Enhancing Solar PV Lifecycle Asset Management through the Autonomous Drone EL Mapping: Part One - Addressing Solar Cell Cracks and Insurance Considerations

Quantified Energy Labs, Singapore, 31 March 2024

Roderick Rennison, Senior Vice President Global Energy Services, Rimkus

Background

Investing in a solar farm is a complex process that requires careful consideration to ensure a successful and profitable investment. Among the most critical factors are project location, irradiance profile, PV technology, project financing, operation and maintenance (O&M), interconnection and transmission issues, as well as risks and returns for the overall project.

A critical tool in evaluating solar farm investments is the Levelized Cost of Electricity (LCOE), which measures the average cost to generate electricity over a solar PV system's lifetime. It is calculated by dividing the total lifetime cost by the total electricity generated, enabling investors to compare project attractiveness and forecast return on investment (ROI).

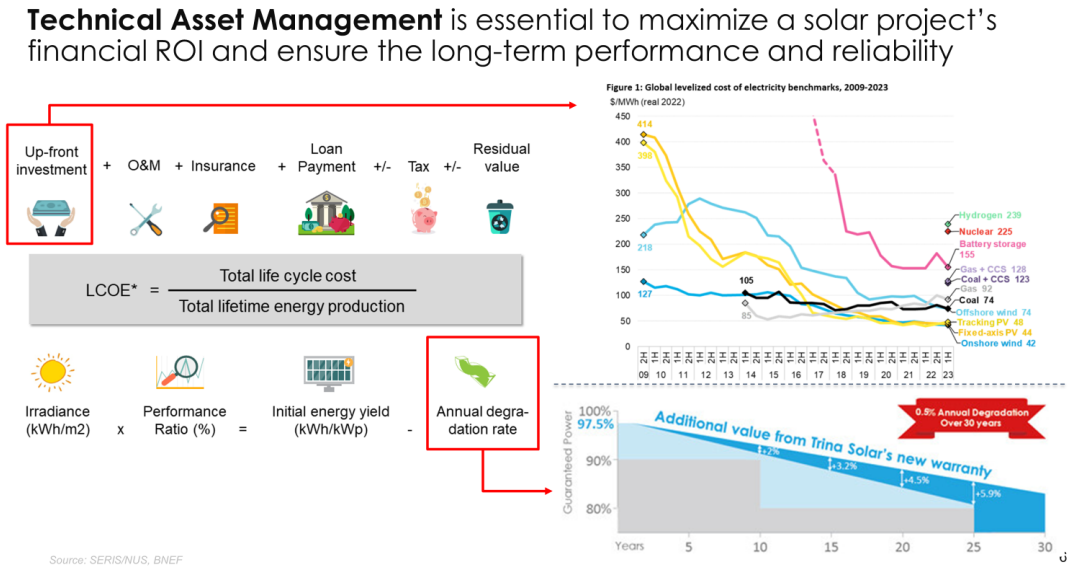


Figure 1. LCOE calculation overview

The PV industry has made significant progress in reducing upfront investments through the adoption of high-efficiency solar cells, high-power density PV modules, and optimized Balance of System (BOS) equipment, all geared towards maximizing energy yield. These advancements have led to a substantial decline in the cost of solar products over the past decade. By leveraging state-of-the-art solar equipment and precise system design, the initial energy yield of a solar power plant can be reasonably estimated once the location is determined, with the only uncertainty related to irradiation values, which are typically extrapolated from historical data.

However, a common oversight in the PV industry lies in neglecting the annual degradation rate of the system, and in particular, the PV modules, which is another crucial parameter in the total lifetime energy production calculation of the LCOE equation. It is commonly accepted that annual degradation rate of a PV system should ideally remain below 0.8% per year over its 25-year lifespan. A lower annual degradation rate translates to a higher energy output over time, thereby yielding a more substantial financial gain. Conversely, a higher annual degradation rate can curtail the system's energy output, thus diminishing the ROI and detracting from the investment's attractiveness.

According to recent NREL published data, the median annual degradation rate of PV plants in the USA is 0.75% per year[1] (P50 value), indicating a relatively stable PV plant performance outlook. However, a upon close inspection of the result, one realizes that a significant number of PV plants experience higher degradation rates, as evidenced by data points falling to the left of the median value, highlighting potential challenges with system longevity and performance. This variation underscores the diverse environmental and operational factors affecting PV plant performance nationwide, including inherent design faults such as seasonal shading on the PV arrays, inadequate maintenance practices (such as excess dust accumulation), and equipment failures including both PV module and BOS equipment, etc. Notably, concerns regarding PV module defects that reduce their performance and/or service life represent a major issue among these other factors. A survey from CEA showed an alarming increase in PV module defects across 148 sites in 16 countries. This result must be taken seriously as these could lead to serious underperformance and even premature catastrophic failure of PV plants in the long term.

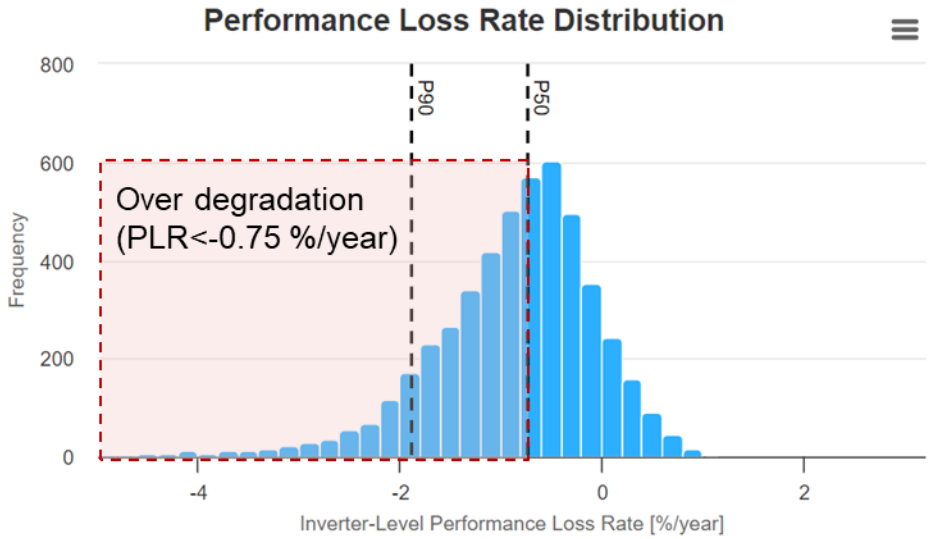


Figure 2. Distribution of Annual Degradation Rates for PV Systems in the USA, according to NREL Study. https://www.nrel.gov/news/program/2024/how-extreme-weather-and-system-aging-affect-the-us-photovoltaic-fleet.html

PV modules can experience excessive degradation due to multiple factors, significantly impacting their efficiency and lifespan. Understanding these causes is essential for effective management and maintenance of PV plants:

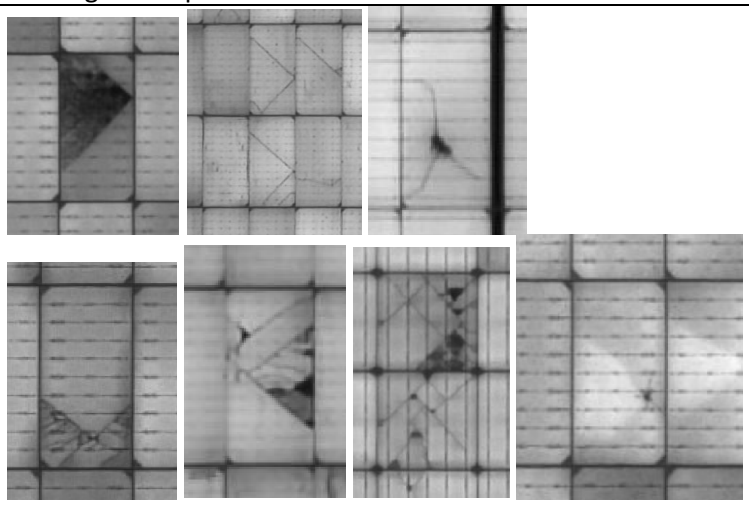
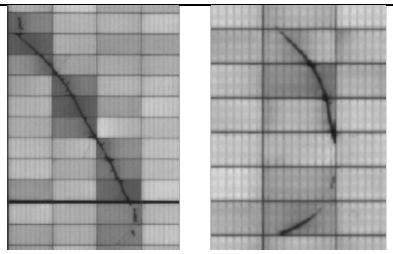
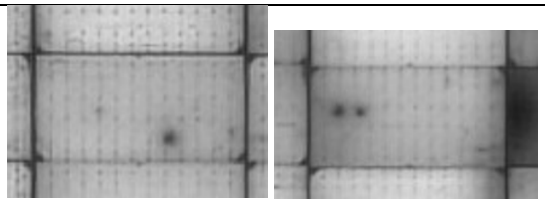
- **Environmental Stressors**: The degradation of PV modules is significantly influenced by environmental conditions. Temperature fluctuations are a primary concern, as they can lead to the expansion and contraction of module materials, causing cell cracks and stressing soldered connections, which may exacerbate manufacturing defects like cold soldering. Similarly, humidity introduces moisture, accelerating chemical reactions in encapsulants such as EVA (ethylene-vinyl acetate), leading to delamination and increased corrosion of components like solar cells and bypass diodes. Furthermore, exposure to UV radiation can degrade EVA, diminishing its mechanical strength and adhesive qualities, and reducing light transmittance, which eventually contribute to reduced power output and even module delamination.
- **Manufacturing Defects**: Beyond cold soldering, manufacturing defects can encompass a range of issues, including microcracks in solar cells, shunting points, finger defects, etc. These flaws may promote premature module degradation and permanent failure. If such a defect became significant, it can even cause hot spots that pose a fire safety concern.
- **Poor installation** can cause a variety of issues that reduce the efficiency and lifespan of solar panels. For example, improper mounting can cause the solar panel to vibrate and eventually cause cracks in the cells of a PV module. Another common installation issue is the use of substandard or incompatible materials. For instance, using inappropriate mounting brackets or screws can cause damage to the PV modules and lead to premature degradation and failure. Furthermore, improper handling such as dropping or scratching the PV modules during installation can also cause physical damage to the modules.
- **Inappropriate design** can compromise the integrity of solar PV plants. For instance, installing trackers without appropriate mounting or dampeners to withstand wind loads can lead to issues. This oversight not only jeopardizes the structural stability, potentially resulting in catastrophic failure during adverse weather conditions but also affects the integrity of the PV modules themselves, leading to decreased performance.
- **Inadequate O&M** can lead to the deterioration of PV module performance and longevity. Neglecting regular maintenance routines, such as allowing soiling to accumulate or failing to address equipment downtime, can significantly impact the efficiency and operational life of PV modules.
- **Extreme environmental factors**: natural disasters, such as strong wind, heavy rain, wildfire, and hail, can cause physical damage to the PV modules, leading to glass breakage, delamination, solar cell cracks, or other types of damage that can reduce PV module efficiency.

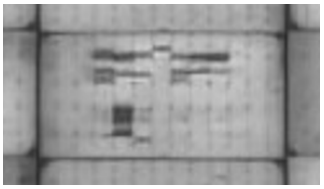
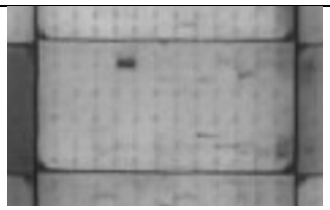
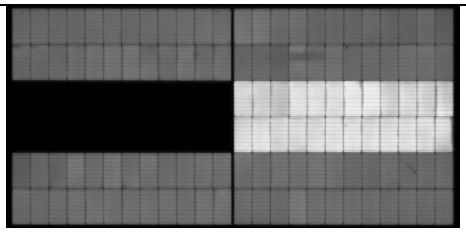
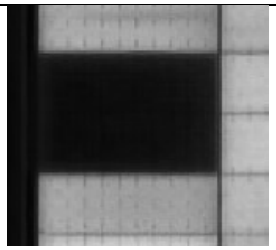
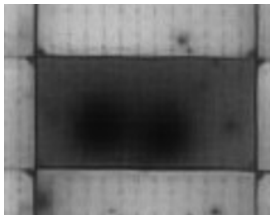
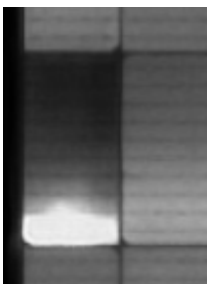
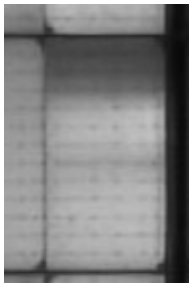
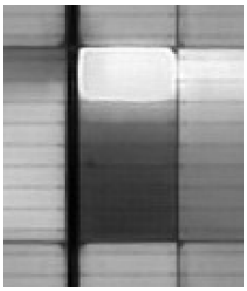
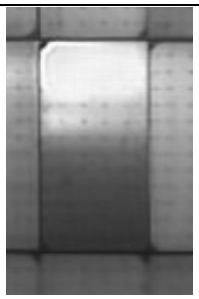
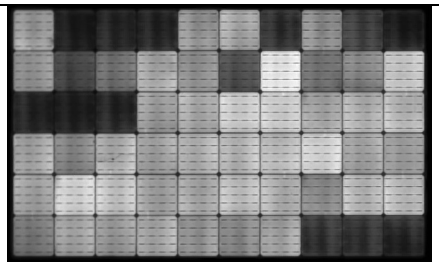
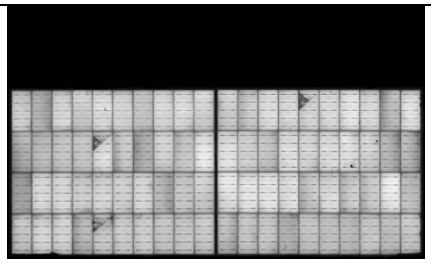
This diverse range of degradation factors underscores the essential need for comprehensive and regular inspections and proactive maintenance. For example, detailed evaluations are needed to identify PV modules that are significantly underperforming. By removing the worst performing PV modules, the so called “bottlenecks”, the optimal performance of the entire PV plant can be ensured, ultimately safeguarding its productivity, and extending its operational lifespan.

Introduction of the Autonomous Drone EL Mapping solution

The advent of Electroluminescence (EL) inspection technology in the PV industry represents a transformative leap in quality assurance practices, drastically improving the detection of defects within PV modules. This method, which involves applying an electrical current to PV cells to induce luminescence akin to that of an LED diode, has become an invaluable quality control tool in the PV manufacturing process. The emitted light, captured by sophisticated EL cameras, reveals the health of each solar cell: strong emissions indicate a well-functioning cell, whereas dimmed emissions point to potential defects. This stark contrast in luminescence provides an immediate, visual representation of a PV module's condition, thereby streamlining the process of identifying defective units. The following table provides examples) of defects observable through EL inspection, though this is not an exhaustive list.

