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MICROCRACKS

ARE THEY REALLY A PROBLEM?

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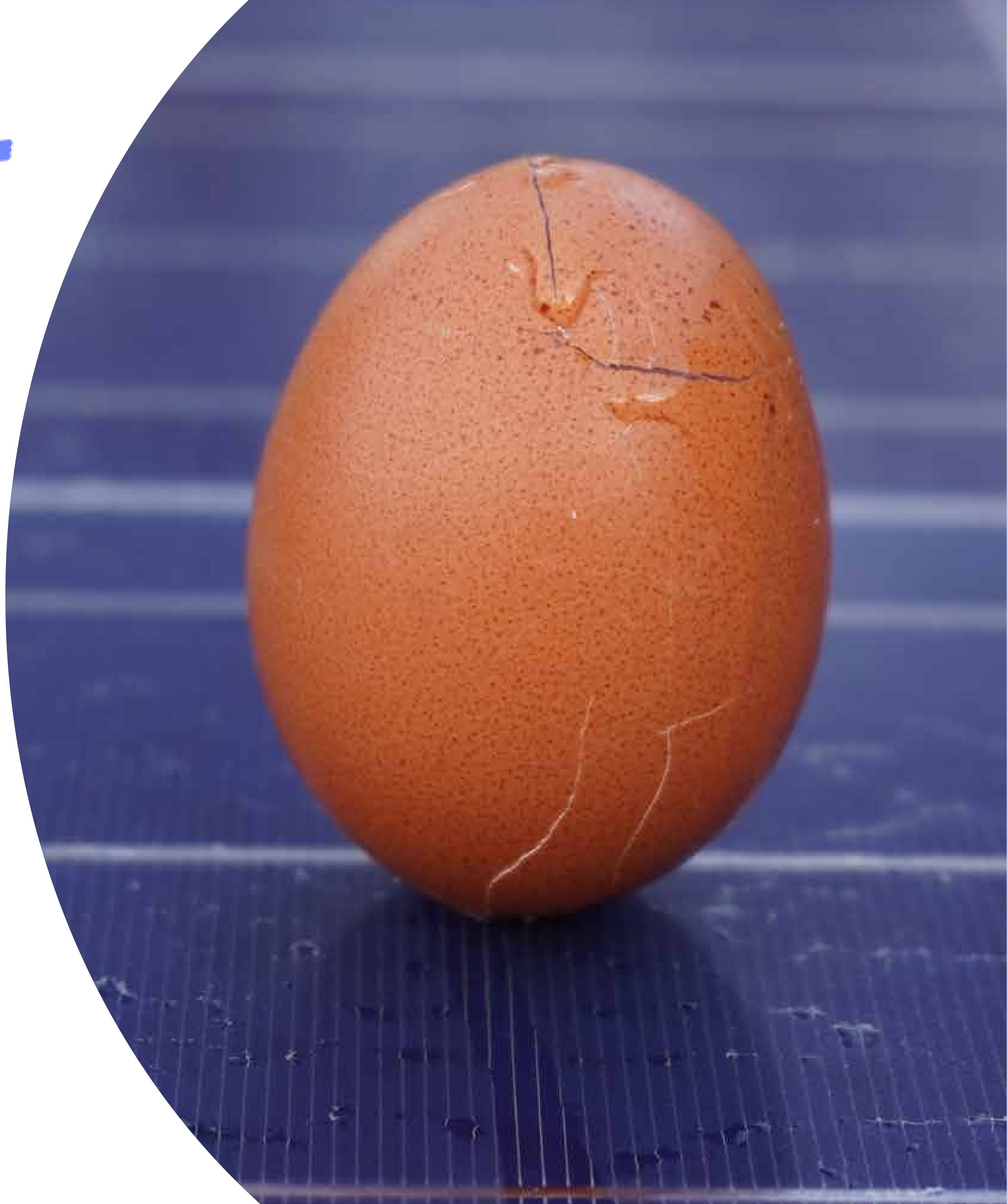
Introduction

Microcracks

Picture yourself shopping for half a dozen eggs

What do you do before heading to the tills? You open the carton, and check they're not cracked. Seems logical. Why? Because no one wants to buy cracked eggs.

