PID issues in thin-film PV plants

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Abstract

Thin-film plants which were installed within the past 10 years have been known to suffer from quality issues such as underperformance and poor module quality. Potential-induced degradation could be identified as one of the major defect types, which sometimes results in an underperformance far beyond the warranty terms. Affected projects end up in legal confrontations and quite often require technical experts to evaluate the situation and to determine and validate the failure. Finally, in many cases the modules must be replaced. In recent years, results of PID-affected PV plants have been collected by the authors showing underperformance. Results of three investigated plants are presented in which the performance of the technologies CIGS, CdTe and μc-Si was studied. Investigation and characterization in the field and in the laboratory, including PID tests, were performed. The CdTe modules during field investigations show a clear degradation towards the negative string end. The PID test proved their sensitivity to the phenomenon and revealed TCO-corrosion. For μc-Si TF modules a PID sensitivity could also be proven but here the power evaluation and failure distinguishing to the "white spot" phenomenon was challenging. The CIGS modules under investigation showed also a very clear PID degradation towards the negative string end which could be proven by PID tests and electroluminescence on complete strings in the laboratory.

Introduction

Nowadays, there is a worldwide production capacity of about 5GW of thin-film module technology. In total, an estimated cumulative installed capacity of 15 to 24GW exists (5-8% of 300GW installed worldwide in 2016). Thin-film plants which were installed within the past 10 years have been known to suffer from quality issues like underperformance and poor module quality. PID could be identified as one of the major defect types, sometimes resulting in an underperformance far beyond the warranty terms. Affected projects end up in legal confrontations and quite often require technical experts to evaluate the situation and to determine and validate the failure. Finally, in many cases the modules must be replaced.

This work does not focus on the development of a thin-film test standard [1,2] or the mechanisms behind PID in thin-film modules [3-6]. When results of TF PID were presented in the past, they almost always focused on results gained in the laboratory. In this work, the authors present real data gathered from the field compared with results from the same test specimen generated in the lab. This approach gives the opportunity to validate the outdoor results and to deepen the investigation of supposed findings.

First, a definition of the terms and methods related to PID for thin film is essential. "Voltage potential that exists between the active circuit and the grounded module surfaces can lead to module degradation by multiple mechanisms including ionic transport in the encapsulant, superstrate or substrate; hot carriers in the cell; redistribution of charges that degrade the active layer of the cell or its surfaces; failure of adhesion at interfaces, and corrosion of module components. These degradation mechanisms in thin-film modules caused by voltage stress and promoted by high temperature and humidity have been labelled potential-induced degradation, polarization, electrolytic corrosion, bar-graphing [, TCO-corrosion,] and electrochemical corrosion. They are most active in wet or damp environments and in environments prone to soiling of modules with conductive, acidic, caustic, or ionic species that lead to increased conduction on the module surfaces. In the field, modules have been observed to degrade in positive as well as negative polarity strings depending on the cell construction, module materials, and design [2]." The cited paragraph is out of the technical specification for TF PID testing (IEC TS 62804-2). This specification describes the test methods to determine module PID susceptibility under positive and negative bias directions. Correlating stress levels from tests to PID durability in a natural environment is important but a completely different topic [4,7].

In recent years, the results of PID-affected PV plants were gathered by the authors showing underperformance. Results of three investigated plants are presented in which the performance of the technologies CIGS, CdTe and μc-Si was studied. Investigation and characterization in the field and in the laboratory as well as PID tests were performed.

Methodology

Once in operation, PV plants have to be regularly inspected and tested to ensure reliable and safe operation and that the investment is providing the expected revenue and is operating in a safe and reliable manner. The operation and maintenance (O&M) teams and the installed monitoring systems are able to provide the first indications of performance ratio (PR) losses. In-depth analysis is necessary to address the origin of the failures. For this purpose, usually external experts are commissioned to work in the field for troubleshooting and to advise the plant owners. The objective is to develop the best approach to solve the issues. The variety of services inter alia range from monitoring data and PR analysis, data monitoring, documentation check, on-site inspections and module selection for laboratory testing. For the PV plants considered in this work, all of these

	I	II	III	
Technology	CIGS	CdTe	µc-Si	
Plant age in years		4	6	2
Size in MW	21	2.3	2.0	
Nominal Module-Power in W		105 & 110	67.5	128
Grounding Instruction		None, APT (Anti PID Technology)	None, not specified	Neg.-pole grounding

Table 1. Overview of the PV plants investigated.

approaches were used to get a complete overview. With the focus on PID-analysis on thin film within this work, only a selection of results gathered during on site inspections and laboratory testing at module level are presented. The results in this work are not representative for a general statement of the quality of a particular module type, manufacturer or technology.