Table 1. Example EL images showcasing a range of defects seen during field EL inspection, images courtesy of QE-Labs.

Defects/Features	EL image examples
Solar cell crack	
Backsheet scratch	
Dark spot	

Finger defect/interruption	 
Substring disconnection	
Shunted cell	 
Dark busbar	   
Excessive dark/shunted cells	
Bypass diode failure	

One of main defects identifiable by EL testing is solar cell cracks, which can significantly impede a module's performance. The classification system for crack severity, developed by Köntges et al., distinguishes between Type A (microcracks with no disconnection), Type B (cracks causing partial disconnection but still allowing for some power production), and Type C (cracks leading to complete disconnection and halting power production). An example EL image of a PV module consisting of all three crack types is shown below:

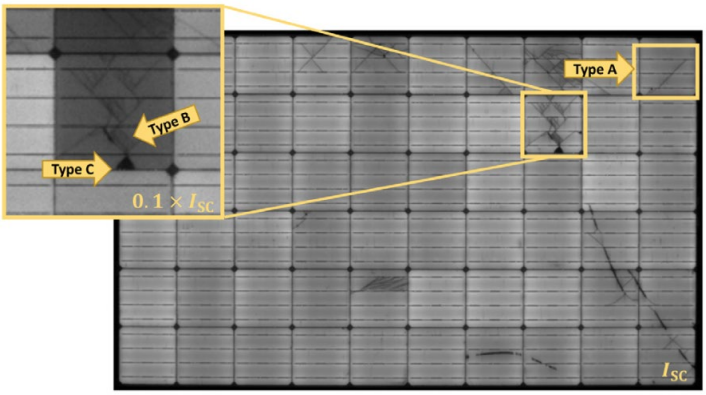


Figure 3. Electroluminescence (EL) image of highly damaged PV module. Highlighted are cell cracks of type A, B, and C, verified by low-current electroluminescence image.

This detailed categorization of crack types, visible through EL imaging, underscores the method's precision in assessing module integrity. Notably, while severe Type C cracks disrupt a cell's electrical continuity, Type A and B cracks, being less pronounced, might not be detectable by conventional infrared (IR) sensors, highlighting the superior diagnostic capabilities of EL inspection and the need for such detailed testing.

The findings of Claudia et al. from FZ-Juelich, published in the journal Progress in Energy, further support the integration of EL alongside other diagnostic techniques like drone IR thermography in the field. The study shows that EL measurements uncover extensive cell damage across nearly all modules, while drone IR) thermography identifies anomalies in only about half of the modules[1]. Consequently, the authors recommend that PV stakeholders consider integrating supplementary measurements, such as EL and Photoluminescence (PL), with drone IR thermography to meet specific inspection objectives.

[1] Infrared imaging of photovoltaic modules: a review of the state of the art and future challenges facing gigawatt photovoltaic power stations - IOPscience

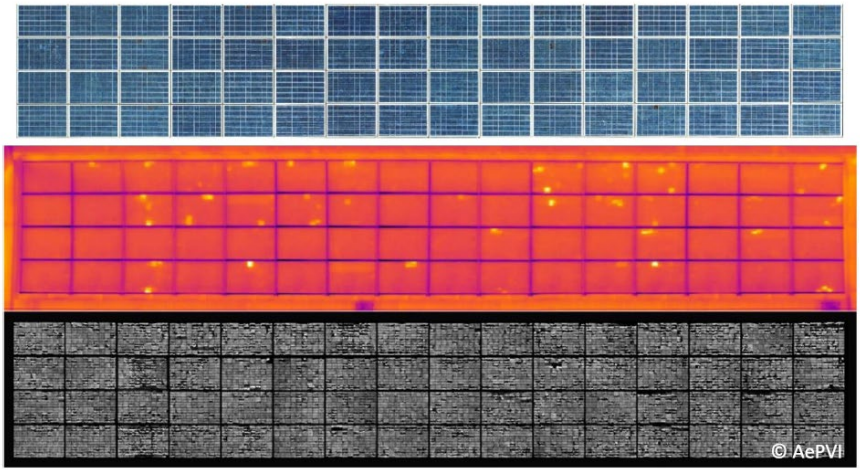


Figure 4. Comparison of visual (top), IR (center), and EL (bottom) measurements of a rooftop PV installation.

The paper by Oliver et al. discusses various outdoor luminescence techniques, highlighting their respective strengths and applications[2]. Despite its effectiveness, the traditional approach to EL testing is not without its challenges, particularly when applied to field inspections. The manual process is inherently slow— typically capable of inspecting fewer than 500 modules per night[3]— which renders it impractical for utility-scale solar projects, which may comprise hundreds of thousands of modules. This limitation has spurred the development of high throughput drone based EL testing, a groundbreaking method developed by Quantified Energy Labs over many years, that harnesses drone technology equipped with EL cameras and machine learning to expedite and scale the inspection process.

Furthermore, while PL and Ultraviolet Fluorescence (UVF) offer valuable insights in certain contexts without an electical current injection into each string, their application in drone-based inspection scenarios faces significant limitations. The primary challenge lies in the requirement for a high-intensity light source to excite the PV modules, which, due to its weight and power consumption, would considerably reduce a drone's flight time. This constraint makes PL and UVF less viable for drone-based inspections, highlighting the advantage of EL as an alternative for drone integration.

[2] https://iopscience.iop.org/article/10.1088/2516-1083/ac9a33
[3] https://www.engineeringnews.co.za/article/rapid-advancement-in-quality-testing-for-large-pv-plants-2024-03-12



Figure 5. UVF inspection at night utilizing high-intensity light source. The substantial weight and power required for external light source excitation, necessary in inspection methods such as UVF and PL, render them impractical for drone applications.

Quantified Energy Labs (QE-Labs) has emerged as a forerunner in this innovative domain. Established in 2019 by experts from the Solar Energy Research Institute of Singapore (SERIS) at the National University of Singapore (NUS), QE-Labs has demonstrated a remarkable capability to inspect up to 15,000 modules per night shift at utility-scale solar farms. This breakthrough is enabled by the comprehensive solutions QE-Labs has developed. The solution features custom-built hardware including a high-sensitivity SWIR camera with an onboard PC that facilitates autonomous drone flight while optimizing imaging parameters for superior quality. Further enhancing their approach is QE-Labs' software for post-processing, an AI model trained with millions of field EL images for accurate feature detection, and an innovative algorithm capable of estimating power loss based on EL images. Complementing these technological advancements is a digital twin interactive dashboard; this platform offers an advanced visualization toolkit, incorporating features like filtering and custom rating systems, to accurately pinpoint defective modules. Together, these elements comprise a full spectrum solution that revolutionizes the efficiency and accuracy of PV module inspections. Among all PV module field inspection offerings, QE-Labs' drone EL solution provides the best value for money, achieving unparalleled benefits to the user in terms of diagnostic throughput, cost-effectiveness, level of details, lifecycle quality management, and overall efficacy.

