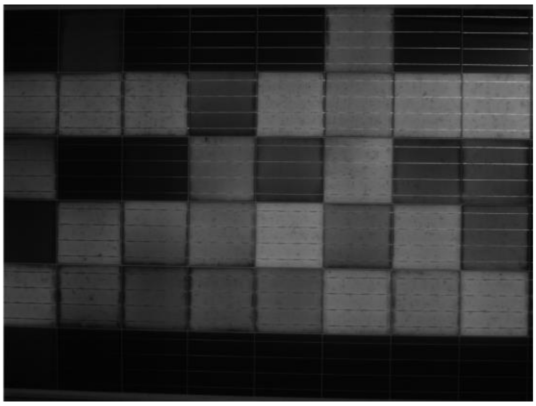

Figure 57: Trees cause significant shading

Figure 58: Trees cause significant shading

Figure 59: Foundation of the mounting structure

Figure 60: Inverters of the system

Figure 61: Soiling on the module surface

Figure 62: Loose fixation of the mounting structure

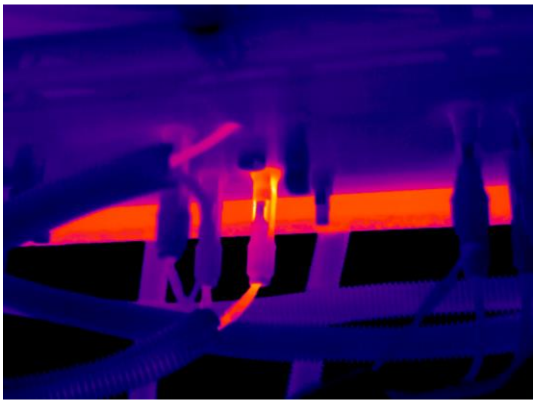

Figure 63: Challenging access to the system

Figure 64: Abnormal temperature of a connection

5

PV plant: ***II.5***

Nominal capacity: ***63.375 kWp***

Average specific yield since COD (December 2017): 375 ***kWh/kWp***

Abstract*: The PV plant shows moderate levels of soiling caused by bird drops and hard water. The system contains design failures such as the disregard of the near shadings and inaccurate DC cable sizing. The east part of the system is heavily shaded by trees. The degree of PID degradation is estimated to be at least 10%. It is recommended to (i) increase the cleaning frequency, (ii) trimming of trees surrounding the system if allowed by the authorities, (iii) rearrange the strings based on the shading situation if the latter is not possible and (iv) implement anti-PID measures. The estimated production boost expected by the retrofitting actions lies between 18% and 23%.*

PV Plant's health

Main Findings

- Many areas are heavily shaded by trees.

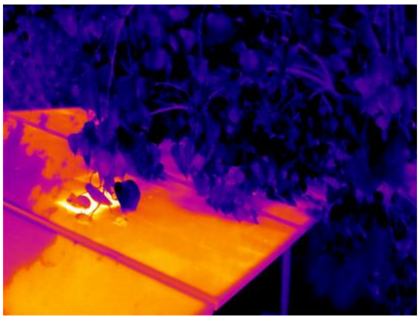

Figure 66: Near shadings disregarded.

- Soiling on the modules was noticed to be moderate during the visit. The system was cleaned two days earlier and it is cleaned every 15 days.
- There is no weather station, and hence no PR monitoring.
- PID presence was detected via IR inspection.

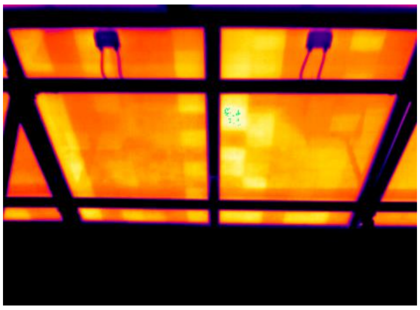

Figure 65: Modules suffering from PID

- String cables are built with a diameter of 4mm² which in increases the DC cable losses.
- Occasionally string cables damaged by sharp edges have been detected.

Impact on Performance

- Soiling losses were determined based on the measurements on site to be 3% on average.
- Based on the simulation, near shading losses are estimated to be 6% at the system level.
- PID loss was determined based on the on-site measurements and can be as high as 26% at the module level. The degradation has already reached advanced stage and reduces the system performance by at least 10%
- 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.

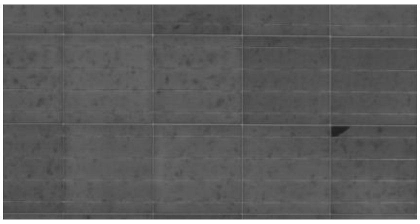

Figure 68: Small cracks at the cell level

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.
- The trees surrounding the system shall be trimmed if allowed. Otherwise, a restringing of the modules shall be conducted in the following way: modules with similar shading conditions shall be installed in the same string or at least assigned to one MPPT.
- The cleaning cycles shall be increased based on the results of a soiling study that adjusts the cleaning needs to each season.
- An anti-PID measure, such as anti-PID box, shall 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 MPPT.
- Covering the ground with white gravel or white paint increases the albedo factor to 0.5, leading to performance boost of approximately 1%.

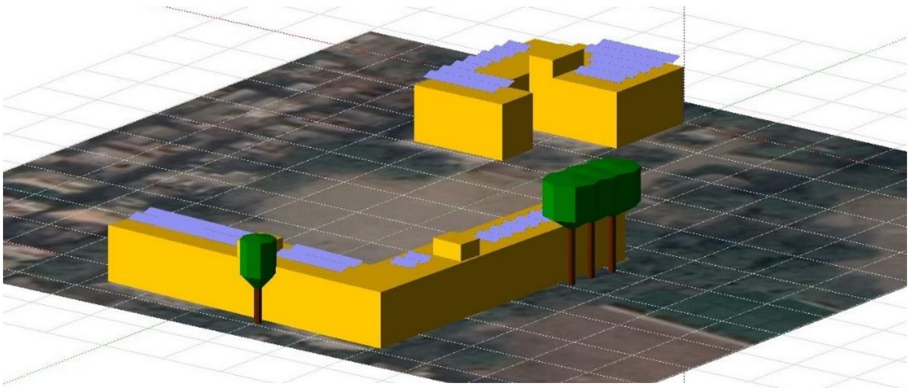

Figure 67: 3D model of the system

Estimated energy boost after conducting the suggested retrofitting actions: 18% to 23%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 0.7 ₹/Wp, 1.2 ₹/Wp/a

Picture Gallery


Figure 69: General view of the system


Figure 70: Foundation of the mounting structure

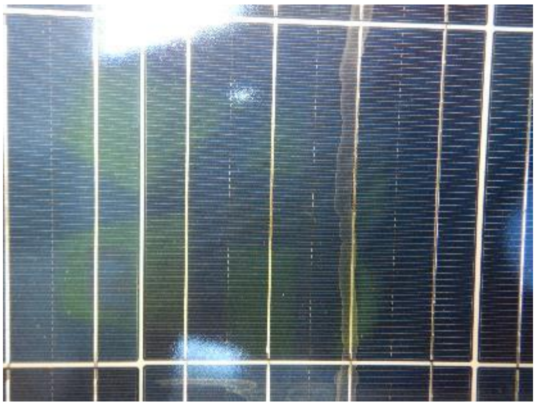
Figure 71: Soil on the module surface


Figure 72: Connectors found disconnected


Figure 73: Poor O&M activities


Figure 74: Cable fixation


Figure 75: Broken module


Figure 76: Damaged cable from sharp edges

6

PV plant: ***II.6***

Nominal capacity: ***27.9 kWp***

Average specific yield since COD (April 2017): ***417 kWh/kWp***

Abstract*: The PV plant is soiled by generator exhaust, bird droppings and foliage. Partial electrical inactivity at the cell level caused by mechanical damages was detected (likely induced during installation and O&M). It is recommended to (i) increase the cleaning cycles, (ii) modify the exhaust direction, (iii) trim the surrounding trees if allowed by the authorities, (iv) resort the modules according to level of mechanical damage and (v) 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 16% and 22%.*

PV Plant's health

Main Findings

- Nearby trees cause significant shading on the system. There is no weather station.