To investigate the modules on-site, engineers conduct IV-curve tracing at module and string level, infrared thermal imaging and electroluminescence tests. Visual inspections also play an important role to evaluate the current status and workmanship of the plants. For the PV plants presented here, the following measurement equipment was used:

- Power measurements were performed with a calibrated HT I V400 peak power measuring device and IV-curve tracer with a measurement uncertainty of +/-5%), including calibrated irradiation and temperature sensors for corrections to STC conditions;
- By means of an electroluminescence (EL) camera EL pictures were taken to visualize module failures like shunts and inactive areas. The modules were powered string-wise with the short circuit current. Further information can be found elsewhere [8,9].

In PI Berlin's accredited test laboratory (ISO 17025) tests are performed according to IEC 61646 Ed.2.0 (2008) and 61215-X Ed.1.0 (2016) [10,11] and beyond. The PID tests were conducted according to TS 62804-2 TF (simulating the original mounting construction and applying maximum system voltage in a climate chamber of 85°C and relative humidity of 85%). They were divided in the categories of sensitivity test (selection of non-affected modules), risk assessment (selection of medium-affected modules) and recovery tests (selecting strongly degraded modules with an application of reverse voltage). Before and after each exposure the IV curves have been recorded using a Class AAA flasher Pasan SSIIIb. The maximum power (Pmax) has been extracted from the IV curve under standard test conditions (STC). The measurement uncertainties are ±2.9% for single junction (CdTe and CIGS) and ±5% for double junction (µc-Si). Furthermore, visual and EL inspections were performed before and after

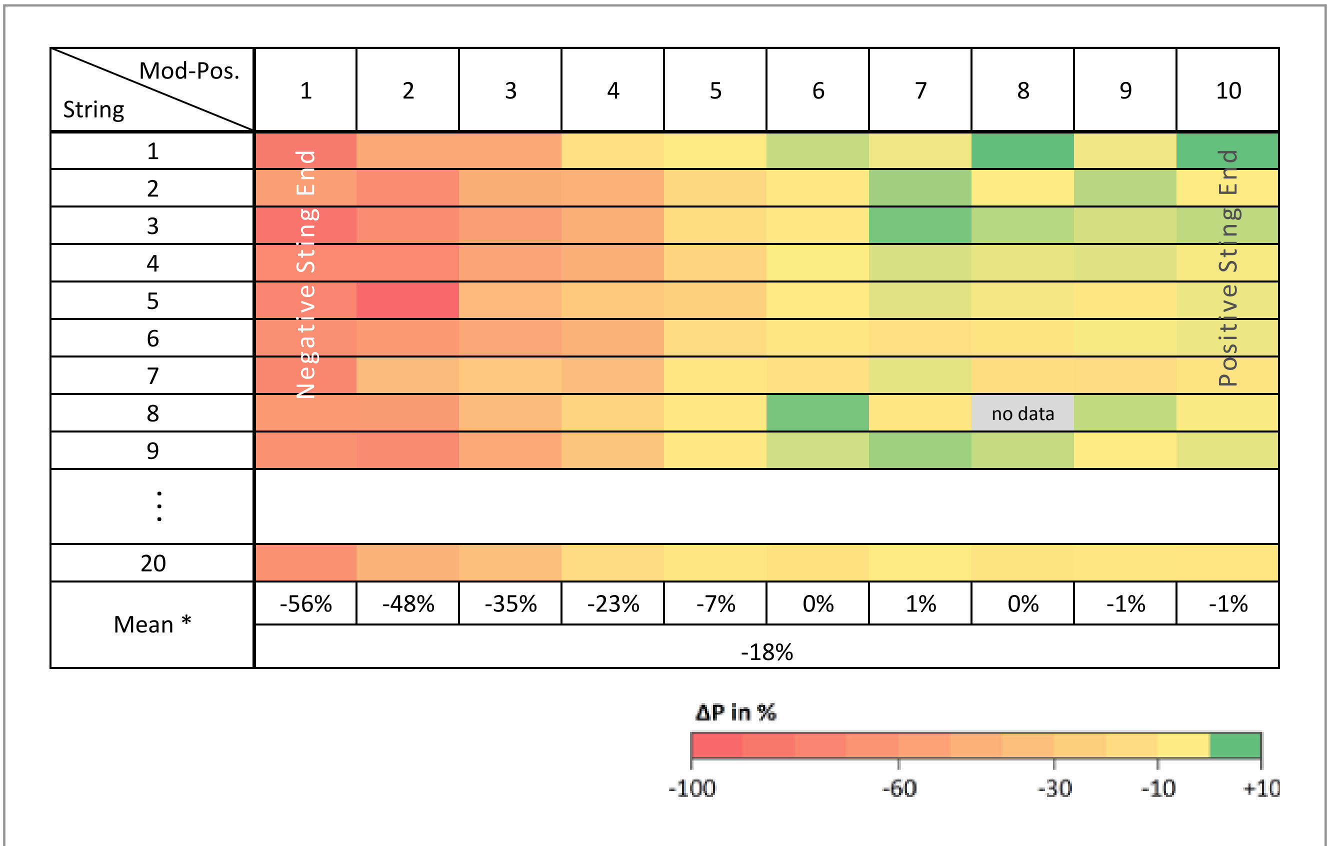


Figure 1. Degradation of power output (compared to label) string-wise for the CIGS plant. Mean power deviations were determined for the marked sections and below for all tested modules.

