Enhancing Solar PV Lifecycle Asset Management through the Autonomous Drone EL Mapping: Part Two – Degradation Monitoring from Day One of Operation

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Background and introduction

This article is the second instalment in a three-part series on the use of autonomous drone-based electroluminescence (EL) mapping across the solar PV project lifecycle. The first paper examined how rapid EL mapping can be employed after extreme weather events to assess storm damage and restore power plants quickly. This instalment focuses on a quieter but equally critical period in a project's life — the transfer of liability and responsibility among the stakeholders. Establishing a comprehensive quality baseline at the Commercial Operation Date (COD) and before the Defect Liability Period (DLP) expires is essential for protecting investments, assigning liability, and enabling predictive maintenance. To support this position, the article reviews stakeholder roles, the milestones and standards governing commissioning, and the link between quality control and project bankability. It then presents case studies from field projects, examines how factory acceptance data can be connected to site inspections, and proposes sampling strategies for large-scale plants.

Responsibilities and liabilities of different stakeholders in solar PV projects

A solar PV power plant project involves numerous stakeholders throughout its development, engineering, procurement, construction, operation, and maintenance phases. Effectively managing risks across these phases in view of time, cost, and quality of a project execution is essential to protect the investment and ensure the anticipated financial return.

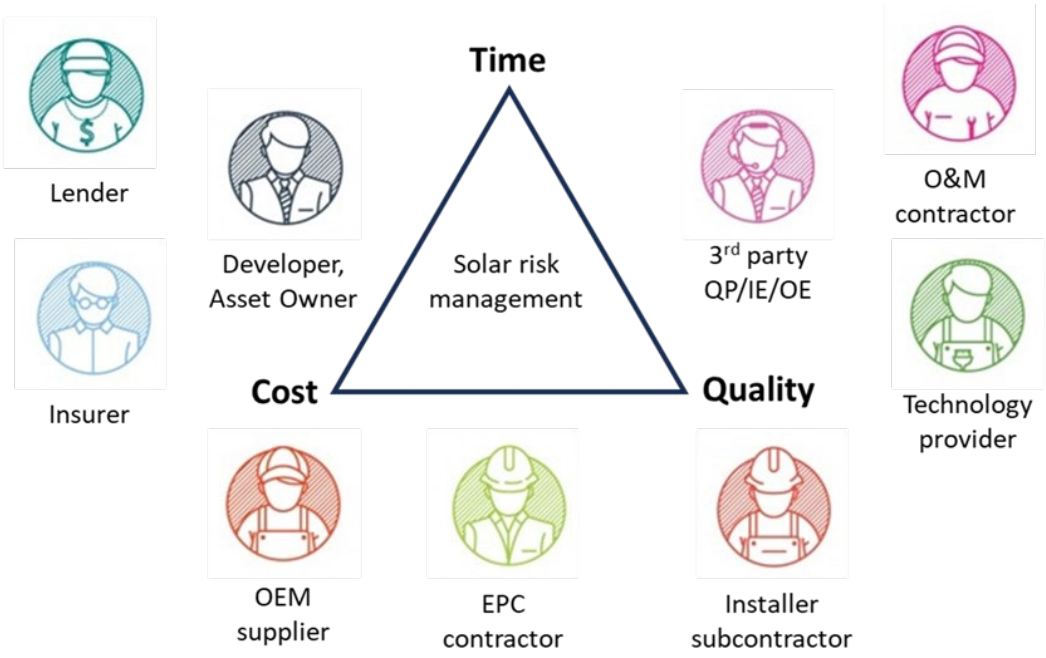

Figure 1. Overview of different stakeholders involved in a PV project

The roles and responsibilities of each stakeholder are crucial for the project's success:

- **Developer**: Responsible for the overall coordination of the solar project, including site selection, securing financing, obtaining necessary permits, and overseeing construction. The developer operates as a Special Purpose Vehicle (SPV) company, which is established by the solar farm investors to serve as the legal entity for the project.
- **Asset Owner**: Manages the solar asset post-construction, ensuring optimal performance and profitability over the system's lifespan. Typically, the developer and the asset owner are the same SPV company until an asset transaction occurs, at which point an external investor will take over the asset.
- **Lender**: Provides financial support to the developer in the form of loans or investments. They may also assess the financial viability of the project. In addition to traditional bankers, other financial institutions, such as infrastructure funds and Environmental, Social, and Governance (ESG) theme investors, can serve as lenders.
- **Insurance Company**: Offers coverage to protect against risks associated with the construction and operation of the solar project.
- **EPC Contractor**: Handles the engineering design, procurement of equipment, and construction of the solar power plant.
- **Equipment Supplier**: Provides the solar panels, inverters, mounting systems, and other necessary equipment for the project.
- **Subcontractor Installer**: Assists the EPC contractor by performing specific tasks such as electrical work or panel installation.
- **Third Parties Owner's Engineer (OE)**: Acts as an independent consultant to the stakeholders, providing technical expertise and ensuring the project meets specified requirements. It is important to note that an OE is not necessarily a certification body (CB), but rather a professional entity that upholds the project's standards and practices. In some countries, they are also known as Independent Engineer (IE) or Qualified Person (QP).
- **O&M Contractor**: Responsible for the routine maintenance after commissioning, such as cleaning panel and trimming grass, and repair of the malfunction equipment.
- **Technology Provider**: Offers innovative solutions and technologies to enhance the performance and reduce operation cost among the parties.

Each stakeholder's action impacts the solar project's success, and their collective efforts ensure that the project is executed on schedule, within the allocated budget, and functions efficiently throughout its operational life. Nevertheless, during a project's lifetime (typically set to 30 years), there are occasions when a stakeholder may express reservations or objections, citing concerns that their interests could be adversely affected by the actions of others. Therefore, establishing a baseline at the day zero of the project operation offers a definitive and quantifiable benchmark for evaluating all subsequent project developments. Any deviation from the established baseline is considered a risk factor that must be promptly identified and rectified to maintain the project's integrity and performance.