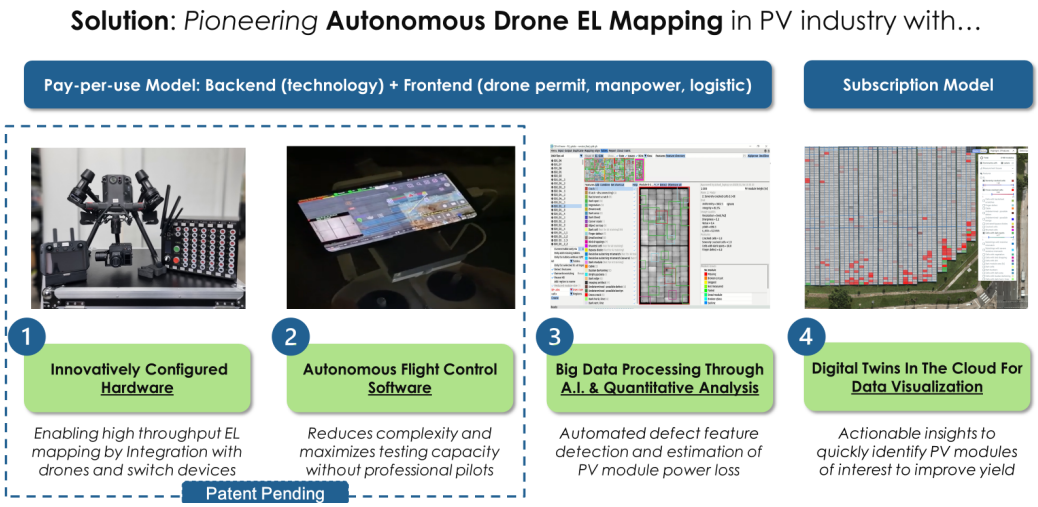


Figure 6. QE-Labs drone EL mapping solution. It is a blend of proprietary hardware, software automation and AI-driven analytics coupled with a digital twin platform.

QE-Labs' technology has been demonstrated across various stages of the PV lifecycle, with millions of modules evaluated. Some key applications include:

- **COD Acceptance Test**: Detects installation faults and establishes a baseline for the PV plant.
- **Pre-DLP Assessment**: Uncovers construction and maintenance-related issues before the site handover from EPC to the owner.
- **Warranty Claim**: Identifies underperforming modules for claims with PV manufacturer.
- **Insurance Claim**: Detects modules damaged caused by natural disasters.
- **Technical Due Diligence**: Evaluates PV asset health for asset transactions.
- **Revamping and Repowering**: Pinpoints and replaces underperforming modules to boost system performance.

Among these use cases, the use of drone EL mapping for insurance claims is growing, given the increasing frequency of extreme weather occurrences at very large solar sites, which are impractical to inspect from the ground.

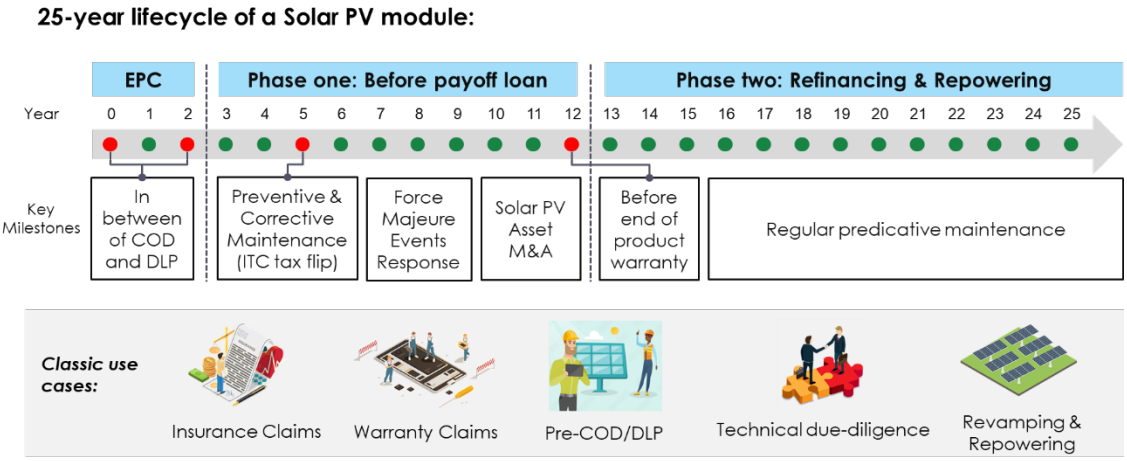


Figure 7. Example use case of drone EL inspection in different stages of PV lifecycle.

Use of drone EL Mapping: evaluation of extreme weather damage to solar farms

In recent years, the escalating impact of global warming has heightened the frequency and severity of natural disasters and the damage to energy infrastructure, leading to substantial financial repercussions. Munich Re[4] reported that in 2022 alone, global natural disaster losses amounted to a staggering $270 billion USD, marking a significant increase from previous years. The solar PV sector has not been spared from these challenges, as evidenced by a 2022 hailstorm in Texas that inflicted damage on several solar sites, with over 400,000 solar panels destroyed on a single site alone. This resulted in insurance losses totalling 150 million USD on one solar site — the largest weather-related loss for a single project on record[5].

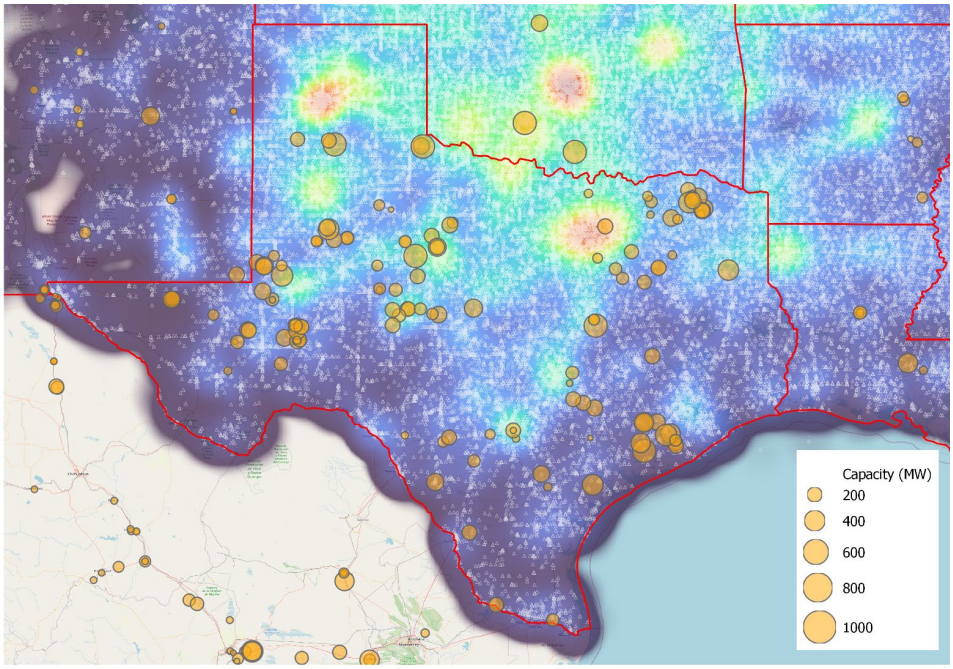


Figure 7. Map depicting the PV installation locations in Texas alongside the frequency of hailstorm incidents. Image Credit: QE-Labs

Following this catastrophic event in Texas, insurance premiums surged by as much as 400% over the subsequent 18 months. Insurance companies have responded by implementing stricter insurance policy provisionswith higher premiums and deductibles and more onerous provisions, whilst necessitating that solar asset owners furnish comprehensive inspection results capable of precisely identifying and quantifying damage at the solar cell level, including the detection of solar cell cracks.