Figure 77: Near shading situation

- Moving between module rows is usually done by crossing over the modules, which often results in modules being stepped on. Since the modules are stepped on, cell damages are inevitable (cracks and broken cells). They could also occur during installation since the access to the roof is difficult.

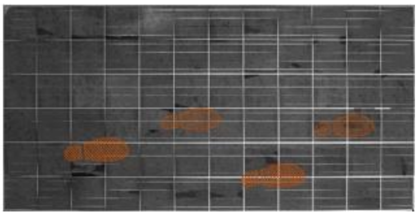

Figure 78: Mechanical damages on modules

- Soiling on the module surface is evident. The system is cleaned only by rain. Due to the flat tilt angle of the modules, the soil accumulates at the bottom edge of the modules causing shading effects.

Impact on Performance

- The simulation shows significant shading losses caused by trees, which are close to 15%.
- Based on the amount of cracks and broken cells and corresponding inactive areas, the power loss is estimated to be 5% at the system level.

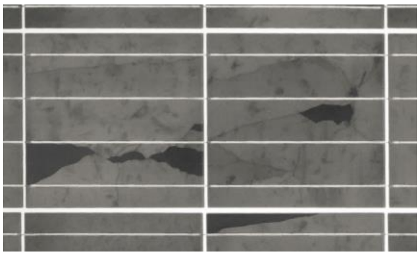

Figure 80: Cracks on a module

- Soiling losses were determined to be 6% on average, based on the measurements on site.

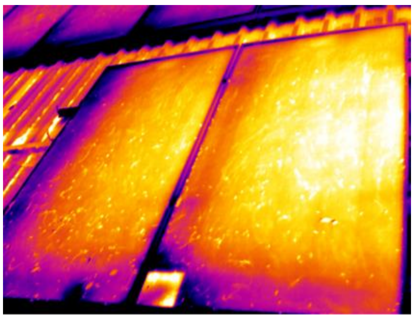

Figure 81: Soiling conditions

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

Figure 79: 3D model of the system

Estimated energy boost after conducting the suggested retrofitting actions: 16% to 22%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 1.6 ₹/Wp, 0.9 ₹/Wp/a

Picture Gallery


Figure 82: Roof on which the system is installed


Figure 83: Access to the system


Figure 84 : Challenging access to the system

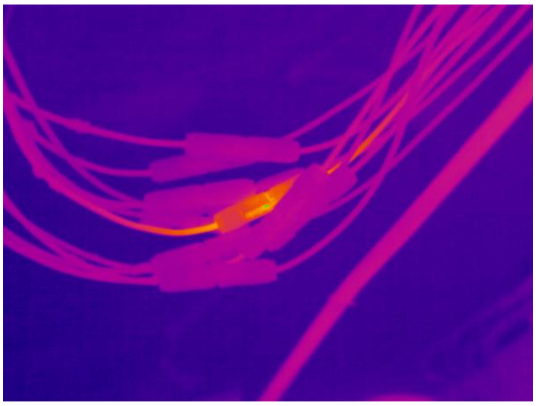
Figure 85: Hot cables at the inverter


Figure 86: Cables exposed to UV radiation


Figure 87: Rusted component of the roof

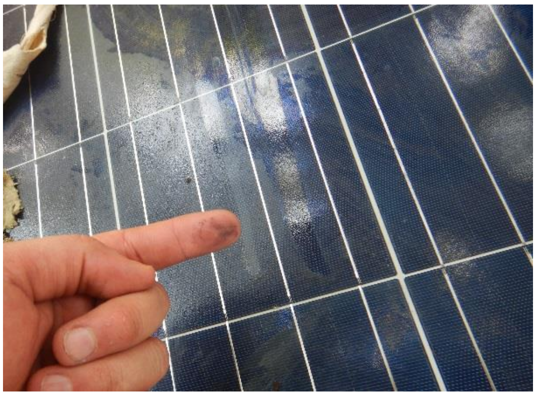
Figure 88: Exhaust residue on the module surface


Figure 89: Diesel exhaust located next to the system

7

PV plant: ***II.7***

Nominal capacity: ***55.8 kWp***

Average specific yield since COD (April 2017): ***896 kWh/kWp***

Abstract*: The PV plant shows moderate levels of soiling caused by dust, bird droppings and foliage. The system design disregarded near shading losses. DC cables lay unprotected on the roof. Significant mechanical damages at the module level were detected. It is recommended to (i) increase the cleaning cycles, (ii) trimming of trees surrounding the system if allowed by the authorities, (iii) drainage maintenance and (iv) restringing of the modules according to the shading situation. The estimated production boost expected by the retrofitting actions lies between 6% and 10%.*

PV Plant's health

Main Findings

- The access to the roof is difficult. This could have caused module damages during handling and installation. The electroluminescense images show a considerable number of cracks, leading to inactive cell areas.

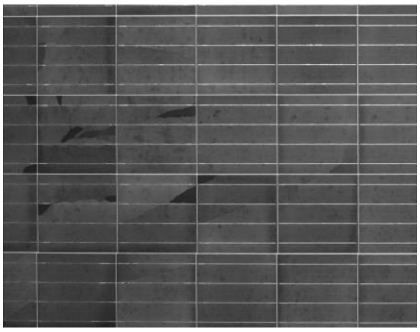

Figure 90: EL image of a module

- The drains are blocked and the cables are exposed to UV radiation. Discoloring of the cables was observed. The cables are not fixed and laid properly. They were seen messily laying on the roof, vulnerable to radiation and mechanical damages.
- Pipes and tubes conveying cables are not sealed, and they are not robust.
- There is no weather station, and hence no PR monitoring.
- Near shading is caused by nearby trees and some of the objects on the roof.

Impact on Performance

- Near shading losses are estimated to be close to 3% on the system level, based on the simulation.

Figure 91: Shading from trees

- Performance losses based on the severity of cell cracks found on site are estimated to be 5% at the system level.
- Soiling losses were determined to be 3% on average, based on the measurements on site.

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.
- The trees surrounding the system shall be trimmed if allowed.
- For the modules shaded by the objects on the roof, a restringing shall be conducted in the following way: modules with similar shading conditions shall be installed in the same string or at least assigned to one MPPT. Otherwise, the objects shall be relocated.
- A manual cleaning of the modules shall be scheduled.
- The cables shall be kept away from possible mechanical damages.