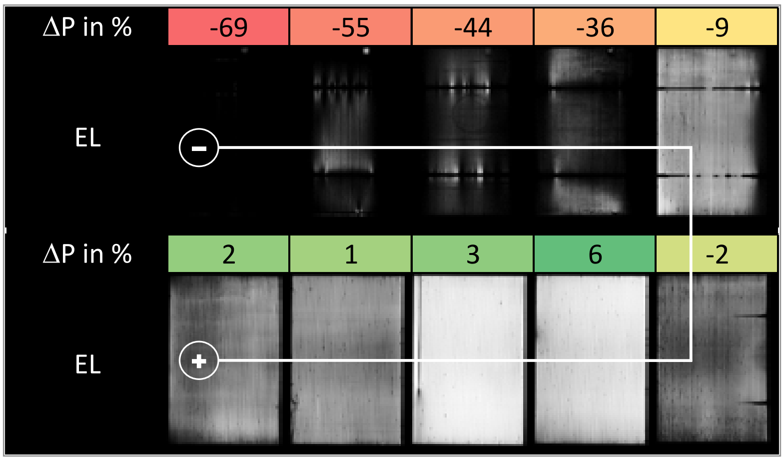


Figure 2. Module power output degradation and corresponding EL pictures for modules of one investigated string. Left top side negative end of the string and left bottom side positive end.

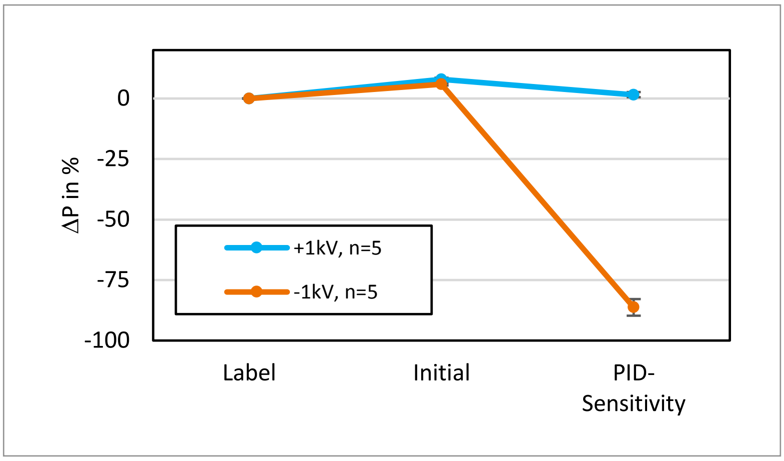


Figure 3. Module power evolution for PID-sensitivity tests. Blue +1kV and orange -1kV PID-Sensitivity tested for 96 hours.

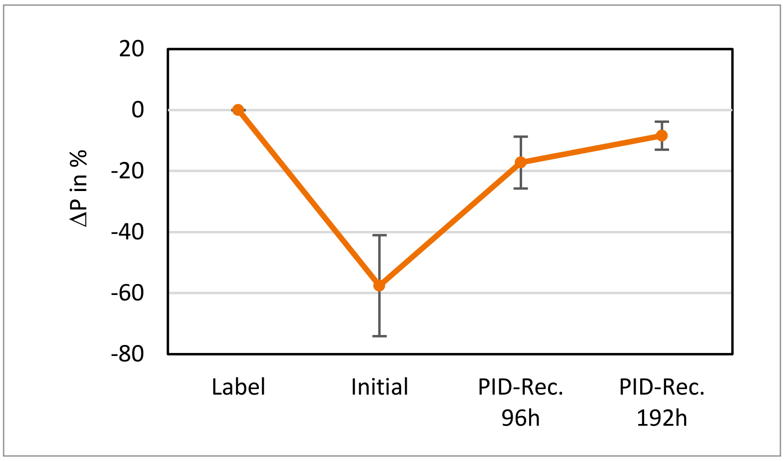


Figure 4: Module power output evolution during the PID-Recovery Tests determined as mean value of 15 modules.

the stress tests to evaluate the results [8]. A Nikon D800 camera, with removed IR-filter with a high-sensitivity 36 megapixel CCD-chip and a 50 mm f/1.4 high-precision IR-optimised optic from Zeiss, was used.