Review of solar PV system commissioning and site acceptance testing

Under the widely adopted EPC and Power Purchase Agreement (PPA) legal frameworks in utility-scale solar power plant projects, the responsibilities and liabilities of each involved party are clearly defined. Critical milestones related to asset handover and takeover are identified and communicated among the parties as conditions to trigger payment terms. The most pivotal

milestone for a solar project is the declaration of the Commercial Operation Date (COD) by end of the construction phase. At COD, the solar PV plant officially commences its operational phase, generating revenue through the sale of electricity to the green electricity off-taker and/or the grid operator. Prior to COD, the solar asset under construction is fully controlled and managed by the EPC contractor. Post-COD, the asset owner assumes liability, with support from the Operations & Maintenance (O&M) contractors. However, due to their inherently risk-averse nature, asset owners commonly require the EPC contractor to temporarily assume the role of Operations and Maintenance (O&M) service provider. This ensures smooth operations during the initial period of the project's operational lifetime and demonstrates a guaranteed performance ratio (PR).. This transition period, known as the Defect Liability Period (DLP), is typically 2 years following COD. This period is characterized by the emergence of early-stage degradation phenomena, such as Light Induced Degradation (LID) or Potential Induced Degradation (PID) of PV modules, as well as design issues with the PV mounting structure. It is during this time that O&M practices are being standardized, and new technologies, like robotic cleaning and mowing, may be introduced to enhance the efficiency and functionality of the plant. The DLP represents the highest risk period in the lifecycle of a PV plant, as it is the final phase before the plant transitions into a routine O&M phase where initial problems are expected to be resolved, and practices normalized. This period serves as the last opportunity for the EPC contractor to address any issues under their liability before the responsibility for the plant is officially transferred to the asset owner. It is essential during this period to rigorously identify and rectify any emerging defects—whether they arise from construction faults, the standardization of O&M practices, or inherent issues with PV module quality—to ensure a smooth handover and continued efficient operation of the plant.

Therefore, a comprehensive site testing and commissioning (T&C) in between the COD and the end of DLP shall be carried out by a third-party professional inspector, such as TÜV Rheinland, to ensure that all systems and equipment of the solar power plant are designed, installed, tested, operated, and maintained according to the operational requirements of the asset owner. Specifically, the International Electrotechnical Commission (IEC) has established a series of standards designed to ensure the quality and safety of PV systems:

- **IEC 62446-1**: The first section on Documentation, commissioning tests and inspection, designated as IEC 62446-1, was initially published in 2016 and subsequently amended in 2018 to reflect updates in industry standards and practices. This standard is essential for ensuring that system designers and installers provide comprehensive information and documentation, as well as perform essential DC testing of the system, including PV string IV scans.
- **IEC 62446-2**: the second section on Maintenance of PV systems, was published in 2020. It outlines essential maintenance requirements and recommendations for grid-connected PV systems, focusing on preventive, corrective, and performance-related maintenance. This standard is not mandated as part of the site acceptance tests.
- **IEC TS 62446-3**: the third part, focusing on Photovoltaic modules and plants - Outdoor infrared thermography, was introduced as a Technical Specification (TS) guideline in 2017, providing a structured approach to thermal imaging inspections. It provides guidelines for thermal imaging inspections, which are crucial for identifying fire safety risks in PV systems through temperature anomalies, such as the hotspot detection.
- **IEC TS 62446-4 ED1**: the fourth part, focus on Photovoltaic modules and plants - Outdoor Electroluminescence imaging, is currently in Approved Draft Technical Specification (ADTS) stage and would be officially published soon in 2026. This standard will provide guidelines

for using EL imaging techniques at the solar power plant to detect defects and evaluate the quality of PV modules and plants without moving PV modules from its original installed position.



Figure 2. Overview of the Three Inspections Conducted at the PV Plant, as Specified by the IEC 62446 Series Standards.

As outlined in Figure 3, the current site acceptance test (SAT) protocol is split into the following three phases:

1. Provision Acceptance Test stage, which mandates PV string IV scans in accordance with IEC 62446-1
2. Intermediately Acceptance Test stage, which typically involves 100% drone thermography as per IEC 62446-3
3. Final Acceptance Test stage, which focuses on system Performance Ratio (PR) test according to IEC 61724

As solar power plants expand to hundreds of thousands—or even millions—of installed modules, the demand for sophisticated, system-wide inspection techniques has grown sharply. At a minimum, such inspections must resolve conditions at the level of individual panels, allowing operators to identify defective or degraded modules for replacement, warranty claims, or batch tracing. Historically, infrared (IR) imaging—whether ground-based or drone-mounted—was the only technique capable of surveying 100% of the modules. IR imaging is critical for identifying cell hot spots and other overheating elements that pose safety risks. However, its lower resolution, limited defect-detection capabilities, and vulnerability to shading artifacts, restricted its effectiveness in assessing and quantifying general module performance and reliability issues.

As a complementary inspection technique, electroluminescence (EL) imaging has long been a standard tool in laboratories and production lines, valued for its high resolution, sensitivity, and ability to reveal a wide range of defects—including cracks, degradation, and solder joint issues—while also supporting quantitative analysis to predict voltage and power loss. Yet until recently, EL imaging had not been adopted as a cost-effective method for field-scale inspections, remaining confined to spot checks or small-scale secondary evaluations. This absence of a practical, full-scale EL solution meant that final acceptance test protocols historically omitted any mandatory EL requirement. Ultimately, the lack of comprehensive field inspection across all installed modules has represented a gap in the quality management of large solar projects.