There have also been multiple wind-related failures of solar tracker systems, and of racking systems, many of which have also resulted in damage to PV modules. This damage may be

[4] https://www.munichre.com/en/company/media-relations/media-information-and-corporate-news/media-information/2023/natural-disaster-figures-2022.html
[5] https://www.pv-magazine.com/2021/03/19/storm-season-has-the-us-solar-industry-looking-to-protect-assets-from-costly-hail-damage/

obvious, in the form of visual damage to the modules, or the modules may have non-visible damage resulting from them being twisted. Similarly, heat damage to modules from fire may also result in non-visible damage. Amidst this backdrop, the potential $20 billion investment for developing 36GW of solar capacity in Texas over the next five years underscores the urgency for robust risk management strategies to protect solar assets against such high-risk weather events, and speed the recovery of those sites that do get impacted by severe weather. The implementation of strategic measures, both at the system and module levels, is essential for minimizing damage. For instance, some tracking systems are now designed to automatically adjust to a safer angle (typically 75 degrees) upon detecting hail threats, using weather service data, effectively mitigating potential damage. However, whilst this may seem like an obvious solution to the hail problem, it is not without its problems. Stowing modules at high angles may result in wind damage to the tracker system and modules, which typically will stow at lower angles to prevent wind damage from severe convective storms. This is a dilemma that has yet to be fully resolved, especially given the drive to reduce tracker system costs by minimising materials and system complexity, which typically results in less robust trackers. One solution would be to employ thicker glass for solar panels, which has been shown to enhance resilience against hail impacts, as illustrated in the comparative resiliency curves below[6], however, this would result in heavier and more costly modules, requiring more robust trackers and foundations

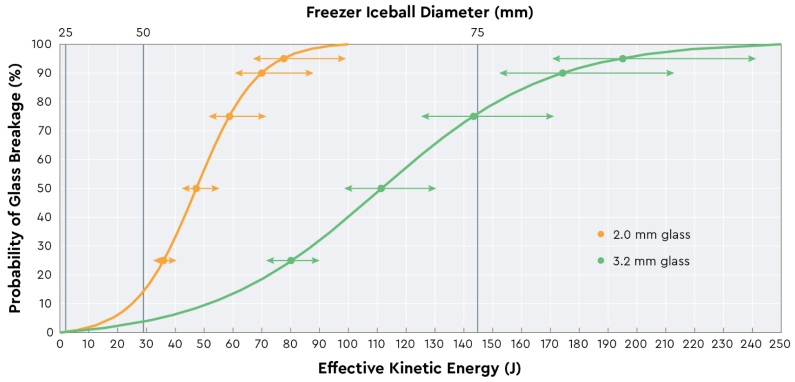


Figure 8: Comparative freezer ice ball resiliency curves for common c-Si PV module packages

These problems underscore the critical role of advanced inspection technologies in the solar industry's ongoing battle to minimise the consequences of extreme weather events and recover fast post-event. Drone EL mapping offers a comprehensive solution for assessing damage accurately and efficiently, enabling solar asset owners to navigate insurance claims more effectively and reinforcing the resilience and sustainability of their solar investments.

[6] https://retc-ca.com/news/module-glass-impacts-hail-resiliency

Proposed best practice for post-natural disaster response: Damage evaluation, insurance claim, rebuilding, and documentations

Following the unfortunate occurrence of natural disasters such as typhoons, sandstorms, or hailstorms affecting PV plants, it is crucial for asset owners to immediately assess the extent of the damage and initiate the insurance claim process to recuperate financial losses from material damages and operational downtimes. The complexity of this situation requires a systematic approach for comprehensive damage assessment, effective substantiation of claims, efficient execution of rebuilding initiatives, and meticulous documentation of the solar PV plant's condition post-recovery. Following workflow is developed based on industry insights and observations of best practices with the aims to guide asset owners through the aftermath of such events effectively.

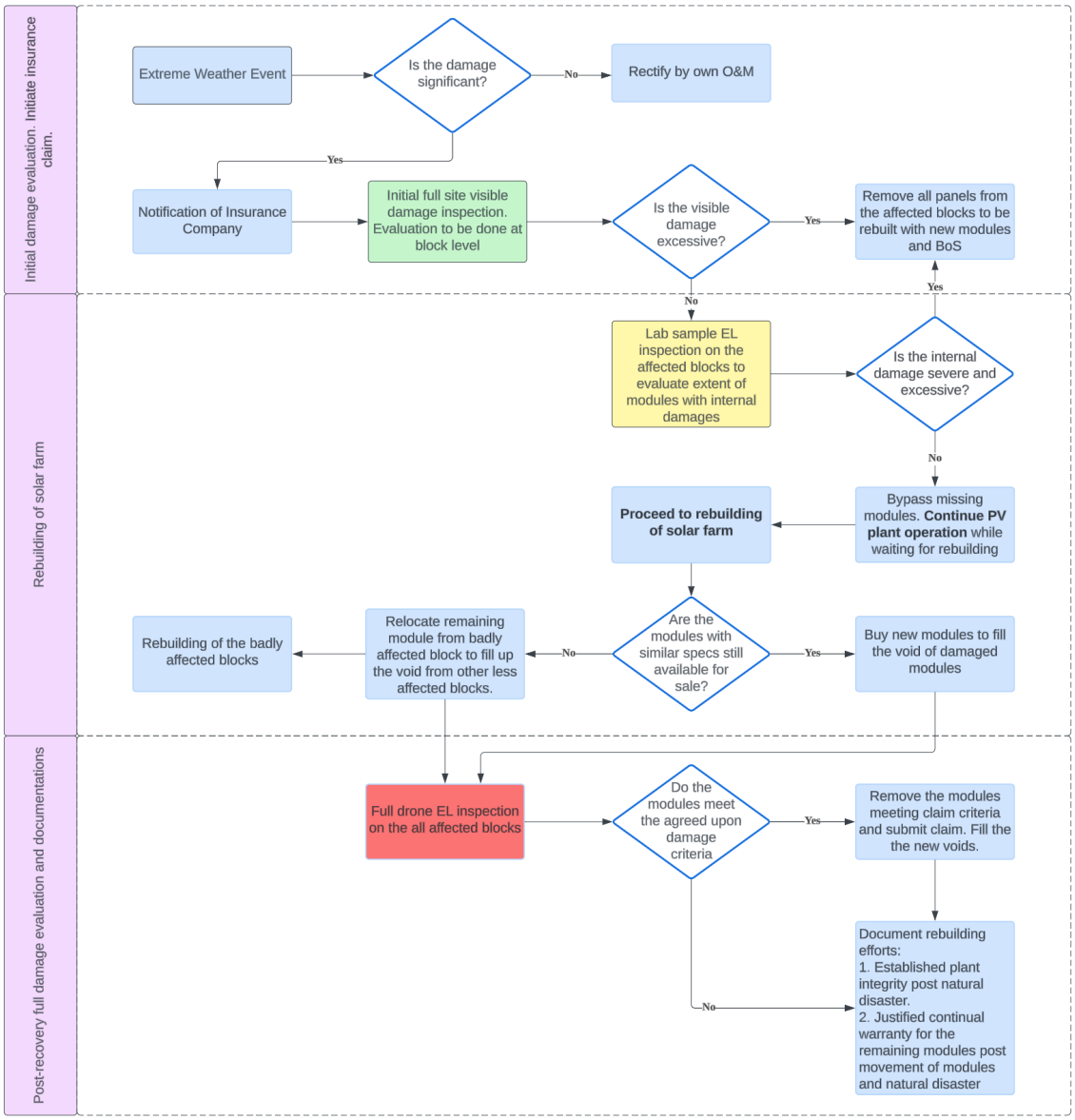


Figure 9. Workflow for post-disaster recovery in solar PV operations: From initial assessment to restoration and comprehensive documentation

Phase One: Initial Damage Evaluation and Insurance Claim Initiation

Key Inspection: Drone Visual Inspection - The identification of all direct physical damage is pivotal at this juncture, providing basic data for the initiation of an insurance claim and the subsequent recovery measures.