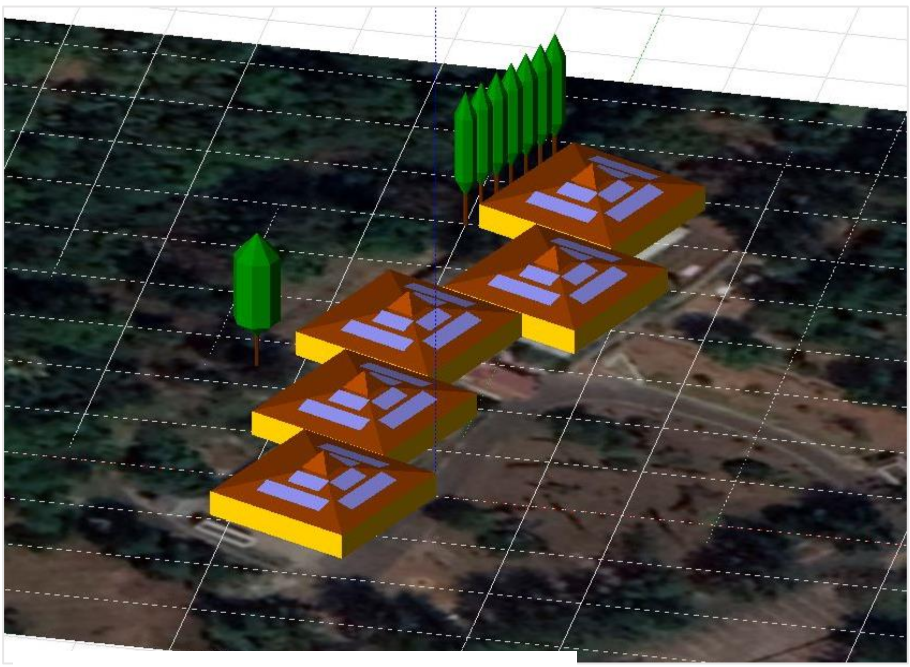

Figure 92: 3D model constructed in PVsyst

Estimated energy boost after conducting the suggested retrofitting actions: 6% to 10%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 0.4 ₹/Wp, 0.5 ₹/Wp/a

Picture Gallery

Figure 93: Access to the system

Figure 94: View of the system

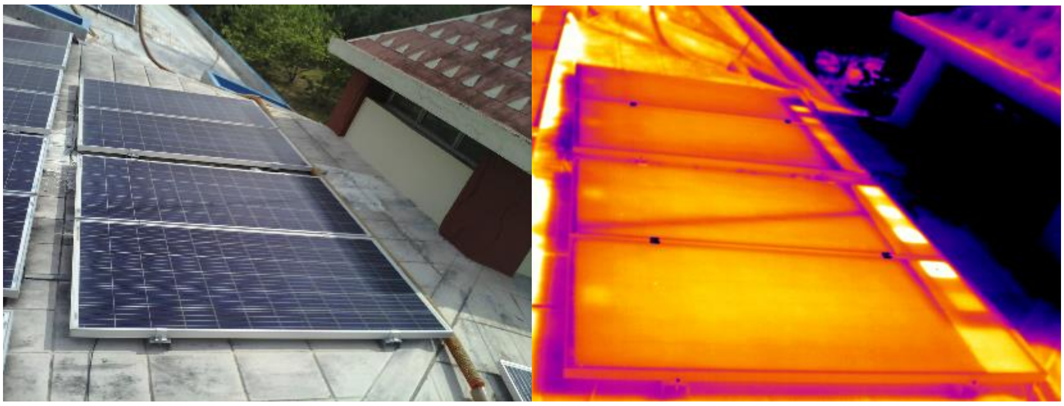

Figure 97: Shading from roof elements (left: real image, right: IR image)

Figure 95: Loose fixation of a module

Figure 96: Connectors and cables exposed to UV

Figure 98: Blocked drainage

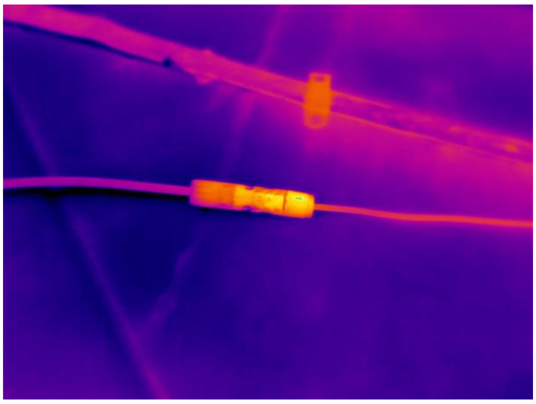

Figure 99: Abnormal temperature of a connector

8

PV plant: ***II.8***

Nominal capacity: ***58.28 kWp***

Average specific yield since COD (April 2017): ***783 kWh/kWp***

***Abstract**: The PV plant shows significant soiling caused by generator exhaust, smog and bird drops. A lack of structural integrity of the sheet metal roofing was detected, the foundations show signs of rust. Cracks of different severities were detected via EL inspection. It is recommended to: (i) conduct a reengineering of the strings according to the shading situation, (ii) increase the cleaning frequency to at least three times per month, (iii) reinforce the rusted metal sheets of the carport and (iv) relocate modules in strings based on the module damages. The estimated production boost expected by the retrofitting actions lies between 13% and 17%.*

PV Plant's health

Main Findings

- The modules are heavily soiled. There is no manual cleaning scheduled.

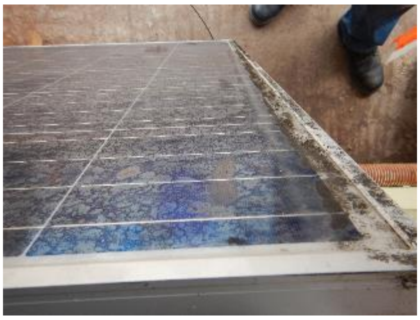

Figure 100: Heavy soiling of the modules

- The soiling is caused by a combination of smog and particles from the exhaust of the generators nearby.
- There is no weather station, and hence no PR monitoring.
- The carport in the parking area, on which part of the PV system is installed, is not stable and the structure is rusty.

Figure 101: Rusty roof

- Cables have been damaged by UV radiation. The pipes conveying the cables are brittle and are partly broken.
- Cracks of different severities were detected via EL inspection.

Impact on Performance

- Soiling losses were determined to be 10% on average, based on the on-site measurements.
- Cell cracks are estimated to result in 7% performance loss at the system level

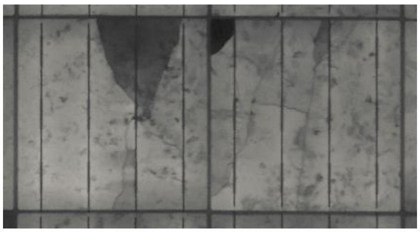

Figure 102: Cracks on a module

- The shading losses caused by the cables and the poles are found to be insignificant based on the simulation.

Figure 103: *Shading from cables and poles*

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 shall be implemented and scheduled based on the results of a soiling study that adjusts the cleaning needs to each season.
- The mounting structure of the carport system shall be reinforced in order to ensure the structural integrity.
- Modules with heavy cracks shall be grouped in the same string or at least assigned to one MPPT. The grouping will be conducted based on infrared inspection with high irradiation levels and after cleaning.
- A restringing of the modules from the shaded areas shall be conducted in the following way: modules with similar shading conditions shall be installed in the same string or at least assigned to one MPPT.