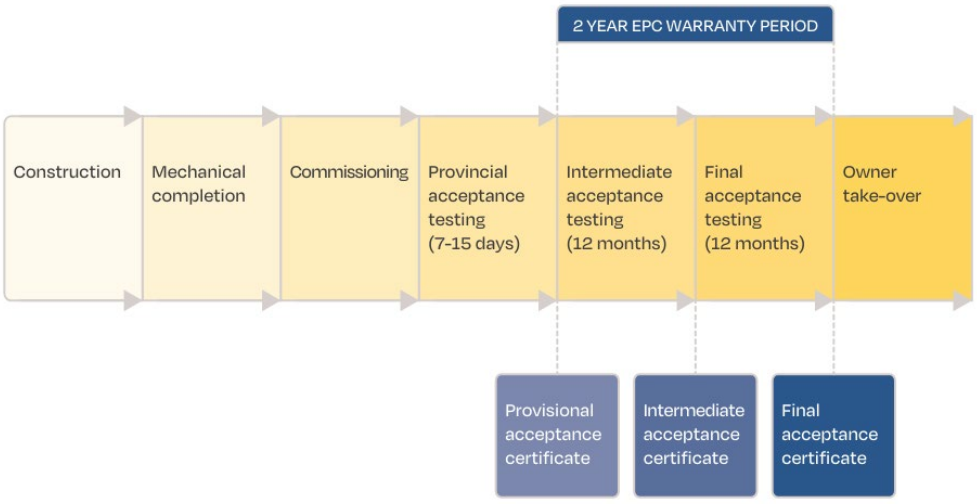

Figure 3. Site acceptance test at system performance milestones defined by SolarPower Europe

Enhancing project bankability and insurability by drone EL mapping

Recognizing this gap, researchers and industry players have pursued solutions to make EL imaging viable at scale in the field. A major step forward is the drone-coupled EL mapping system developed by Quantified Energy (QE), which delivers cost-efficient, high-volume inspections across entire PV plants. By enabling comprehensive post-installation EL assessments, this technology directly strengthens lifecycle quality control and addresses critical factors influencing project bankability and insurability.

Bankability—the ability of a solar investment to generate reliable cash flows and attract financing—depends heavily on rigorous quality assurance across the entire value chain. This typically begins with product design qualification and type approval certification at accredited laboratories, followed by third-party auditing during manufacturing and material sourcing. At production's end, all PV modules undergo standard testing conditions (STC) IV flash, insulation, and EL tests to filter out defects, with random samples often subjected to third-party verification before shipment. Upon arrival at project sites, additional sampling-based acceptance tests may be conducted; for example, the SolarPower Europe O&M Best Practice V5.0 report recommends G-I level testing of delivered modules. Yet despite these layers of quality control, post-installation inspections remain largely absent. As noted earlier, final acceptance protocols do not mandate EL testing of the installed array. The absence of thorough field inspections for all installed PV modules poses a significant challenge in the quality management of a solar project.

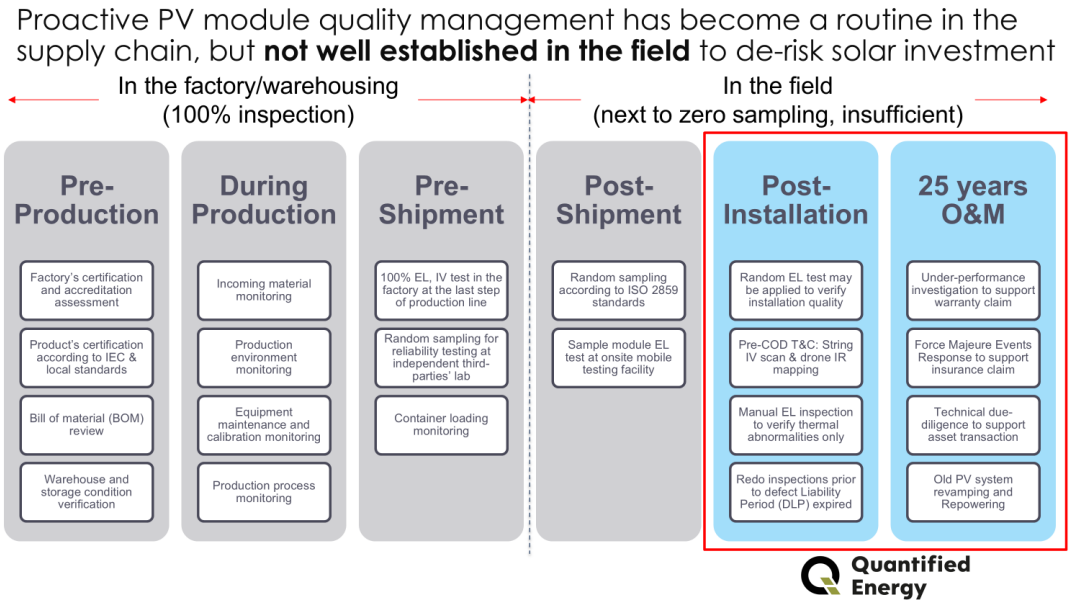

Figure 4. Quality management along the lifecycle of PV plants

In parallel with bankability, the concept of insurability plays a crucial role in securing solar PV investments. Insurability encompasses a range of policies designed to mitigate project risks, and it is most effectively applied once a clear, well-documented quality baseline has been established. Comparing this baseline with subsequent inspection results enables consistent evaluation of system performance over time. For example, standard PV module performance insurance—commonly backed by reinsurance companies—guarantees less than 20% accumulated power degradation over 30 years. Reinsurers, serving as a financial safeguard, often establish quality guidelines that suggest lab testing for accelerated reliability and durability, with criteria that may be more stringent than the standard IEC 61215 and IEC 61730. These guidelines may also call for additional extended testing and third-party production audits to ensure comprehensive quality assurance.

Looking ahead, integration with complementary technologies such as IoT-based monitoring and automated O&M could enable more advanced insurance products. An energy yield insurance policy, for instance, would protect developers not only from variability in renewable resources but also from excessive downtime due to equipment failures, ensuring predictable returns. Such policies could also shield asset owners from the financial risks of underdelivering contracted green electricity.