Three different TF PV plants with CIGS, CdTe and microcrystalline silicon tandem (μc-Si) module technologies were selected. For a short overview, basic parameters of each site can be found in Table 1. All plants are ground-mounted installations and located in central Europe.

Results and discussion

Plant I (CIGS)

For the laboratory investigation, 20 complete strings of 10 modules were selected randomly out of the power plant to ensure a representative result distribution. Figure 1 shows the power output measurement results string-wise of all modules. The deviations of the module performance were determined by a comparison of the measured results with the nominal value. In the result presentation of Figure 1, the colour code ranges from green, representing compliance of guaranteed performance values, over yellow and orange to red, which indicates the modules with the lowest residual power output. One can see that all strings show degradation in a few modules up to -40% to -90%. If one looks at the individual string and correlates the power loss to the module position in the string, it can be seen that modules at the negative string end degrade most (see Figure 2). The corresponding EL pictures confirm the results with increasing inactive cell areas by a darkening of the cells towards the negative string end. These evenly distributed results lead to the suspicion of a potential-induced degradation as the main reason for the power deviation.

To verify this suspicion, PID tests were performed to evaluate the modules in terms of general susceptibility, further risk during operation and regeneration potential. The sensitivity tests were each carried out with five modules per polarity. Only the least affected modules were selected for the 96 hour-long PID test. Figure 3 shows the results. The module's power output evolution is shown (including the standard deviations) for modules tested at positive bias (blue) and at negative bias (orange). The initial power measurements have revealed results with 7% higher power output compared to the nominal value for all modules. The group of modules connected to positive bias degraded slightly whereas the modules stressed at negative bias degraded about -86%.

A recovery test was also performed with 15 severely degraded modules by an exposure to the opposite polarity during the PID test. Figure 4 shows the average deviation to the nominal value received at the final measurements. Initially, the modules suffered from an average degradation of (58 ± 17)%. After 96 hours of PID recovery exposure, the modules recovered to an average power loss of (17 ± 9)%. An additional recovery cycle of 96 hours led to a further improvement, ending with an average negative power output deviation of (8 ± 5)%. In the case that the used module type possesses the property of recoverability, an adaption of the plant design by grounding the negative pole could be a feasible solution to stop the degradation and to induce the recovery process.

In this presented case study, a change of the plant design was not possible and the test specimen suffered also from other types of ongoing degradation effects, partly induced by the PID recovery procedure. Figure 5 shows exemplarily such induced degradation mechanisms in the appearance of discoloration and bubbles in the edge sealing leading to a reduced insulation. Furthermore, worm-like delamination has occurred directly over the semiconductor. The backside of the module showed strong glass corrosion at the edges and in front of the rails of the mounting structure. A closer look at the distribution of power deviations within the strings reveals another degradation effect at the positive end (see Figure 2, visible in power loss and EL). The highest power output of an individual module in the string is around module position seven (counted from the negative string-end, left side – see Figure 1). Towards the positive string-end, a slight decrease is visible for the majority of strings.

The results of PV plant I can be summarized as

- PID with increasing severity towards negative string-end;
- PID-sensitivity tests validate this result;
- Regeneration at positive bias not possible due to superimposed degradation mechanisms induced during exposure leading to new module failures.

Finally, all modules in the plant were replaced by new modules.