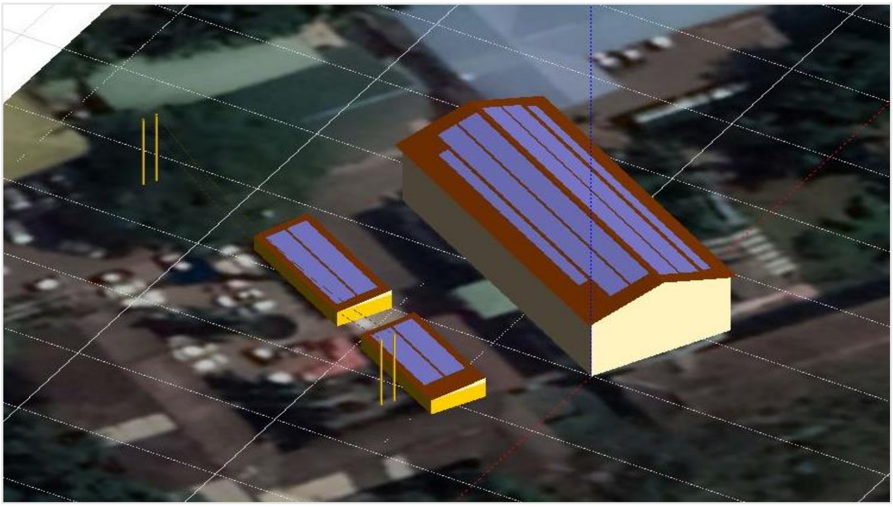

Figure 104: 3D scene

Estimated energy boost after conducting the suggested retrofitting actions: 13% and 17%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 4.8 ₹/Wp, 0.4 ₹/Wp/a

Picture Gallery

Figure 105: View of the system (left and right)

Figure 106: Dirty and clean modules

Figure 107: Broken protective tube

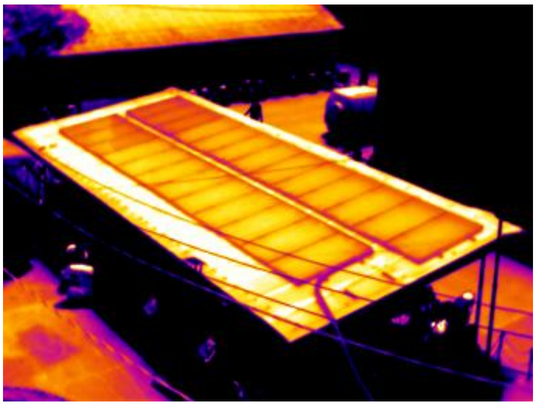

Figure 108: IR image of parking section of the system

Figure 109: Inverters of the system

Figure 110: Examples of poor structural integrity

9

PV plant: ***II.9***

Nominal capacity: ***105.71 kWp***

Average specific yield since COD (April 2017): ***1233 kWh/kWp***

Abstract*: The PV plant shows extreme soiling caused by smog and dust. Lack of structural integrity of the sheet metal roofing and mechanical damages at the module level were also observed. It is recommended to (i) increase the cleaning frequency to at least three times per month, (ii) replace and/or install UV cable protection means (iii) reinforce the structural integrity of the roofing material (iv) rearrange the modules based on the damage categories and (v) restring the circuits based on the shading conditions. The estimated production boost expected by the retrofitting actions lies between 17% and 22%.*

PV Plant's health

Main Findings

- Pipes carrying cables are brittle and some parts have already broken, exposing cables to UV radiation. The colors have already started to fade. Delamination and cell corrosion were observed on the front side of the modules.

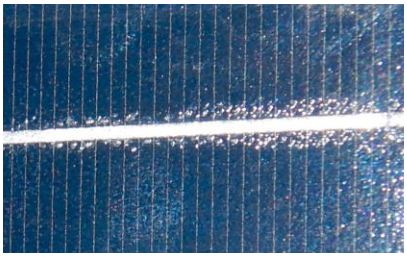

Figure 111: Delamination

- Heavy soiling has been detected on site. The dense traffic (smog) in the street next to the system increases the dust accumulation on the modules.
- There is no weather station in any part of the system and hence, no PR monitoring.
- Electroluminescence imaging confirms the presence of cell damages caused during the installation and O&M activities.

Figure 112: Modules are heavily soiled

- The roof supporting structure is not entirely robust.
- Cables hanging above the system cast shadows onto the modules throughout the day.

Impact on Performance

- Soiling losses in the parking section at the Municipal HQ were calculated in 19% on average.

Figure 113: Severe soiling losses

- The EL images show a few cracks on the inspected modules. This could result in a performance loss of 4% at the system level.

Figure 114: Cracks on a module

- The simulation shows shading losses caused by the cables of 1.5%.

Proposed Solutions

- The structural integrity of the roof shall be reinforced. The cables shall be protected from UV radiation by robust pipes or tubes.
- 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 shall be implemented and re-scheduled based on the results of a soiling study that adjusts the cleaning needs to each season.
- Modules with heavy cracks shall be grouped in the same string or at least assigned to one MPPT. The grouping will be conducted based on infrared inspection with high irradiation levels and after cleaning.
- A regrouping of the modules shall be conducted in the following way: modules with similar shading conditions shall be installed in the same string or at least assigned to one MPPT.

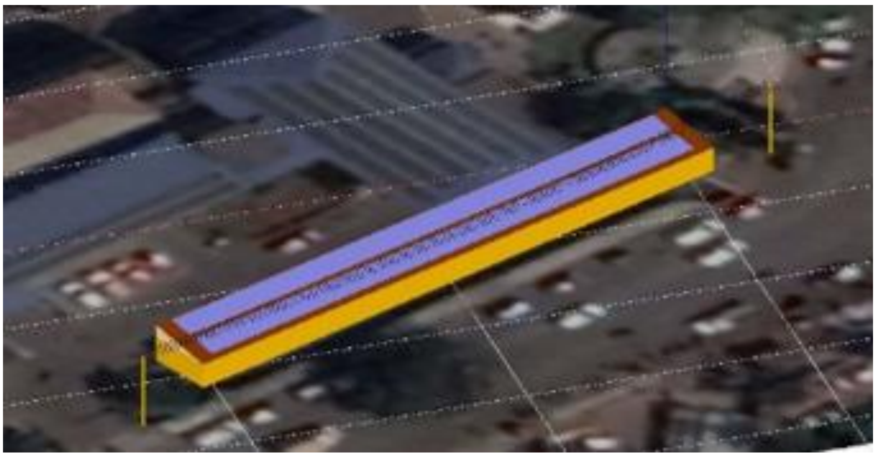

Figure 115: 3D scene

Estimated energy boost after conducting the suggested retrofitting actions: 17% to 22%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 4.4 ₹/Wp, 0.5 ₹/Wp/a