Together, these advances in quality control and risk management reinforce both the bankability and insurability of solar projects, creating a more secure investment environment. In the following section, we highlight real-world cases where drone-based EL inspections during COD and DLP milestones have directly supported these objectives, demonstrating their practical value.

Case studies of drone EL mapping for pre-COD/DLP T&C

TÜV Rheinland provides testing and certification services for PV products and solar power plants worldwide. The organization helps clients understand and adhere to international safety and performance requirements, supporting their business objectives efficiently. With over 30 GW of PV installations inspected globally, TÜV Rheinland responds to the increasing demand for high-volume on-site inspections to address operational challenges in a timely manner. The company prioritizes client needs and collaborates with the PV community to implement innovative solutions.Quantified Energy (QE), renowned for its expertise in drone coupled EL inspection services, has extensive experience with large scale solar power plants, having assessed over 3 million crystalline silicon PV modules. These projects range from installations on single-axis trackers and floating solar systems to commercial and industrial (C&I) rooftops equipped with lightweight modules. QE acts as a technology partner of TÜV Rheinland to provide an end-to-end solar asset lifecycle management solution based on QE's patent-pending autonomous drone EL mapping technology.

This chapter will highlight the importance of mass EL inspections at key project milestones through several real-world project case studies, showcasing QE' dedication to enhancing the quality and reliability of solar projects. It further emphasizes the value of such innovative technologies in the solar industry.

Case study 1: Reveal severe cell cracks due to stepping on PV modules

The first case study focuses on a C&I rooftop solar installation in the Southeast Asia, featuring glass-backsheet modules. A comprehensive EL test was conducted as provisional acceptance test to ascertain the quality of the PV modules installed. This procedure serves as a quality control measure to oversee the workmanship of subcontractor installers. Any defective panels identified are to be replaced promptly, ensuring the initiation of a defect-free system for its 30-year operational lifespan.

Moreover, due to the presence of high-value activities within the premises, the building owner mandated a thorough inspection to exclude modules with cracks, which isolate an area of a solar cell, which poses performance losses and in extreme cases even fire risks due to arcing effects, or hotspots. In tropical countries, it can be challenging to achieve stable weather conditions that meet the requirements of 600 W/m² irradiance and less than 2 oktas of cloud coverage for drone thermography, as specified in the IEC 62446-3 standard.As a result, hotspot detection is not always accurate and many potential fire risks were overlooked. The night shift EL test, unaffected by Sun conditions, can meet the stringent requirements specified by the PV plant owner.

In this project, the drone EL inspection revealed a significant number of PV modules exhibiting severe cell cracks, with cluster cracks visible in the Figure 5, as shown below. Micro-level analysis at the module level pinpointed these cracks at the edges of the modules, while a macro-level examination at the system level disclosed a linear distribution of defective modules across the arrays. These observations suggests that the damage was inflicted by installers walking across the PV modules as a shortcut, rather than circumventing them.

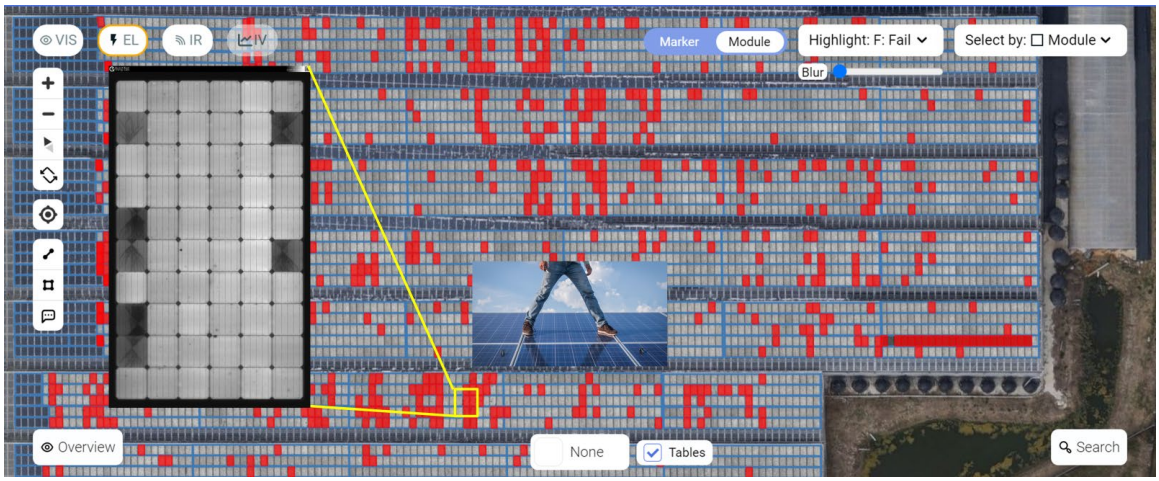

Figure 5. EL mapping of a Commercial & Industry (C&I) roof PV plant showing severe construction mishandling

Research from the National Renewable Energy Laboratory (NREL) USA corroborates has shown that cell cracks can result from walking on modules. Such stepping on PV module must be strictly prohibited to prevent substantial losses for the EPC and avoid delays in COD that could adversely affect the asset owner's operations. We advocate for the inclusion of EL testing within the COD specifications to eliminate construction-phase damage.

Case Study 2: Detecting early-stage degradation before the end of DLP

The second case study explores the early detection of degradation modes such as Light Induced Degradation (LID), Potential Induced Degradation (PID), and Light and Elevated Temperature Induced Degradation (LETID) within glass-glass bifacial, *p*-type PERC cell modules. These conditions, often elusive at the initial stages, which require time to become discernible. Identifying these defects during the final acceptance test at the end of the DLP is crucial for the asset owner, ensuring a system free of defects moving forward. For instance, the 'bright pocket' defect was recently identified and reported by QE during a drone EL mapping project at a utility-scale solar power plant. This defect was first reported at the 10th Bifacial Photovoltaic Workshop in Doha[1].