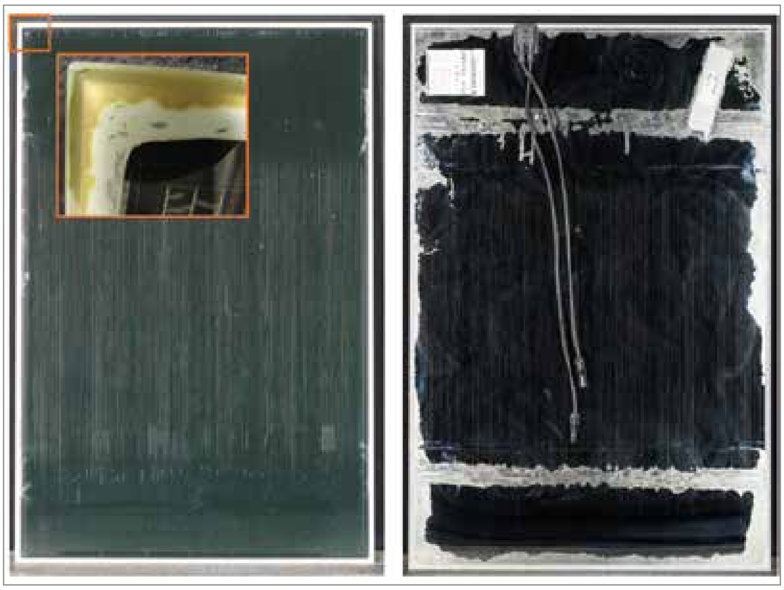
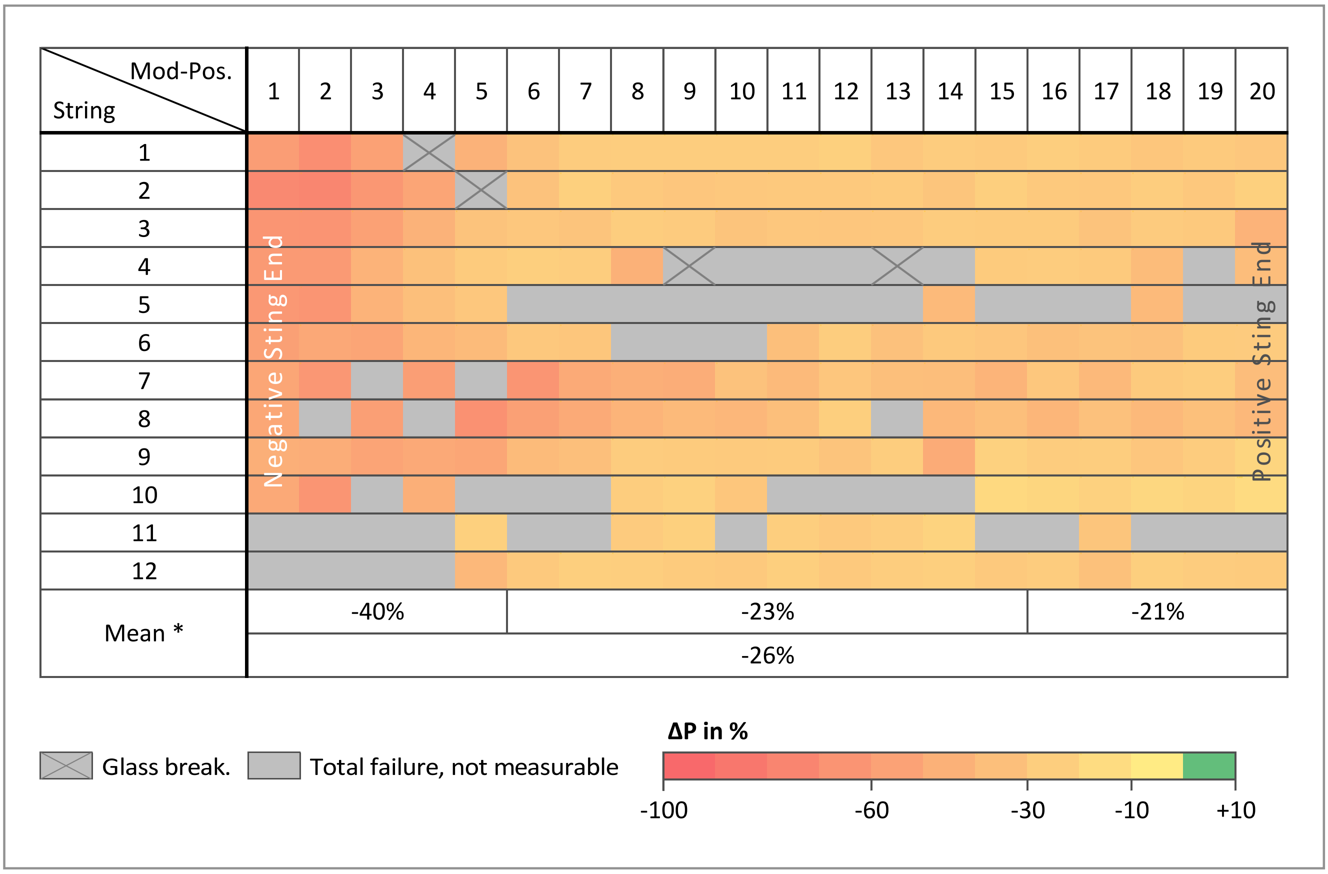


Figure 5: Visual degradations after PID-recovery test at +1kV 196h on module front (left) and back (right).

Plant II (CdTe)

In PV plant II, 12 strings with 20 modules each were investigated with IV-curve measurements and electroluminescence. Figure 6 shows the STC-corrected data for each module in its string position. The 67.5W CdTe modules were in the sixth year of operation, which results in a maximum allowed power output deviation of 12.6% to the nominal value according to the producer's guarantee conditions (90% guaranteed for the first 10 years). This value is also taking into consideration a

Figure 6. On-site power measurements of 12 strings, each with 20 modules. Some modules already show a total failure (grey) in the sixth year of operation. The power deviations for each module are presented according to the colour code. *Mean power deviations were determined for the marked sections and below for all tested modules.



measurement uncertainty of 2.9% according to EN 50380 (2003) on the 90% value. Some modules were not able to be measured due to a total electrical failure (grey) and four were mechanically destroyed due to glass breakage.