The initial stage post-disaster focuses on a thorough evaluation of the PV plant's physical damage. This crucial phase determines the required immediate corrective actions and sets the foundation for the insurance claim initiation. In instances where the damage is minimal, asset owners might opt to address the issue directly through their O&M team.

Upon deciding to proceed with a claim, the insurance company should be promptly notified, and the process of gathering evidence of damage begins. Modules that are either displaced from their original positions or exhibit visible damage generally qualify for insurance claims. Utilizing drone aerial photography facilitates the rapid creation of a detailed 2D map, offering a complete bird's-eye view of the entire solar farm.

By integrating the visible map with the layout design of the PV system and employing AI to automatically recognize broken modules, the asset owner can precisely identify the number of PV modules that are visibly damaged, thereby providing concrete evidence for the claim. For large-scale utility projects, fixed-wing UAVs or manned aircraft capable of flying at 500m above ground are occasionally employed to achieve a quicker response compared to the slower conventional drone mapping methods.

Points to note - While drone visible damage mapping is fast, it may not be able to capture smaller damage such as minor glass cracks at the module edges. These defects can be picked up in the final phase of EL inspection, and should be captured, as they may affect the longevity of the modules

Phase Two: Rebuilding the Solar Farm

Key Inspection: Sample EL Inspection - This phase is crucial for verifying the extent of internal/non-visibledamage to modules, thereby informing the decision-making process for the solar farm's effective rebuilding or repair.

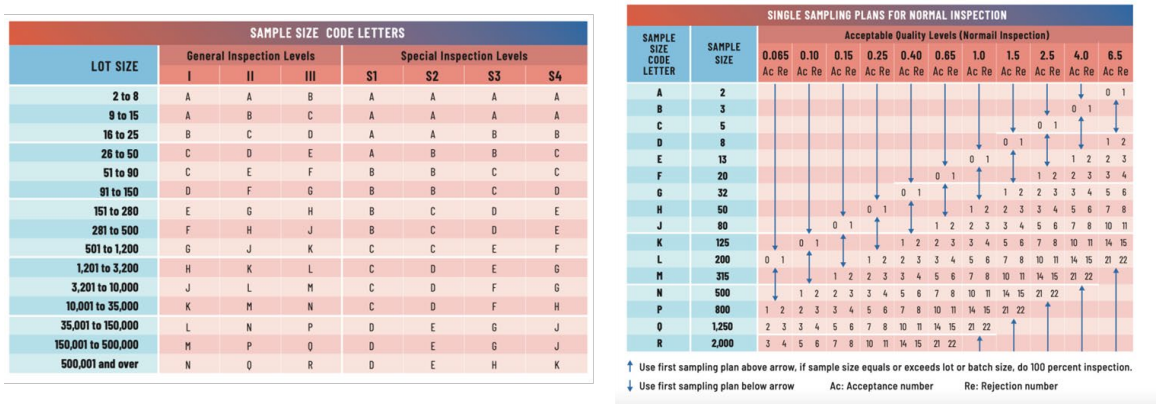
Following the completion of the initial visual damage assessment and the initiation of the insurance claim process, the focus shifts towards the reconstruction of the solar farm. The first crucial step in this phase is to assess whether the modules that appear intact have sustained severe internal damage. For this, a targeted sample EL inspection should be conducted.

The rationale behind opting for a sample EL inspection lies in the urgency to commence the rebuilding process without delay. By selectively examining a representative sample of modules through EL inspection, one can efficiently assess the extent of internal damages, if any, across the entire block or affected areas. This approach allows for initial swift determination of the modules'

condition, facilitating an informed decision on the necessity and scope of rebuilding efforts. It's a strategic balance between thoroughness and speed, designed to expedite the restoration of the solar farm to its operational state as swiftly as possible.

A strategic approach to sample EL inspection should be implemented, such as using the Acceptable Quality Limit (AQL) table outlined in ISO 2859-1 standard. This involves selecting a representative sample of modules from different areas across the PV plant, acknowledging that damage severity may vary significantly between locations due to the heterogeneous nature of natural disaster impacts. Given the general subdivision of the PV plants into distinct blocks, samples are chosen from each block to provide a well-rounded assessment of the entire installation.

For illustrative purposes, consider a 100MW system comprising 150,000 modules, segmented into 5 blocks. Each block consists of 30,000 modules. Adopting a General Inspection Level I, the sample size code K dictates that 125 modules from each block are to be sent to the lab for measurement. Consequently, a total of 625 modules will be sent to the lab.



SAMPLE SIZE CODE LETTERS

LOT SIZE	General Inspection Levels			Special Inspection Levels			
	I	II	III	S1	S2	S3	S4
2 to 8	A	A	B	A	A	A	A
9 to 15	A	B	C	A	A	A	A
16 to 25	B	C	D	A	A	B	B
26 to 50	C	D	E	A	B	B	C
51 to 90	C	E	F	B	B	C	C
91 to 150	D	F	G	B	B	C	D
151 to 280	E	G	H	B	C	D	E
281 to 500	F	H	J	B	C	D	E
501 to 1,200	G	J	K	C	C	E	F
1,201 to 3,200	H	K	L	C	D	E	G
3,201 to 10,000	J	L	M	C	D	F	G
10,001 to 35,000	K	M	N	C	D	F	H
35,001 to 150,000	L	N	P	D	E	G	J
150,001 to 500,000	M	P	Q	D	E	G	J
500,001 and over	N	Q	R	D	E	H	K

SINGLE SAMPLING PLANS FOR NORMAL INSPECTION

SAMPLE SIZE CODE LETTER	SAMPLE SIZE	Acceptable Quality Levels (Normail Inspection)											
		0.065	0.10	0.15	0.25	0.40	0.65	1.0	1.5	2.5	4.0	6.5	
		Ac Re	Ac Re	Ac Re	Ac Re	Ac Re	Ac Re	Ac Re	Ac Re	Ac Re	Ac Re	Ac Re	
A	2										↓	0	1
B	3										0	1	↑
C	5									0	1	↑	↓
D	8								0	1	↑	↓	1
E	13							0	1	↑	↓	1	2
F	20						0	1	↑	↓	1	2	3
G	32					0	1	↑	↓	1	2	3	4
H	50				0	1	↑	↓	1	2	3	4	5
J	80			0	1	↑	↓	1	2	3	4	5	6
K	125		0	1	↑	↓	1	2	3	4	5	6	7
L	200	0	1	↑	↓	1	2	3	4	5	6	7	8
M	315	↑	↓	1	2	3	4	5	6	7	8	10	11
N	500	↓	1	2	3	4	5	6	7	8	10	11	14
P	800	1	2	3	4	5	6	7	8	10	11	14	15
Q	1,250	2	3	4	5	6	7	8	10	11	14	15	21
R	2,000	3	4	5	6	7	8	10	11	14	15	21	22

↑ Use first sampling plan above arrow, if sample size equals or exceeds lot or batch size, do 100 percent inspection.
↓ Use first sampling plan below arrow Ac: Acceptance number Re: Rejection number

Figure 10. Sampling Strategy and AQL Table According to ISO 2859-1

Ideally, the selected sample modules should be sent to an ISO 17025 accredited third-party testing laboratory for EL inspection, ensuring the highest standards of testing accuracy and reliability. However, onsite manual EL inspections may be conducted as an alternative if mutually agreed upon by both the insurance provider and the asset owner. This flexibility is important to accommodate various logistical or operational constraints, providing a viable pathway for internal damage assessment when laboratory inspections are not feasible.