This anomaly presents itself as a new defect feature. In the EL image, the majority of solar cells within the module appear dark grey, indicating a degradation in power output relative to their nameplate value. Some solar cells display much brighter areas resembling a "jean pocket." These brighter areas often come in pairs; for example, rotating a cell 180 degrees will show that it matches its counterpart, suggesting that these defects likely arose during the cell production stage before the cells were split into half-cut cells for module assembly. Researchers from the University of New South Wales (UNSW) in Australia have also observed a similar feature during their daytime Photoluminescence (PL) inspections, which they have termed the "Yin-Yang" defect[2].

[1] https://www.linkedin.com/posts/qe-labs_bifipv2023-droneel-solarpv-activity-7132998651232059392-lFKZ?utm_source=share&utm_medium=member_desktop

[2] https://onlinelibrary.wiley.com/doi/10.1002/pip.3807

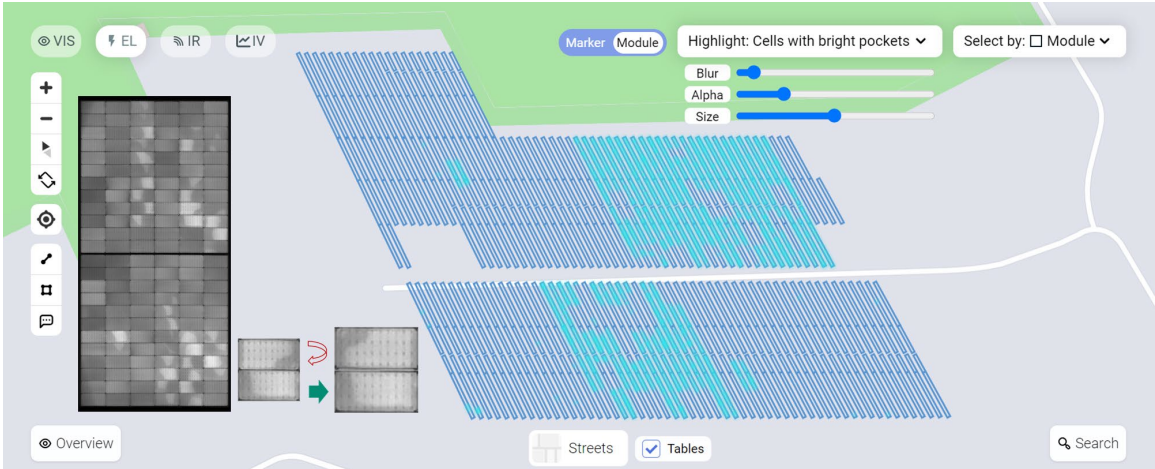

Figure 6. Top: Distribution of modules of bright pockets cell. Bottom: EL image of modules with bright pocket

Although the exact cause of this new feature is not fully understood, it is suspected to be related to the metallization manufacturing process, as modules exhibiting these defects are localized in a specific zone, hinting that they stem from the same production batch. This finding suggests that asset owners should consider thorough inspection to identify early phase degradation that may be deteriorating faster than what is promised by the supplier. Proper documentation should be maintained to facilitate a smooth transition to O&M service providers.

Case Study 3: Assessing new degradation mechanism of advanced solar PV technologies

As the solar industry rapidly adopts high-efficiency technologies like n-type TOPCon modules, new reliability challenges are beginning to emerge. While these modules offer superior efficiency and are becoming the dominant technology deployed globally, their accelerated rollout has, in some cases, outpaced long-term field validation under diverse environmental conditions.

One such emerging issue is UV-Induced Degradation (UVID). This phenomenon, linked to prolonged UV exposure, is gaining attention due to its early appearance in certain field deployments. Unlike conventional degradation modes such as PID or LETID, UVID has been observed specifically in newer module architectures and can result in rapid performance losses within the first few years of operation.

In a recent inspection conducted at a utility-scale site in Europe, sign of early-stage UVID was observed in a significant portion of the installation. Almost all of the inspected modules exhibited excessively dark cells in EL images, a key indicator of UVID-related degradation.

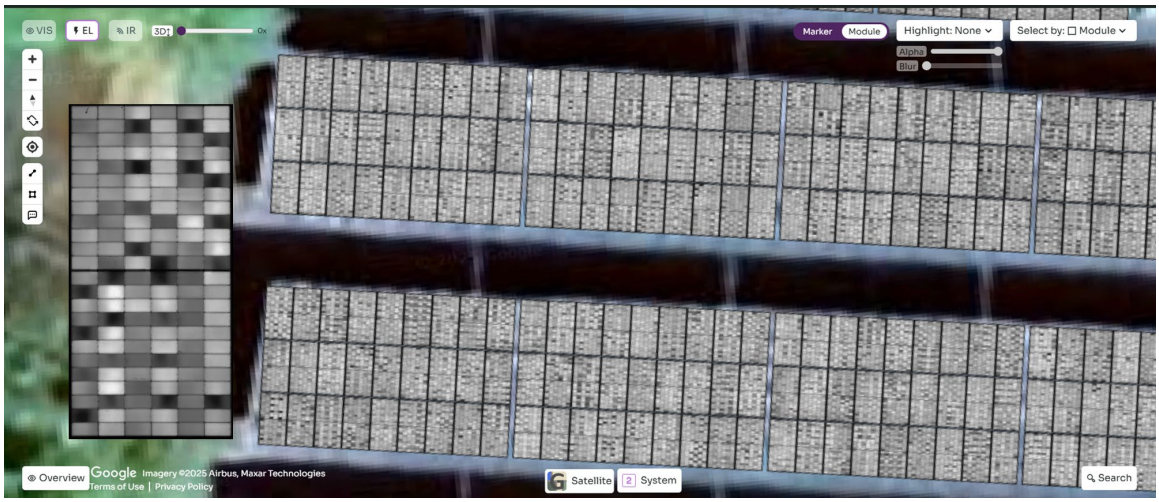

Figure 7. Excessively dark cells observed in EL images, potentially indicating UVID

Given the limited availability of long-term field data for n-type TOPCon modules, asset owners and EPCs must be proactive in monitoring for such degradation signatures. Incorporating drone EL inspections towards the end of the DLP provides a critical opportunity to capture these early-stage defects before EPC warranties expire. Identifying UVID at this stage not only helps in exercising warranty claims but also ensures that underperforming modules do not go unnoticed until significant power loss occurs.