Only two modules passed the above mentioned threshold value resulting in a failure quote of 99%. The average deviation of all test specimens is -26%. An analysis of the power loss distribution shows a mean degradation of 40% of the first five modules at the negative string end, across all analysed strings. In contrast, the mean deviation of the five modules at the positive string end lies only at -21%. This tendency indicates very likely a potential-induced degradation (towards the negative string end) superimposed by a very prominent “normal” degradation (at all other module positions) far beyond the guaranteed values.

Figure 7 shows the EL-signal of four modules powered with current in forward mode. Inhomogeneous semiconductors with many failure patterns are affecting the modules from the edges inwards. For this module type, in its current state, it is hard to distinguish between production induced inhomogeneities and field-induced failure patterns. Figure 8 shows a picture taken on site where many modules with glass breakage are visible with the naked eye.

During the field measurement campaign 20 modules were selected for further in-depth laboratory analysis. To summarize the laboratory results:

- All investigated modules failed the guaranteed minimum power output (90% after 10 years) already in the sixth year of operation significantly with a mean deviation of -54% (including all failures, determined in the laboratory and not depicted);
- Burn marks (18% of all modules affected) at the current collector straps inside the modules indicate a too low specified or a too low reverse current overload protection (RCOP);
- 20% of all investigated modules (n=300) in the plant show glass breakage, most likely induced by the insufficient RCOP;
- A plant design failure in the form of an interconnection of six strings in parallel without string protecting diodes (knowing that this is common but not feasible for that module type) is fostering the two above mentioned module failures.

Moreover, accelerated stress tests in the climate chamber have confirmed PID susceptibility of all modules resulting in a development of TCO corrosion around the clamps. Figure 9 shows the test results as an evolution of the power output deviation compared to the label. The modules originate from different string positions: two modules from the positive string end (red) and three from the negative string end (black, illustrated as -/+End). After the initial laboratory power measurement, four modules were stressed during PID tests at negative bias and one module as a reference in damp heat (DH, dotted line) without an applied voltage. The modules from the negative string end have a mean initial deviation of -43% whereas the modules from the positive string end have a mean initial deviation of -17%. The modules from the positive string end degraded further (A and B). The modules from the opposite string end regenerated, despite the negative potential during the exposure. The DH module (E) behaved like the modules from the positive string end.

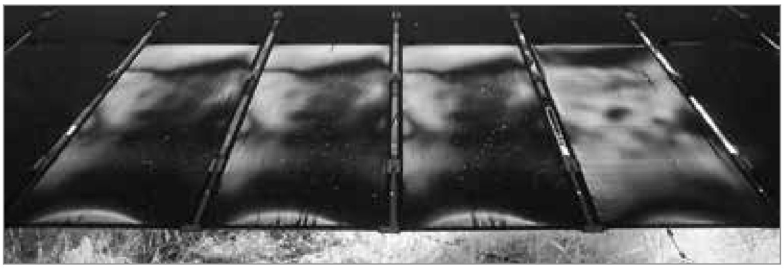


Figure 7. EL pictures taken on-site.

Figure 8. Picture of a table in plant II.

It can be concluded that the modules are sensitive to PID due to the further power decrease and the visible TCO-corrosion around the clamps and edge region. The power output increase of the two test specimens can most likely be explained as an improvement of the semiconductor due to stabilization by high temperatures of 85°C during the climate chamber treatment (some manufacturers prescribe pre-conditioning before power measurements after dark storage in a warm environment, which was not the case here) and not due to a recovery process. Finally, the plant owner was advised to replace all modules in order to assure the economic viability of the plant.

Plant III (μc-Si)

Solar plant III was built with μc-Si modules and investigations were conducted in the laboratory. Figure 10 (left) shows the modules abnormalities with suspicion for TCO-corrosion (orange) and white areas (blue) indicating a low shadowing tolerance. For a further investigation of these issues and to validate the suspicion, eight modules were selected: two from the positive end of a string (A,C) and two from the negative end (B,D) all showing no TCO-corrosion; two more modules from the negative string end, already showing TCO-corrosion after two years of operationn (E,F) and two reference modules (G,H) (free from any degradation signs and from the positive string end). A summary of the module selection with the performed tests is shown in Table 2.

	Free of TCO-corrosion		Already affected with TCO-corrosion
	Take from + string end	Take from - string end	
(+1kV) PID	A	B	
(-1kV) PID	C	D	E,F
DH, HS	G,H		

Table 2. Module conditions and performed tests.

"A combination of field and laboratory tests increases the opportunities to receive precise and confident results and to come to the right conclusions"

The hot-spot tests revealed that the µc-Si TF modules are highly sensitive to shading. A brief partial shading leads to irreversible spots on the semiconductor (hot-spots) visibly as grey marks/white spots. During the test, no significant power loss could be found despite measured temperatures of maximum 80°C. The failures reported from the power plant could be reproduced during the laboratory test.