Points to note - If any blocks fails the initial sample EL inspection, the owner may opt for a second round of testing within the block by expanding the sample size. This subsequent inspection might employ General Inspection Level II protocols, facilitating a more comprehensive verification of the initial findings.

If the EL inspection reveals excessive damage within a block, the most viable option may be to remove all modules from that particular block and proceed with a complete rebuild. This comprehensive approach is necessary when the integrity and functionality of a substantial portion

of the modules are compromised beyond repair, posing a significant risk to the overall performance and safety of the PV plants.

For blocks that pass the sample EL test, the next part of the strategy involves bypassing the damaged modules, allowing those blocks to continue operation during the rebuilding process. The subsequent steps depend on the market availability of PV modules with matching specifications. If identical new modules are unavailable, then modules from the more severely damaged areas could be relocated to fill the gaps in less affected blocks, and new PV systems with differing module specifications would be constructed in the severely affected areas. Owners generally view this option unfavourably due to the additional costs and uncertainties associated with module removal and relocation. Conversely, if matching new modules are readily available, they represent the most efficient and cost-effective way to fill the void after replacing all visually damaged modules. If identical modules are not available, this may create mismatch problems both electrically and with physical attachment to the tracker system, which should also be considered.

Each of these actions—whether it involves a complete rebuild of a block, bypassing damaged modules for continued operation, reallocating available modules, or purchasing new ones—requires careful planning and execution. This phase of the recovery process underscores the importance of a flexible yet strategic approach to post-disaster rebuilding, tailored to the specific conditions and needs of the PV plant.

Phase Three: Comprehensive Post-Recovery Evaluation and Documentation

Key Inspection: Full-Scale EL Inspection - This thorough evaluation is indispensable for identifying all damaged modules for claims and for documenting the new baseline condition of the PV plant post-recovery.

Following the strategic rebuilding and restoration efforts undertaken in Phase Two, Phase Three focuses on a thorough post-recovery evaluation and documentation of the new baseline performance of the PV plant. This critical phase ensures that all recovery efforts are comprehensively assessed and accurately recorded, serving as a crucial step for both operational resumption and finalizing the insurance claim process. In this phase, a mass EL inspection is carried out across all the affected blocks that have been rebuilt. It aims to uncover any overlooked damage or new defects that may have developed during the rebuilding phase. Figure 10 shows an example of uncovered modules with cell cracks after the EL inspection of a solar farm affected by a hailstorm. With the advent of drone EL and post-processing technology, minute defects up to the microcrack level can be detected.

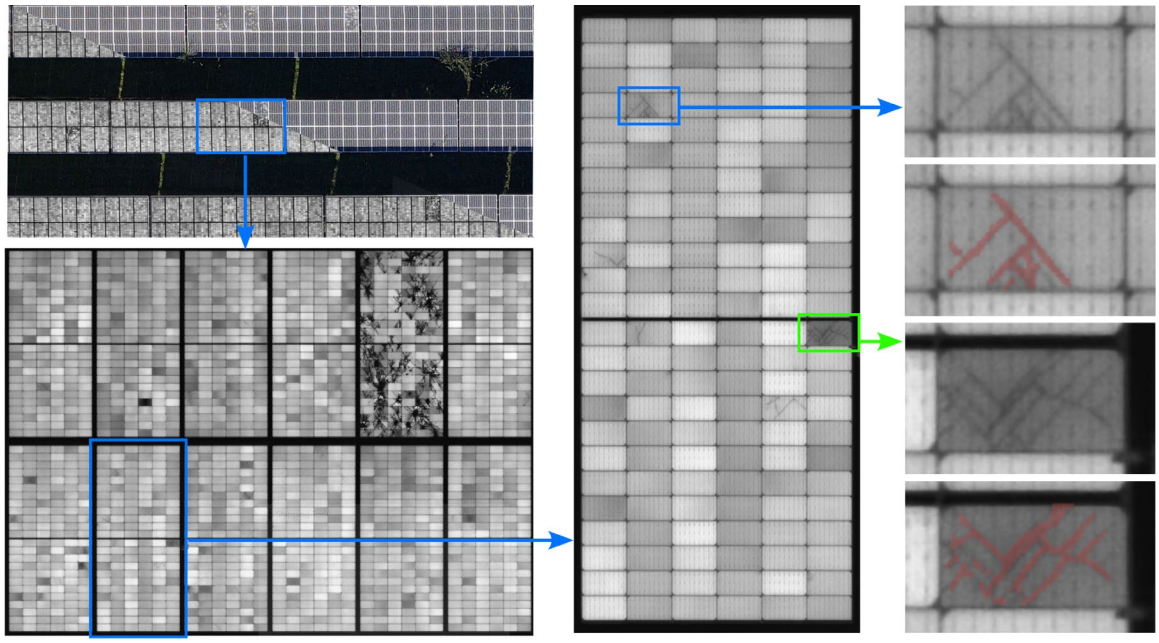


Figure 11. Following a hailstorm, this solar farm underwent a comprehensive Electroluminescence (EL) inspection to identify damaged modules. Utilizing AI technology, cracks within the cells were automatically detected and categorized.

All of the modules meeting the damage criteria previously established and agreed upon with insurers are designated for claims submission. These criteria differ among insurers and PV plants. Nevertheless, the use of advanced digital solutions, including AI to automatically detect various defects, simplifies the identification process. The criteria of interest can be easily modified, enabling asset owners to quickly pinpoint modules requiring attention.

Points to note – With the increasing frequency of extreme weather events and a rise in insurance claims, insurers are looking more closely at their criteria for claim eligibility. For example, in the past, hail-damaged modules that would have qualified for claims would have been modules with more than 3 cracked cells detected in an EL inspection. Howeversome insurers have more strict criteria, who demand that over 25% of a module's cells must be cracked to consider the module “damaged”.

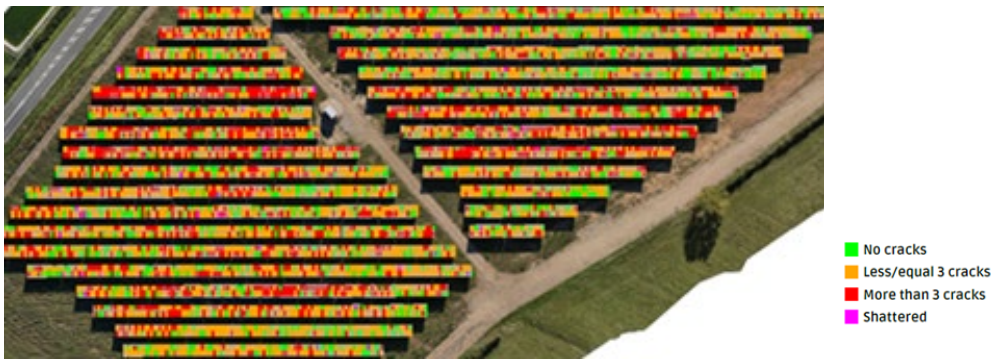


Figure 12: Interactive dashboard displaying condition of modules according to criteria agreed upon with the insurer for the claim, offering a clear overview of modules that require further action.