Case Study 4: Uncovering rear glass breakage that may introduced by improper maintenance activities

EL inspection is widely recognized for detecting cell cracks, soldering defects, shunted cells, which are otherwise invisible to the naked eye. Additionally, it can uncover less obvious and less documented problems, as well as issues that may be visible but require a thorough visual inspection that is not easy to perform.

In this case, drone EL mapping was carried out shortly before the end of the DLP. Several modules presented abnormal EL patterns characterized by dark cells, prompting closer examination. While such patterns are often attributed to manufacturing defects or material degradation, further rear-side visual investigation revealed a different root cause: breakage of the rear glass.

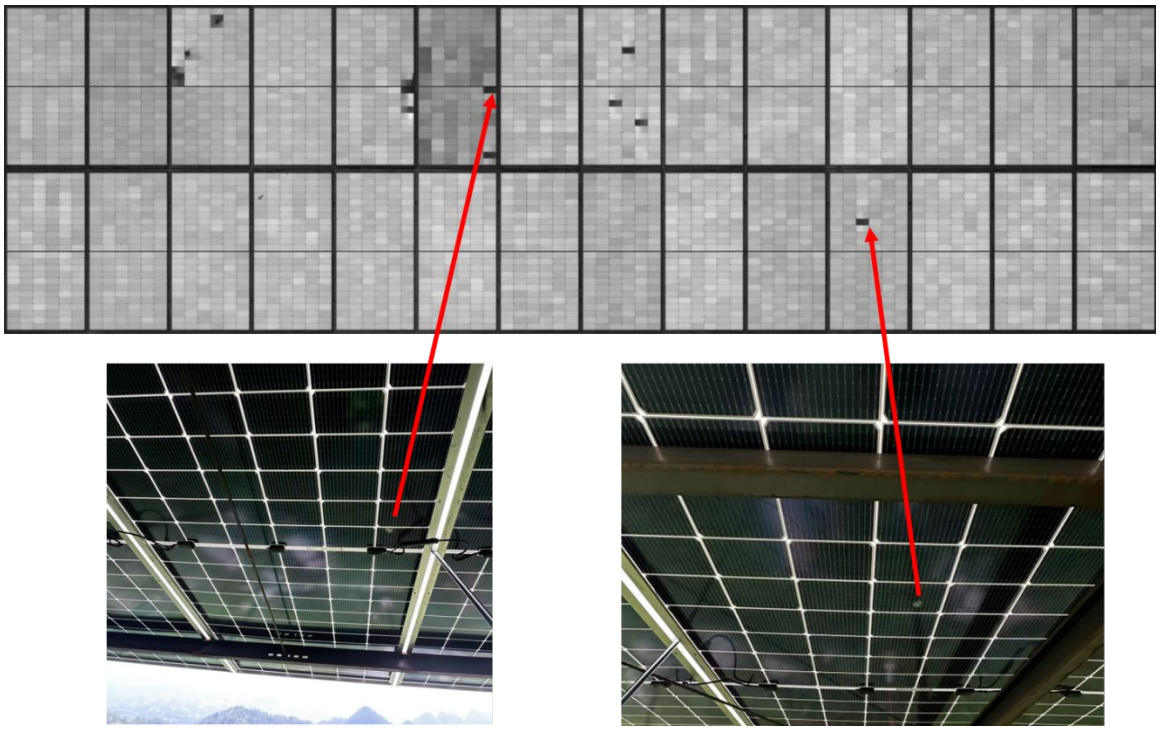

Figure 8. Top: EL images showing dark cells. Bottom: Visible images confirming rear glass breakage corresponding to EL anomalies

The rear glass breakage, concealed from front-side view, had caused cracks in the cells. The severity of crack correlated with the intensity of the EL anomalies. This led to localized current redistribution, with neighboring cells carrying more current than intended. In EL image, these adjacent cells appeared unusually bright—signaling elevated current stress and the risk of accelerated degradation.

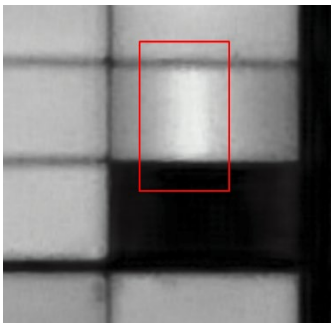

Figure 9. EL image showing a dark cell and adjacent cells with higher current flow, suggesting localized current redistribution caused by cracking

This case demonstrates EL's unexpected benefit beyond conventional defect detection. Rear glass breakage can compromise insulation, accelerate moisture ingress, and reduce performance long before it is visible or measurable in energy yield. Identifying such defects within the DLP period enables warranty claims, avoiding post-DLP repair costs and long-term yield losses.

For asset owners and O&M teams, this reinforces the importance of integrating EL inspections into COD and pre-DLP programs—not only to verify expected quality parameters, but also to capture unexpected faults that could have major financial consequences across large portfolios.

Connecting FAT and SAT EL inspections for streamlined claims and predictive maintenance

With the increasing awareness of importance of mass EL test in quality assurance, developers are implementing drone EL inspection both at the COD and prior to the end of DLP to ensure the integrity and functionality of the PV plant during the critical early phases of operation. Asset owners are keen to determine whether defects in PV modules occurred during manufacturing, or if they were introduced during the logistics and construction phases. Linking the EL database from site acceptance test with factory acceptance test records would ideally address this need.

From production lines, each PV module is assigned a unique serial number in barcode form that links directly to a production database. This database contains essential information, including the PV module's bill-of-material, production batch, and EL/IV testing result, reflecting the stringent quality controls maintained within the manufacturing environment. However, once these modules are installed, the systematic method for tracing them is no longer practiced.