The PID test results are presented in Figure 11. Modules from a negative string position in the plant show partially visible TCO corrosion and an initial power deviation up to -18% (E,F). All investigated modules revealed significant further power degradation at negative bias resulting in power losses up to -55% (C to F). Furthermore, TCO-corrosion could also be proven as shown in the corner of the middle picture of Figure 10. The picture on the right hand side shows an example of an EL picture of module E after 500 hours' PID test exposed to negative bias. The module shows dark areas at the edges and corners in the EL picture. However, modules tested at positive bias reveal no power-related degradation processes but show visually a change of the semiconductor layers (fog-like). In contrast, an exposure to positive bias led to a power increase (up to labelled power). This was observed for the tested modules originating from a negative and positive string position due to a temperature regeneration effect (A,B). Accordingly for this module type, it can be stated that PID (such as TCO-corrosion) can be stopped by avoiding negative potential on site and an application of a proper grounding. Another opportunity would be a shift of the whole string potential further into the positive direction. Not shown are the results of modules G and H after the DH test. Both test specimens behaved in the same way as the positive PID tested modules indicating again that positive bias is not degrading the modules and that warm conditions (85°C) induce a regeneration process.

The presented results have shown that it can be challenging to differentiate between degradation mechanisms and temperature-driven power improvement of Si TF modules. This demonstrates the necessity to choose an appropriate module characterization procedure for reliable results and their correct interpretation. Consequently, it is necessary and recommended to follow the test specifications from the manufacturer of µc-Si modules for an evaluation of power output degradation. In this presented case, the procedure prescribes a regeneration at 90°C for 48 hours (e.g. damp heat chamber) followed by a light-induced degradation. This enables an evaluation of the power state of the modules before all treatments. Furthermore, it is important to distinguish between the "white-spot" phenomena and the TCO-corrosion. The authors presented this already elsewhere on the same module type [12].

Summary and conclusion

Field measurements (IV-curve tracing, EL and IR) have many positive benefits like analysis of large quantities of modules in the range of hundreds. Degradation effects at module level during operation can be detected and possible root causes investigated. One of the important advantages is that the modules are already performance-stabilized and no pre-conditioning, as with laboratory measurements, are necessary. Disadvantageous are the instable measurement conditions (intraday and seasonal) and particularly the high measurement uncertainties (5 to 10% for power output) [13].

Laboratory measurements are the environment-independent and more precise alternative solution but often limited due to financial constraints mostly resulting in low module quantities (low double-digit range). Nevertheless, using a representative and string-wise sample allows a validation of PID-related degradation. Despite higher accuracy (in this case 2.9%), pre-conditioning procedures due to dark storage (CdTe and CIGS) or seasonal power-output variations (Steabler-Wronski effect in silicon thin film), are mandatory. PID tests enable evaluation of the modules' sensitivity to this degradation mechanism, their regeneration potential and further risk to operate the modules in the plant at the given conditions. Table 3 summarizes the presented advantages and disadvantages between on-site and laboratory measurements.

A combination of field and laboratory tests increases the opportunities to receive precise and confident results and to come to the right conclusions. This enables the parties involved to take measures against PID (e.g. negative pole grounding, regeneration or module replacement). A complete module replacement was necessary in two of the three presented projects.

The following recommendations are proposed to improve inspection methods of modules in operating plants:

- Further automatization is needed in failure detection and analysis field. Many measures were already implemented by monitoring service providers but an extension of automatization for module tests like electroluminescence would be very useful. A renouncement of IV-curve measurements could be taken into consideration as the good correlation of power output degradation with visibly failures on the EL images have shown in this article. This becomes even more critical as plant sizes continue to increase towards the GW range. The results provide evidence that a correlation between power drop and EL signal would lower inspection time, increase the number of inspected modules and lower the costs. This could be realized by performing only EL measurements without doing time intensive power measurements.
- Intense work towards a deeper understanding of mechanisms behind module failures of TF is necessary. Therefore, knowledge exchange along the whole value chain is essential.

To follow the presented recommendations, the PEARL project was established: "Performance and Electroluminescence Analysis on Reliability and Lifetime of Thin-Film Photovoltaics". The PEARL project aims to reduce the cost of electricity produced by thin-film PV power plants, by improving plant reliability, yield and prediction of the overall plant lifetime. For this purpose, large and small thin-film photovoltaic plants will be inspected by using particularly electroluminescence imaging. During the project, the applicability and understanding of electroluminescence imaging methods scaled to large-scale measurements on thin-film solar cells and modules will be improved. Furthermore, the objectives are to obtain knowledge about the appearance, behaviour and progression of failure mechanisms in thin-film PV plants. The gathered information will be used to increase the long-term profitability of thin-film photovoltaic projects by increasing operating yield, reducing operational and maintenance costs, improving accuracy of investment models and to improve bankability.