Municipal HQ


Figure 116: View of the system

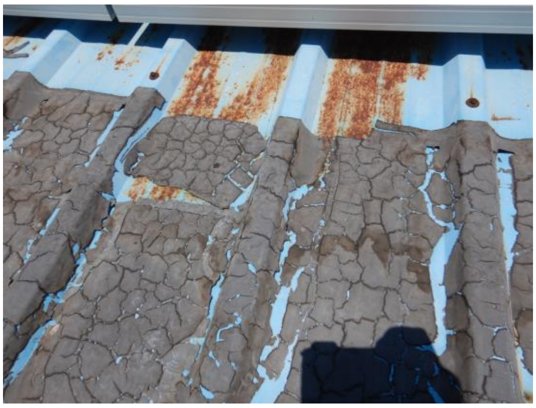
Figure 117: Rusted roof structure

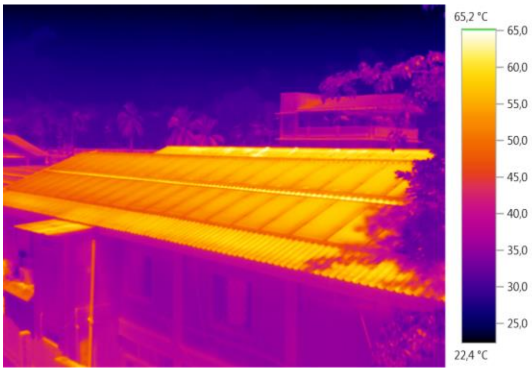
Figure 118: On-site IR analysis


Figure 119: Visual evaluation of modules


Figure 120: On site IV curve measurements


Figure 121: Mechanical damages in module BS


Figure 122: Module cleaning for IV curve test


Figure 123: Connections at the inverter

10

PV plant: ***II.10***

Nominal capacity: ***89.28 kWp***

Average specific yield since COD (2017): ***1173 kWh/kWp***

Abstract*: The PV plant shows moderate levels of soiling caused by dust and bird droppings. Limited access to the system and lack of structural integrity of the sheet metal roofing were also detected. The PV modules show significant mechanical damages at the module level. It is recommended to (i) increase the cleaning frequency to at least twice per month, (ii) replace and/or install a UV cable protection, (iii) reinforce the rooftop structure and replace the rusted fixation elements, and (iv) resort the modules based on the module damages. The estimated production boost expected by the retrofitting actions lies between 8% and 13%.*

PV Plant's health

Main Findings

- The roof structure and its components are rusty, and the roof is not robust.
- There is no weather station, and hence no PR monitoring.
- Pipes carrying cables are brittle and some parts have already broken, exposing cables to weather.
- The modules are considerably soiled.

Figure 124: Heavy soil on the modules

- A significant number of cracks were seen from the EL images, showing considerable amount of inactive areas.

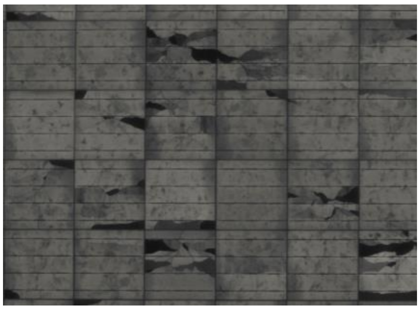

Figure 125: Cracks in a module

Impact on Performance

- Soiling losses were determined to be 4% -6.0%, based on the on-site measurements.
- The performance loss at the module level was determined to be 8% on average, based on the severity of the cell damages discovered via EL imaging and IV curve measurements.
- High module operating temperature (~60°C) results in decrease of the output power, hence efficiency.

Figure 126: NW-SE system orientation

Proposed Solutions

- The cables shall be protected from UV radiation by robust pipes or tubes.
- 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 shall be implemented and scheduled based on the results of a soiling study that adjusts the cleaning needs to each season.
- Modules with heavy cracks shall be grouped in the same string or at least assigned to one MPPT. The grouping will be conducted based on infrared inspection with high irradiation levels and after cleaning. These modules with cracks will be grouped in strings with same MPPT.
- The structural integrity of the roof shall be reinforced.

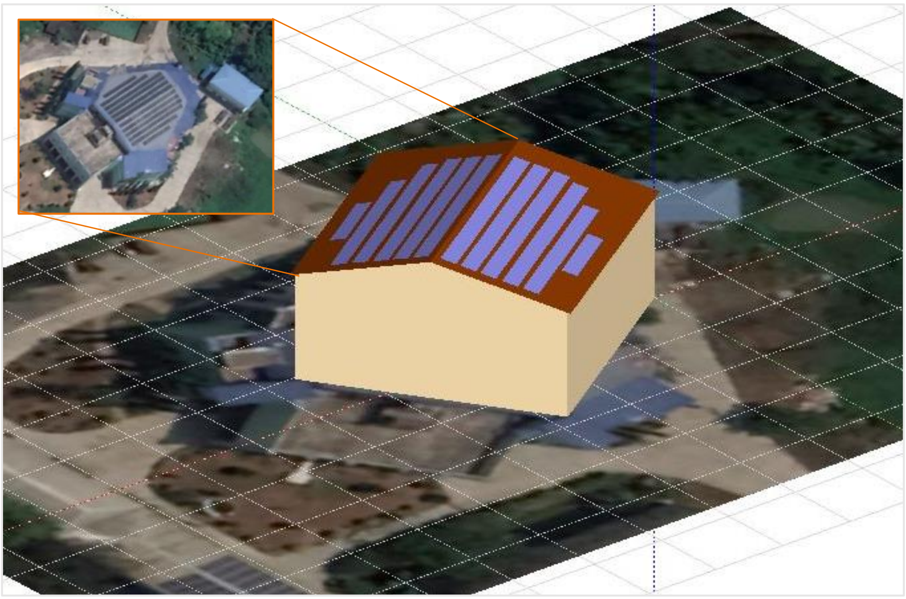

Figure 127: 3D model constructed in PVsyst

Estimated energy boost after conducting the suggested retrofitting actions: 8% and 13%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 4.3 ₹/Wp, 0.6 ₹/Wp/a

Picture Gallery

Figure 128: View of the system

Figure 129: Rusty roof elements

Figure 130: Inverters of the system

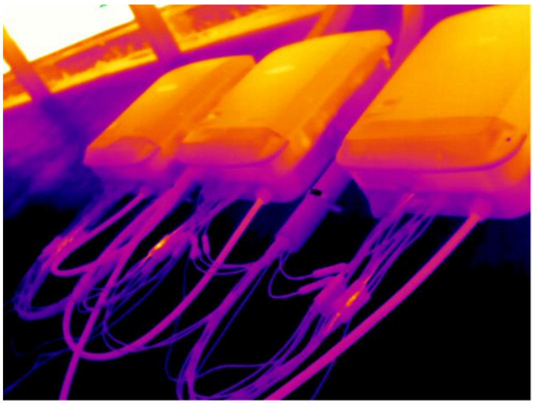

Figure 131: Faulty connections (IR)

Figure 132: Modules installed on metal sheet

Figure 133: Bird drops on module glass

Figure 134: Rusty roof elements

Figure 135: Broken protective conduit

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.

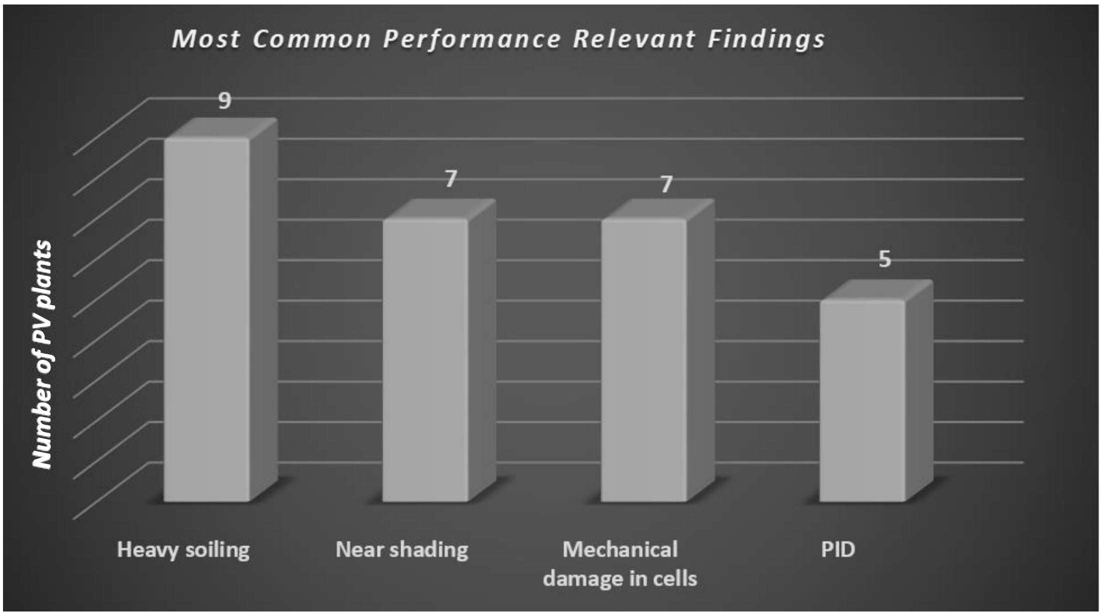

Figure 143: Chart showing in how many PV plants each finding is present (sample: 10 plants)

It can be seen how *heavy soiling* and *near shading* appear in almost all PV plants. The appearance of *Potential Induced Degradation (PID)* in half of the PV plants 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. Finally, *mechanical damages in cells* which is related to the electromechanical integrity of the modules, is a defect that also appears in a large number of sites and is caused by improper module handling during the installation and operation phase[2].