In typical rebuilding scenarios where PV plants integrate new modules to replace the broken modules, there will be a mix of new and existing modules in the PV plants. This integration, although it may be the quickest and most cost-effective, could introduce mismatches in the PV plant that could affect PV plant overall efficiency, and therefore should be monitored post recovery. With high sensitivity, EL inspection also serves as a good tool to document the final position of the old and new modules in the PV plant by differentiating the difference in luminescence signal: new modules exhibit brighter luminescence, signaling higher efficiency and minimal degradation, in contrast to the older modules' dimmer output, indicative of wear and reduced performance.

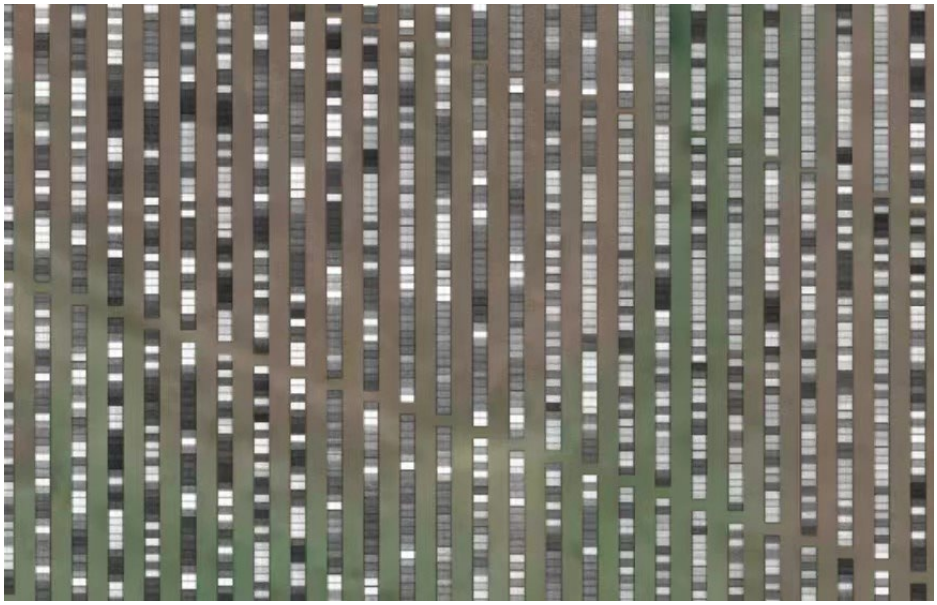


Figure 13. Showcases an EL map of a PV plant, illustrating the distinct mismatch between newly replaced modules and their older counterparts.

By accurately capturing this mismatch, EL inspection can precisely determine which part of the plant contains new versus old modules. This serves as a powerful tool for comparison and traceability in asset management.

Phase Three is not merely the conclusion of the recovery process; it exemplifies a transition from overcoming mishaps to demonstrating operational excellence and resilience. This pivotal phase involves a thorough evaluation and meticulous documentation, enabling asset owners to establish a robust foundation for the PV plant's enduring success and sustainability. Through this transition, the phase highlights the capacity for strong management and adaptability in addressing challenges, setting a new standard for resilience and operational efficiency in the solar industry.

Discussion

Upon identifying module defects through a comprehensive EL inspection, insurance companies may request verification of the defects' origins to determine if they resulted from natural disasters. Figure 14 presents EL images from a PV plant after a severe hailstorm, depicting modules with cell cracks. The modules with dendritic cracks and dark areas are a clear indicator of hail impact damage. However, without a baseline established before the hailstorm, the module on the right with minor cracks may fail to meet insurance policy criteria due to the inability to conclusively determine their origins, despite the potential long-term reliability issues they pose due to potential future crack propagation.

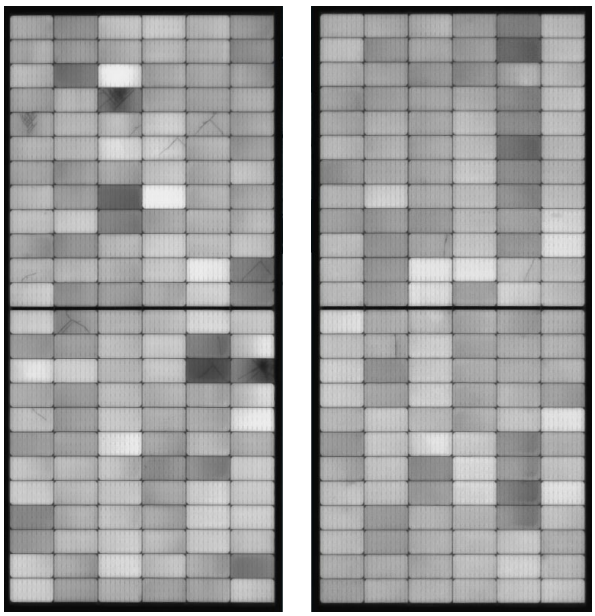


Figure 14. EL images of modules following inspection of a PV plant affected by a severe hailstorm. Excessive cell cracks are observed. However, only the first and second modules that exhibit the cracks suggestive of hail impact qualified as being “damaged” undre the insurance policy.

This underscores the importance of establishing a health baseline for modules at critical project milestones to enhance the insurability of PV projects. Such practices ensure accurate identification of the root causes of module defects—whether from natural disasters, manufacturing defects, installation errors, or operational issues—providing clear evidence for insurance claims and facilitating financial recovery.

In conclusion, setting a baseline is crucial for effective PV asset management, particularly for insurance claims. It forms the foundation for accurately identifying the origins of defects, leading to fair and efficient resolutions of claims.

Summary

This paper discusses the critical role of EL inspection technology throughout the lifecycle of PV plants, particularly emphasizing its significance in the context of insurance claims after natural disasters. It systematically details the three phases for managing such event and the strategic use of different inspection technologies at each juncture. For some insurance claims, coverage is only available for damage that can be directly attributed to the natural disaster. As such, it is important to establish the baseline condition of PV plants to pinpoint the origins of defects. This baseline data is essential for substantiating insurance claims at later stage.

Moreover, the paper explores various challenges and considerations important to navigating post-disaster recovery, offering insights into best practices for comprehensive damage assessment, claim substantiation, rebuilding efforts, and meticulous documentation of PV plant status. EL inspection is not only important for defect identification, but also serves as a tool for ongoing asset management, especially in documenting and managing the mix of new and old modules within a rebuilt system.

By collating QEL-Labs' experiences, observations, and industry best practices, this paper aims to serve as a comprehensive guide for stakeholders in dealing with solar farm insurance issues after extreme weather events. It seeks to provide a roadmap for not only weathering the storm of natural disasters but also emerging with a more robust, better documented system, through informed decision-making and strategic use of technology. The overarching goal is to enhance the resilience and sustainability of solar PV investments, contributing to the broader narrative of building a more durable and adaptive solar energy landscape.