To bridge this gap between field inspections and factory tests, some developers have implemented a barcode scanning system at the installation site to record the serial number of each PV module at its geographical position. There are various methods for conducting barcode scanning, each suitable for different project scales and logistics. The most common method is manual scanning, which is straightforward but labor-intensive. As depicted in Figure 10 shown below, an operator walks along the solar tracker, using a barcode scanner attached to a pole to scan each module individually. This method, although simple, can be time-consuming and prone to human errors. Alternatively, more technologically advanced methods utilize ground robots or drones equipped with scanning capabilities. These automated systems can significantly speed up the process and reduce human errors, making them highly effective for large-scale operations. However, it is important to note that such technologies are not yet universally available and may require additional investment and technical support to implement.

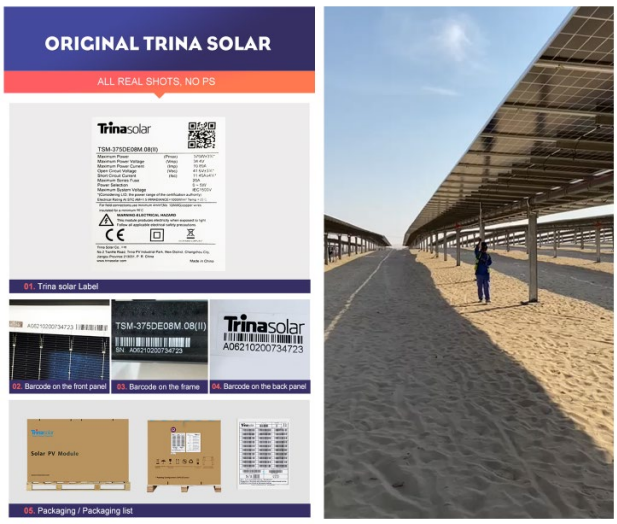

Figure 10. Left: Example of barcodes on PV modules. Right: Barcode scanning being carried out in PV plants.

Although barcode scanning is straightforward yet effective approach that significantly enhances the traceability and quality assurance of PV modules, the current onsite testing methods, such as PV string IV scan and drone IR test, do not facilitate a direct comparison with factory data. EL imaging, is a credible quality test in factory settings, uniquely provides an 'apple-to-apple' comparison of field data with factory results. EL imaging is advantageous because (1) it is a direct test that captures the light emitted from the PV module, (2) does not require strict STC environment like the module IV flash test, and (3) does not necessitate the removal of modules from their mounting racks. Moreover, it is a fast inspection technique where the effect of module temperature variation is unimportant. Responding to industry needs, IEC TC 82 initiated a new project in September 2020 and was turned into the draft of IEC TS 62446-4 standard. This global effort aims to standardize the onsite EL inspection to align with industry demand. From our point of view, a combination of ID mapping and drone EL mapping, which effectively connects the dots, is the solution not only streamlines warranty management and fault identification, but also provides a solid foundation for comprehensive asset management and predictive maintenance strategies.

In one exemplary project, barcode mapping was implemented at the solar farm to enhance traceability. Additionally, full site drone EL mapping was conducted at both the COD and just prior to the DLP to ensure continuity between factory and field EL data. Initial inspections at the factory revealed no defects. However, during subsequent short-term deployments, soldering defects began to surface. Over time, these issues worsened, leading to complete disconnections of the cells and substring failures within two years.

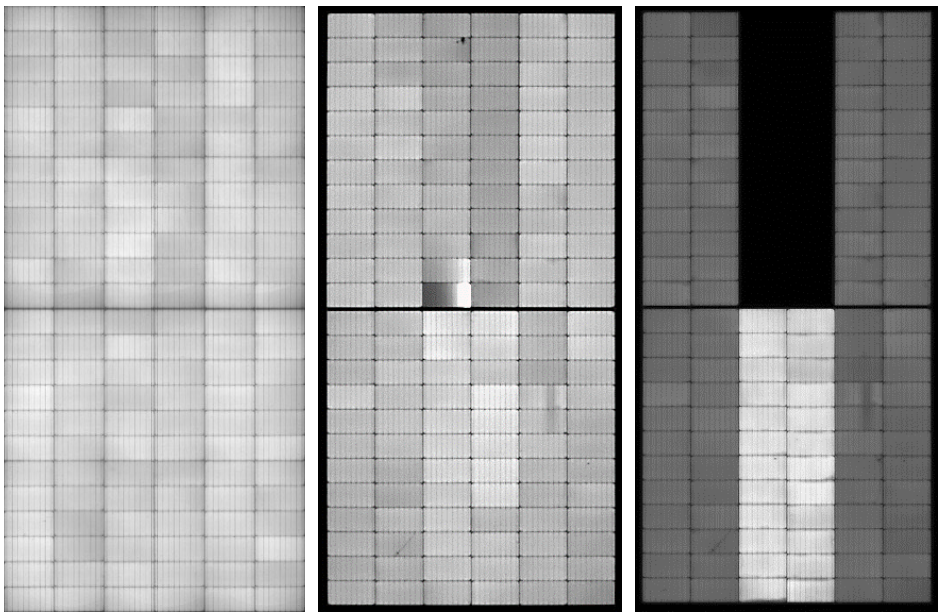

Figure 11. Left: Factory EL, middle: COD EL test, Right: DLP EL test

Upon further investigation, this failure was directly linked to deterioration of the soldered bonds. Initially confined to a few busbars, the soldering issues had further progressed, extending across all busbars and leading to an isolation of the electrical current, resulting in complete substring failures. The site EL inspections enabled us to determine the degradation rate of the soldering and come up with an effective maintenance schedule.