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

[2] *Walking and stepping on the modules also 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 spare parts on site coupled with high reaction times, are two aspects that directly result in loss of availability and therefore in a drop of the yield. 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 regards to the extremely low specific yields recorded in some of the PV plants, it is important to consider that although in some of them less nominal power was installed than initially planned, the calculation of the specific yield is carried out with the latter. This undoubtedly leads to unfairly low performance indicators. The following graph shows which of the 4 findings shown previously has the highest impact on the performance of the inspected PV plants. The graph also indicates the maximum energy loss values associated to each of these findings.[3]

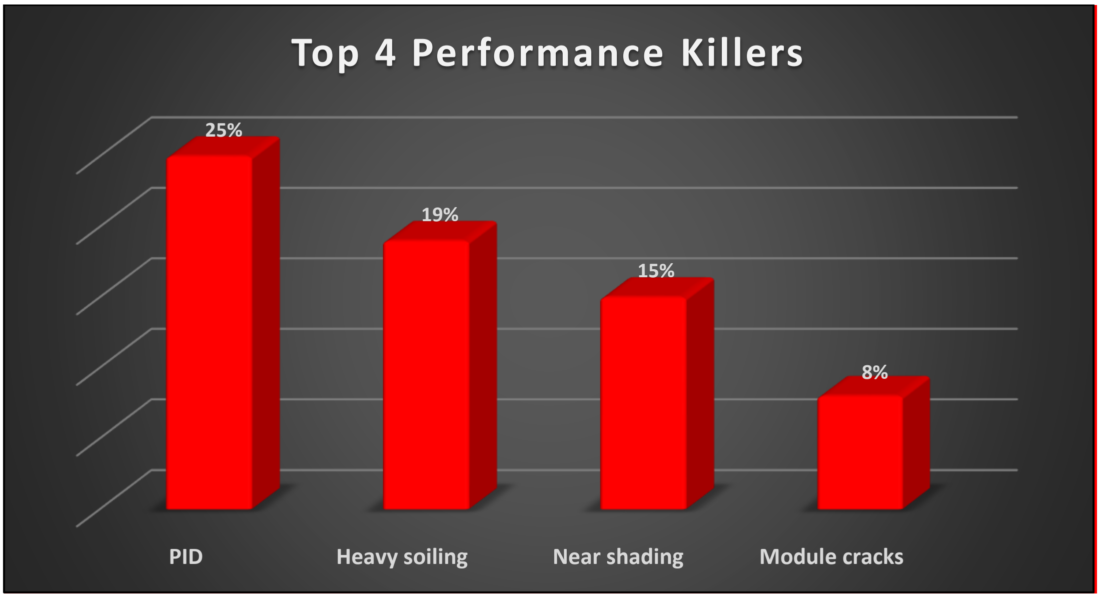

Figure 144: Top 4 findings with the highest performance impact on the inspected PV plants

The graph above shows how an advanced stage of *Potential Induced Degradation (PID)* can lead to a loss of global production at the PV plant level of more than 25%. In some of the analyzed plants, this degradation value has been reached in less than two years[4]. This rapid

[3] These values have been calculated by PI Berlin through (i) estimates based on PI Berlin's long-term experience, (ii) 3D simulation, (ii) processing of data obtained directly on site by means of special equipment.
[4] The PV plant II.4 for instance was connected to the gird in 2017.

degradation is explained by the high PID sensitivity of the PV used modules and the typical hot and humidity conditions in the area where the PV plants 1 to 5 were installed. The presence of bird droppings, debris or pollution, result in soiling losses close to 20% in some of the PV plants. In this regard, it is important to bear in mind that some PV plants visited by PI Berlin underwent a natural cleaning a few days before by means of a rainfall that likely removed part of the accumulated dirt on the modules. The values measured on site by PI Berlin can therefore be greatly exceeded during the dry season.

According to PI Berlin calculations, the global losses at the PV plant level caused by *PID* exceed 25% in 2 years, while the losses associated with soiling can widely exceed 19% in the dry season.

The losses caused by *near shading* are estimated in some of the inspected PV plants at around 15%. These losses are difficult to avoid since they are due to constraints caused by buildings and vegetation which should have been properly addressed during the design phase. The 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% accoring to PI Berlin's estimations.

In some of the inspected PV plants, the losses caused by *near shading* exceed 15% according to PI Berlin's estimations. In PV plants with severe *mechanical damage* at the module level, the nominal power of the PV plant can be reduced by up to 8%.

These mechanical damages are in all cases caused by mishandling of the modules during the installation and O&M phase. Unfortunately, since the warranties offered by the installation company are limited to the product and do not include workmanship and in some cases the EPC warranty has also expired, the damages resulting from mishandling during the installation remain contractually uncovered.

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

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

Re-sorting of modules and strings. A re-sorting of the modules shall be conducted in those cases where the present configuration leads to significant mismatch at inverter level or to low output currents of some strings due to the low performance of individual modules. Modules affected by 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.

Increasing of the module cleaning frequency. The source of soiling in most of the inspected PV plants is either bird droppings, pollution, debris or a combination of all three. In order to figure out what the optimum cleaning interval is, the output of clean[5] and dirty strings shall be compared for at least 3 months. As soon as the difference in the output leads to a loss of revenue that offsets the cleaning costs of the whole plant, a cleaning visit will be needed. This study will be performed separately for the dry and rainy season, as natural cleaning comes into place in the rainy months. Cleaning becomes particularly relevant in those plants where the modules are mounted with very flat angles.

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

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

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

Increase of the albedo factor. It is recommended to cover or paint the ground with white gravel or light colors and stick reflective materials to the walls and shading objects surrounding the PV modules. These measures aim at increasing the overall albedo factor to 0.5 and thus, the amount of kWh/m² reaching the PV module surface. Glaring of 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 6% and 39%. These actions do not require large investments in the OPEX.

Besides the retrofitting actions needed to increase the energy generation, any necessary improvements to operate the PV plants in a safe environment shall also be carried out. These improvements shall be conducted regardless how high the estimated performance boost is[6].

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

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

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

[6] *An example of this is the reinforcement of the rooftop structures or the installation of overvoltage protection.*

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

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

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

Literature and References

[1] Photon International; June 2017

[2] pv magazine; April 2017

[3] "How soiling and cleaning impact module performance in deserts"; Ferretti N., Berghold J.; December 2015.