The PEARL TF-PV project is an international collaboration of industrial partners and research centres from Germany, Austria and the Netherlands, brought together via the Solar-era.net framework, namely: Forschungszentrum Jülich, Helmholz-Zentrum Berlin für Materialien und Energie (PVcomB), PI-Berlin, Austrian Institute of Technology, Crystalsol, TNO, ECN, TU-Delft, Solar Tester, KiesZon, eigenenergie.net and Straightforward. Interested parties willing ro contribute to this project are invited to contact the authors!

	Field	Laboratory
Sample number	+ High	- Low
Costs	- Low	+ High
Measurement cond.	- Instable	+ Stable
Accuracy	- Low	+ High

Table 3. Evaluation of field and laboratory measurement advantages and disadvantages.

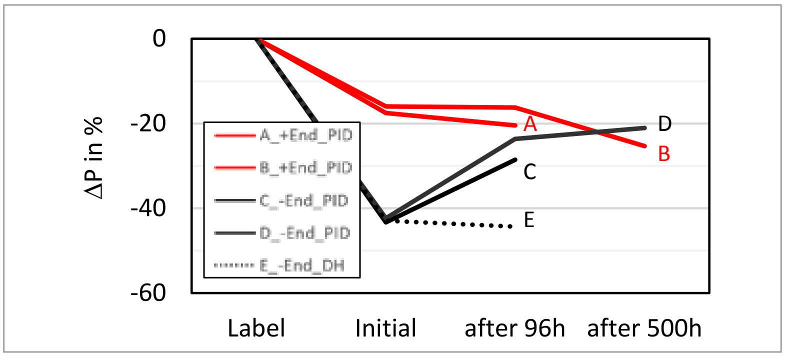


Figure 9. Module power evolution of CdTe modules from producer/plant II. The modules were taken from the negative (black) and the positive string end (red). After initial laboratory power measurement the modules were stressed at PID tests at negative bias and one module as a reference in damp heat (DH).

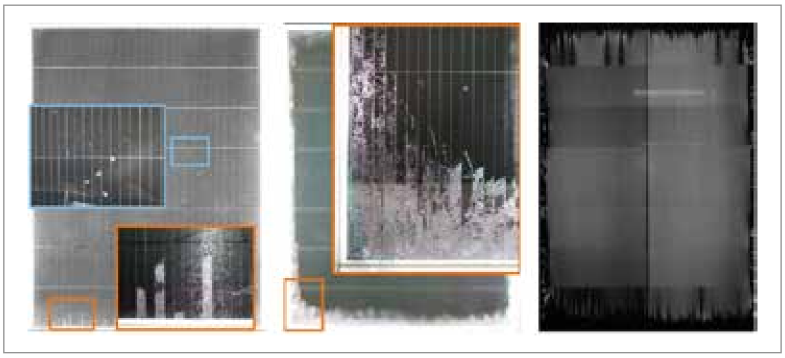


Figure 10. Left: Pictures of µc-Si module (E) of producer III with initial visual degradations showing TCO-corrosion (orange) and "white spots" (blue). Middle: TCO-corrosion after 500h PID(-) test. Right: Electroluminescence pictures after the test revealing dark areas around the edges indicating TCO-corrosion.

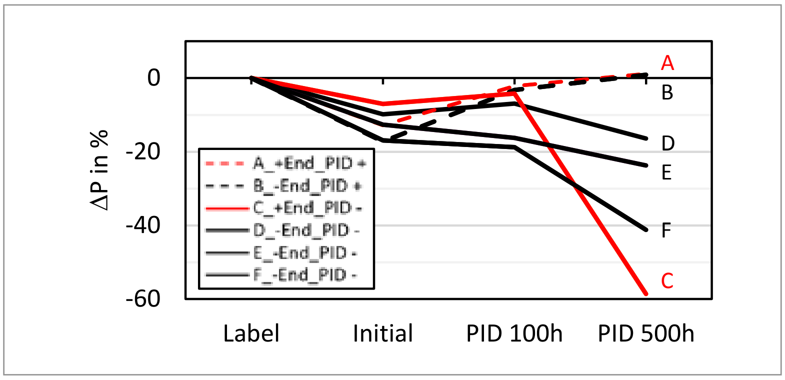


Figure 11. Module power evolution of µc-Si modules out of plant III. The modules were taken from different string positions. After initial power measurement in the laboratory, PID tests were conducted at positive and negative bias.

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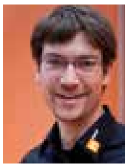

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Cyril Hinz studied renewable energies at the University of Applied Science Berlin and completed his degree in 2016 with a master of science. Following his graduation, Hinz began working at PI Berlin as a project manager within the business unit PV Systems, conducting on-site measurements, and as a research associate within the R&D department with a specialization in 'regeneration of potential-induced degradation' and module cleaning.

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