Recommended best practice on two steps sampling of EL inspection for large-scale PV plants

For large scale PV plants, e.g. exceeding 100MW, opting for EL inspections on selected sample size instead of a comprehensive EL inspection of the whole plant can be a cost-effective approach to establish a baseline and identify potential faults within the PV plants. This strategy can be implemented by utilizing the Acceptable Quality Limit (AQL) table outlined in ISO 2859-1. However, before this approach is applied, several key parameters must be defined:

- Lot size: Unlike typical post-shipment inspections, concerns at this stage extend beyond module production to include construction-related issues. Therefore, the production lot selection must comprehensively cover both module quality and installation practices to ensure a thorough evaluation.
- Inspection level: The accepted inspection level, G-I, G-II, or G-III, with G-I being the most relaxed that suitable for fast decision-making scenarios such as module arrival testing, and G-III being the most stringent that will be chosen in case of strong arguments. G-II inspection level is recommended to balance the inspection requirement and the cost.
- Acceptance Quality Level (AQL): An AQL of 1.0 for major defects is generally applied, which is commonly used in quality-sensitive industries.

Let's assume a fictitious 100MW_{AC} solar PV power plant called "PV Plant A" to allow us to go through the sampling determination exercise. Below is the plant information:

- 500 Watt per PV module
- 30 modules per PV string
- 12 PV strings per string inverter
- 35 string inverters per power conversion unit (PCU) or transformer stations as a block
- 20 blocks in total

With these configurations, the PV plant consists of 302,000 modules (30 x 12 x 35 x 20) and has an installed DC capacity of 126MW (a DC to AC of 1.26).

The next step involves determining the lot size for our inspections. For drone EL inspections, DC current is injected into the entire string for EL measurement, establishing the string as the basic unit for this inspection. This is a significant change to the lot size definition based on number of PV modules because traditionally EL imaging is captured in a module-by-module manner. As a result, each block contains 420 strings, which is selected as the lot size for our sampling inspection.

Referring to the AQL table, with a lot size of 420 strings, the sample code H specifies that the sample size is 50 strings. Thus, 50 strings are to be chosen from each block for drone EL inspection. Overall, for the entire PV plant, this results in 1,000 strings (30,000 modules) being inspected. A string is considered to be defective, if more than one module exhibits severe defects. As the typical AQL for major defects is set at 1.0, according to ISO 2859-1 standard table 2-A, if two or more strings fail, a full inspection of the entire block is mandated.

Below is a summary table outlining the inspection criteria and total modules to be tested:

Description	**String based**	**Module based**
Total modules in PV Plant A	302,000	302,000
Total transformer stations or blocks	20	1

Lot size	420 strings	302,000 modules
Applied sample code	H	P
Sample size	50 strings	800 modules
Modules to be tested (per block)	1,500 (50x30)	800 modules
Total modules to be tested in stage 1	30,000 (1,500 x 20)	800
Sampling ratio	11.9%	0.3%
Criteria to trigger whole block inspection	2 failed strings (AQL 1.0)	15 failed modules (AQL 1.0)
String failure criteria	More than 1 module with severe defects	N.A.

When comparing string-based sampling with module-based sampling, it is clear that the inspection ratio for module-based approaches is significantly lower. This low sampling ratio often leads to higher per-unit costs, especially when considering the logistics involved in transporting equipment to the site. In contrast, higher volume inspections using drone EL technology can significantly reduce costs. Many PV owners prefer a higher inspection ratio, leveraging economies of scale to decrease the unit cost of large-scale drone EL inspections. For instance, inspecting 30,000 modules over three nights spreads the front-end inspection costs, resulting in 50% lower overall costs per unit compared to inspecting just 6,300 modules.

Moreover, some PV owners, aiming to establish a robust maintenance program, may opt for 100% inspection. This thorough inspection ensures that all defect patterns are captured, which is crucial for accurately calculating the degradation rates of various defects. These detailed insights enable precise and proactive maintenance planning, offering valuable information that serves as a benchmark for comparison throughout the lifespan of a PV system and also provides credible data that can be used in warranty claims.

Conclusion

The implementation of EL inspections at both the COD and during the DLP sets a robust baseline for evaluating the health of solar PV power plants. These thorough inspections document the initial condition of the PV modules post-installation, pinpointing any defects from the start. By analysing macro-level EL data across the entire site and comparing micro-level EL images with factory EL data, the origins of specific PV module defects can be observed, clarifying stakeholders' responsibilities and liabilities for resolving issues. This meticulous record-keeping proves essential when pursuing insurance or warranty claims, as it simplifies the process by establishing clear defect origins. Consequently, a comprehensive quality control strategy is now firmly in place, bolstering the bankability and insurability of solar investments.

To ensure comprehensive lifecycle asset management of PV power plants, four distinct types of tests are essential, each serving a unique purpose:

1. **String IV Testing:** This test is critical for detecting electrical parameters, ensuring that all components are performing to specification before the plant begins operation. It shall be conducted at the provisional acceptance test stage.
2. **Drone Visual Inspections:** These are conducted to create as-built drawings of the installation, providing a detailed visual record of the plant's initial setup and aiding in future maintenance or modifications. It shall be conducted at the provisional acceptance test stage.

3. **Drone Infrared (IR) Inspections:** Carried out at the provisional, intermediate, and final stages of acceptance tests, drone IR inspections are indispensable for ongoing operations and maintenance. They guide daily maintenance activities such as cleaning and are crucial for identifying hotspots in modules that could pose fire risks.

4. **Drone EL Inspections:** Initially conducted during the provisional acceptance test to verify the quality of installation by subcontractors, and subsequently at the final acceptance test to check for early signs of degradation, or damage due to use of O&M automation tools, EL inspections are pivotal in validating the integrity of the installation and the initial health of the modules.

All data layers — visual, IR, IV and EL — can be integrated into a digital-twin platform, empowering stakeholders to monitor performance, schedule maintenance and maximize asset value throughout the plant's life. By embracing this detailed and highly traceable approach, stakeholders can not only safeguard immediate asset performance but also lay a strong foundation for a more resilient PV plant to maximize the return on investment in the decades to come.