[4] "Influence of cleaning using water and surfactants on the performance of photovoltaic panels"; Moharram Ka, Abd-Elhady MS, Kandil Ha, El-Sherif H.; Energy Convers Manag 2013;68:266–72.

[5] "Influence of micro cracks in multi-crystalline silicon solar cells on the reliability of pv modules"; Grunow P. et al.; 20th European Photovoltaic Solar Energy Conference, 6 –10 June 2005, Barcelona, Spain.

[6] "Dynamic mechanical load tests on crystalline silicon modules"; Koch S. et al; 25th European Photovoltaic Solar Energy Conference and Exhibition/5th World Conference on Photovoltaic Energy Conversion, 6-10 September 2010, Valencia, Spain.

[7] "Investigation on performance decay on photovoltaic modules: snail trails and cell microcracks"; Dolara A. et al; IEEE Journal of photovoltaics, vol. 4, no. 5, September 2014.

[8] "Impact of micro-cracks on the degradation of solar cell performance based on two-diode model parameters"; Van Mölken J. I. et al; SiliconPV: April 03-05, 2012, Leuven, Belgium.

[9] "Cable care"; PV Magazine; issue 05-2013, 3rd May 2013.

[10] "A Comprehensive Review of the Impact of Dust on the Use of Solar Energy: History, Investigations, Results, Literature, and Mitigation Approaches". Renewable & Sustainable Energy Reviews 22 (2013): 698-733. Sarver, Travis, Ali Al-Qaraghuli, and Lawrence L. Kazmerski; June-July 2014.

[11] Performance and Reliability of Photovoltaic Systems - Subtask 3.2: Review of Failures of Photovoltaic Modules - IEA PVPS Task 13 External final report IEA-PVPS (March 2014)

[12] Munoz et.al; An Investigation into Hot-Spots in Two Large Grid-Connected PV Plants

[13] "Manual of good and bad practices to improve the quality and reduce the cost of PV systems"; PV Crops; 2013.

[14] "Review of failures of photovoltaic modules"; IEA - International Energy Agency; Report IEA-PVPS T13-01:2014.

[15] "Investigations on crack development and crack growth in embedded solar cells"; M. Sander, S. Dietrich, M. Pander, and M. Ebert, S. Schweizer, J. Bagdahn; Proc. Reliability of Photovoltaic Cells, Modules, Components, and Systems IV, 81120I (SPIE, San Diego, California, USA, 2011), doi:10.1117/12.893662).

[16] "Quality in India: battling the stereotypes"; pv tech; September 2017

[17] "World Map of the Köppen-Geiger climate classification updated"; Biometeorology Group, University of Veterinary Medicine Vienna, Vienna, Austria; Global Precipitation Climatology Centre, Deutscher Wetterdienst, Offenbach, Germany; 2006

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

Annex I – IV Curve Tracing Results

Site	Module No.	Meas. No.	Pmax (P)	Voc (V)	Vmpp (V)	Impp (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**	1	253.3	44.0	34.2	7.4	8.5	1045	61	68	Dirty	8.96	1022	7060	
1	**1**	5	253.3	43.8	33.9	7.5	8.5	972	58	68	Clean	8.60	970	7060	-13.9%
1	**2**	2	269.7	44.1	34.9	7.7	8.3	938	61	73	Dirty	7.90	940	7069	
1	**2**	6	272.1	44.1	35.3	7.7	8.4	1019	62	74	Clean	8.83	1030	7069	-7.6%
1	**3**	3	213.5	43.0	31.9	6.7	8.4	873	59	59	Dirty	7.70	904	7065	
1	**3**	7	217.7	42.9	31.9	6.8	8.4	1010	60	61	Clean	8.82	1019	7065	-26.0%
1	**4**	4	270.7	44.0	35.1	7.7	8.3	860	59	74	Dirty	7.50	880	7068	
1	**4**	8	271.7	43.9	34.6	7.9	8.5	973	61	73	Clean	8.42	960	7068	-7.7%
3	**1**	9	218.0	43.6	31.4	6.9	8.5	684	36	59	Dirty	7.20	850	7100	
3	**1**	12	235.6	43.3	32.5	7.2	8.7	1188	37	62	Clean	10.38	1173	7100	-25.7%
3	**2**	17	241.2	43.7	33.8	7.1	8.6	1173	48	65	Dirty	9.07	932	7094	
3	**2**	19	240.0	44.3	32.2	7.5	8.8	744	37	61	Clean	4.77	538	7094	-24.3%
3	**3**	20	281.8	44.7	35.7	7.9	8.4	1000	41	75	Dirty			7095	
3	**4**	21	281.5	44.9	35.7	7.9	8.3	955	36	75	Dirty			7089	
3	**4**	22	280.1	44.8	35.5	7.9	8.4	939	36	75	Dirty			7089	
4	**1**	23	151.2	38.2	24.1	6.3	8.2	970	55	48	Dirty	8.64	960	7108	
4	**1**	29	137.1	37.0	23.6	5.8	8.3	859	47	45	Clean	8.22	933	7108	-56.7%
4	**1**	30	142.6	37.3	23.9	6.0	8.1	977	47	47	Clean			7108	-55.0%
4	**2**	24	168.8	40.6	27.3	6.2	8.5	988	52	49	Dirty	8.62	980		
4	**2**	31	141.9	39.5	28.9	4.9	6.2	976	51	58	Clean	8.21	979		-55.2%
4	**3**	25	112.2	41.7	33.0	3.4	5.5	934	47	49	Dirty	5.30	973		
4	**4**	26	283.0	44.4	35.5	8.0	8.6	912	52	74	Dirty	8.81	990		
4	**4**	32	285.4	44.7	35.5	8.0	8.5	991	51	75	Clean	8.82	991		-9.9%
4	**5**	27	288.0	44.5	35.1	8.2	8.7	961	55	75	Dirty	8.99	981		
4	**5**	33	288.3	44.9	36.4	7.9	8.5	992	52	75	Clean	8.52	992		-9.0%
4	**6**	28	286.2	44.2	34.8	8.2	8.7	940	57	74	Dirty	9.01	1003		
4	**6**	34	281.3	44.3	35.4	8.0	8.5	1000	53	75	Clean	8.75	1001		-11.2%
4	**6**	35	280.8	44.3	35.2	8.0	8.5	997	53	74	Clean				-11.4%
5	**1**	36	278.5	44.1	35.5	7.9	8.4	963	55	75	Dirty	8.51	965	7110	
5	**2**	37	280.6	44.4	35.5	7.9	8.3	955	55	76	Dirty	8.47	945	7116	
5	**2**	44	287.4	44.7	35.6	8.1	8.6	1011	51	75	Clean	9.03	1020	7116	-9.3%
5	**2**	45	288.2	44.6	35.6	8.1	8.6	1010	51	75	Clean			7116	-9.1%
5	**3**	38	281.7	44.5	35.7	7.9	8.4	992	53	75	Dirty	8.33	965		
5	**4**	39	274.8	44.1	35.3	7.8	8.3	970	55	75	Dirty				
5	**5**	40	280.7	44.2	35.2	8.0	8.5	1010	58	75	Dirty	8.33	965	7122	
5	**5**	46	288.6	44.8	35.9	8.1	8.5	993	51	75	Clean	8.70	994	7122	-8.9%
5	**5**	47	288.0	44.7	35.9	8.0	8.6	996	51	75	Clean			7122	-9.1%
5	**6**	41	282.2	44.4	35.5	7.9	8.6	995	59	74	Dirty	8.70	999	7120	
5	**7**	42	283.7	44.9	35.9	7.9	8.5	1003	59	74	Dirty	8.78	1001		
5	**7**	43	282.9	44.8	35.9	7.9	8.5	1002	59	74	Dirty				
6	**1**	48	268.7	44.0	35.0	7.7	8.3	959	52	74	Dirty	8.00	952	7126	
6	**1**	57	303.2	46.1	37.3	8.1	8.6	928	45	76	Clean	8.04	926	7126	0.8%
6	**1**	58	296.6	45.5	36.6	8.1	8.6	936	45	76	Clean			7126	-1.4%
6	**2**	49	275.5	44.7	36.7	7.5	8.2	959	45	75	Dirty	7.35	964	7125	
6	**2**	53	290.1	44.8	36.1	8.0	8.6	957	45	76	Clean	8.27	950	7125	-3.5%
6	**3**	50	277.1	44.6	35.8	7.7	8.3	967	43	75	Dirty	8.21	968	7129	
6	**3**	51	274.9	44.5	35.5	7.7	8.3	966	43	75	Dirty			7129	
6	**3**	55	294.8	45.2	35.9	8.2	8.7	939	42	75	Clean	8.32	934	7129	-2.0%
6	**3**	56	290.0	44.9	36.0	8.1	8.7	939	45	75	Clean			7129	-3.6%
6	**4**	52	272.8	44.8	35.6	7.7	8.2	971	43	75	Dirty	7.94	968	7127	
6	**4**	54	284.4	44.8	36.0	7.9	8.6	937	43	74	Clean	8.23	942	7127	-5.4%
7	**1**	59	265.4	43.0	33.7	7.9	8.5	950	60	72	Dirty	8.42	960	7135	
7	**1**	63	279.8	44.1	34.6	8.1	8.7	954	47	73	Clean	8.49	953	7135	-7.0%
7	**2**	60	264.6	44.1	34.4	7.7	8.3	965	53	72	Dirty	8.43	963	7138	
7	**2**	66	274.7	44.6	35.5	7.7	8.6	950	48	72	Clean	8.25	953	7138	-8.7%

Site	Module No.	Meas. No.	Pmax (P)	Voc (V)	Vmpp (V)	Impp (A)	Isc (A)	Irr. (W/m²)	Module Temp. (°C)	FF	Status	Isc (A)	Irradiation (W/m²)	EL Pic. No.	ΔP from Min. Expected
7	**2**	67	275.1	44.4	34.8	7.9	8.6	947	48	72	Clean			7138	-8.5%
7	**3**	61	280.1	45.2	37.0	7.6	8.4	964	53	73	Dirty	8.50	966	7137	
7	**3**	68	286.3	45.0	35.9	8.0	8.6	949	46	74	Clean	7.88	952	7137	-4.8%
7	**3**	69	284.0	44.8	35.6	8.0	8.6	947	46	74	Clean			7137	-5.5%
7	**4**	62	294.6	45.7	36.5	8.1	8.6	962	52	75	Dirty	8.31	960	7132	
7	**4**	64	296.6	45.1	36.2	8.2	8.7	954	44	75	Clean	8.42	953	7132	-1.4%
7	**4**	65	293.9	44.9	35.9	8.2	8.7	954	44	75	Clean			7132	-2.3%
8	**1**	70	256.5	43.6	35.1	7.3	7.6	1101	55	78	Dirty	8.08	1041	7143	
8	**1**	76	285.8	44.7	35.7	8.0	8.6	1027	44	74	Clean	9.30	1076	7143	-5.0%
8	**2**	71	244.3	42.9	35.1	7.0	7.6	1013	51	75	Dirty	7.73	999	7141	
8	**2**	75	254.3	43.4	35.6	7.1	8.2	1047	48	72	Clean	8.95	1055	7141	-15.4%
8	**3**	72	254.6	44.1	36.2	7.0	7.3	1008	52	79	Dirty	8.15	1044	7145	
8	**3**	79	284.0	44.9	36.1	7.9	8.4	1030	42	75	Clean	8.50	995	7145	-5.6%
8	**3**	80	282.4	44.8	36.3	7.8	8.5	1041	42	75	Clean			7145	-6.1%
8	**4**	74	256.2	44.1	36.1	7.1	7.5	1056	50	77	Dirty	8.25	1050	7148	
8	**4**	77	283.0	44.8	35.5	8.0	8.5	994	50	74	Clean	8.50	995	7148	-5.9%
8	**4**	78	282.6	44.7	35.2	8.0	8.5	986	50	74	Clean			7148	-6.0%
9	**1**	81	237.2	43.4	35.4	6.7	7.2	566	57	76	Dirty	2.56	553	7149	
9	**1**	82	229.5	43.5	35.2	6.5	6.8	562	57	78	Dirty	4.68	540	7149	
9	**1**	85	288.7	44.5	36.2	8.0	8.6	537	43	75	Clean			7149	-4.0%
9	**1**	86	290.4	44.4	36.2	8.0	8.7	532	43	75	Clean	4.63	547	7149	-3.4%
9	**2**	83	230.5	43.5	36.0	6.4	7.0	525	47	75	Dirty	2.65	434	7152	
9	**2**	84	229.5	43.5	35.9	6.4	7.0	531	47	75	Dirty			7152	
9	**2**	87	281.6	44.6	36.4	7.7	8.4	499	42	75	Clean	4.01	480	7152	-6.4%
9	**2**	88	278.6	44.6	36.7	7.6	8.3	490	42	75	Clean	3.99	475	7152	-7.4%
9	**2**	89	280.2	44.5	36.7	7.6	8.4	483	42	75	Clean	3.85	463	7152	-6.8%
10	**1**	90	259.1	43.8	36.0	7.2	8.0	719	54	74	Dirty	6.15	726	7155	
10	**1**	94	276.7	44.5	35.8	7.7	8.4	779	48	74	Clean	6.79	773	7155	-8.0%
10	**1**	95	274.4	44.4	35.6	7.7	8.4	774	48	74	Clean			7155	-8.7%
10	**2**	91	260.2	43.9	34.7	7.5	8.0	630	50	74	Dirty	5.64	666	7161	
10	**2**	96	273.8	44.4	35.0	7.8	8.4	776	46	74	Clean	6.13	767	7161	-9.0%
10	**2**	97	272.2	44.2	34.7	7.8	8.4	772	46	73	Clean			7161	-9.5%
10	**3**	92	273.3	45.0	35.9	7.6	8.1	810	48	75	Dirty	5.06	756	7157	
10	**3**	98	284.0	45.0	36.2	7.9	8.5	805	48	74	Clean	5.91	784	7157	-5.6%
10	**3**	99	278.0	44.9	36.3	7.7	8.3	820	48	75	Clean			7157	-7.5%
10	**3**	100	275.0	44.7	35.8	7.7	8.2	777	48	75	Clean			7157	-8.6%
10	**4**	93	268.8	44.5	36.2	7.4	8.1	743	46	75	Dirty	6.25	752	7156	
10	**4**	101	280.7	44.7	35.9	7.8	8.6	814	48	73	Clean	6.10	742	7156	-6.7%
10	**4**	102	273.5	44.7	35.2	7.8	8.4	801	48	73	Clean			7156	-9.0%
10	**4**	103	276.2	44.5	35.4	7.8	8.6	807	48	72	Clean			7156	-8.2%

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					

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

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

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

Annex IV – Measurement Equipment used on Site

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

Figure 116: HT SOLAR-IV IV curve tracer [source: pv-engineering]

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

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

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

Figure 138: Infrared camera [source: Testo]

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

Figure 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