Now let's apply our egg selection theory to Solar PV modules. Would broken, cracked modules, destined for future energy loss, make the cut for your new build sites? Hopefully not. So why are the majority of operational solar fleet in the UK riddled with micro-cracks? Is the UK industry a Lion Stamp short of proper quality testing, or are we making a mountain out of a micro-crack? Let's find out.



A Sunny Start...

The UK experienced a solar boom between 2012-2017; with the assistance of the feed in tariff (FiT) and renewable obligation certificates (ROC) subsidy regimes, over 8GW's of ground mount solar was installed. This was an amazing accomplishment, and the UK positioned itself as a global pioneer and leader in the renewable energy revolution.

A competitive, price-driven market ensued, and the cheapest energy became most desirable. With the diminishing ROC levels falling in March annually, the vast majority of construction happened during the cold & wet UK winter months. Subsequently, from a practical and operational perspective, a large proportion of the UK fleet was constructed using substandard materials; equipment selection, construction profit-based designs and installation standards were also an afterthought. This laid the foundations for widespread issues, as many EPC contractors were naturally looking for ways to cut corners, save money and maximise profits. Experts from more mature European markets agree that this is a recurring cycle; it happened in Germany, Spain and Italy, and it will continue to happen in emerging markets globally.

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A Bleak Investment?

The main concern we have, and the market should have, is the primary piece of CAPEX investment contained within a solar farm: the solar modules themselves. Understanding their origins, the quality standards in which they were manufactured, the shipping & transportation methods, the way they were (in some cases) thrown on to the mounting structure and handling during the construction phase of a plant. All damage inflicted, whoever is to blame, was and is avoidable. And by acknowledging this negligence, we can ascertain that potential future losses are avoidable.

Based on the testing of over 20,000 modules, and conducting site assessments on over 125 sites, our perception is that micro-cracks are by far the most widespread module damage characteristic in existence in the UK, and perhaps worldwide. This is naturally due to the fragile nature of the silicon wafer itself. This has been exacerbated by manufacturing standards, poor packing and transportation methods, and worst of all, the handling and installation methods on site. From our data, based on modules containing defects of any type, 98% of them are micro-cracks on a cell-count basis; this means that they are by far the most popular and prevalent cell-based defect that exists. The other 2% are everything else which exists (PID, LeTID, soldering related issues, grid finger interruptions etc).

Research and Misconceptions

It is estimated that in over 75% of sites in the UK (taking 125 as a representative sample), you will find significant widespread mechanical damage in the form of micro-cracks. These will vary in intensity, distribution and potential long-term impact. Interestingly, in most cases, certainly in 3-to-5-year-old plants, these micro-cracks have a negligible effect on output power of the modules.

And due to this single point on power output, the findings generally lead to no action; this perpetuates the perception that advanced testing techniques such as Electroluminescence & flash testing is over-priced, and it highlights defects that have little impact on the owners bottom line. This misconception needs to be explored and discussed.

So, what's going on here? What is a micro-crack, and how does it affect production? And if it's not affecting production now, will it do in the future, and to what extent? Further research, and the sharing of knowledge is needed to identify micro-cracks in the field, and to effectively manage them to maximise future generation. This article aims to explore these questions.

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What is a Micro-crack?

The term 'micro-crack', or' micro-fracture', refers to fine cracks in the crystalline silicon cells which make up solar modules. They are invisible to the eye, and in most cases, the original cause will be from manufacture, installation and/or operational environmental sources. These micro-cracks will propagate further when subjected to mechanical and/or thermal stresses to form established cracks. In the case of this report all cracks (micro or not) will be referred to as micro-cracks.

It's important to realise that, although these cracks are widespread and will (at some point) impact on cell/module/string production, they are not actually a surprising flaw; in our view, they are inevitable. If you think about it, manufacturing square cells of a brittle material is in itself problematic. They are approximately 700 times wider than they are thick, and existing outside to heat up, cool down and be buffeted by the wind tests the material. They are designed to endure such conditions, and indeed exposure to rain and snow, but human forces such as packing, loading, handling, installation, and mechanical forces bring opportunity for cracks.

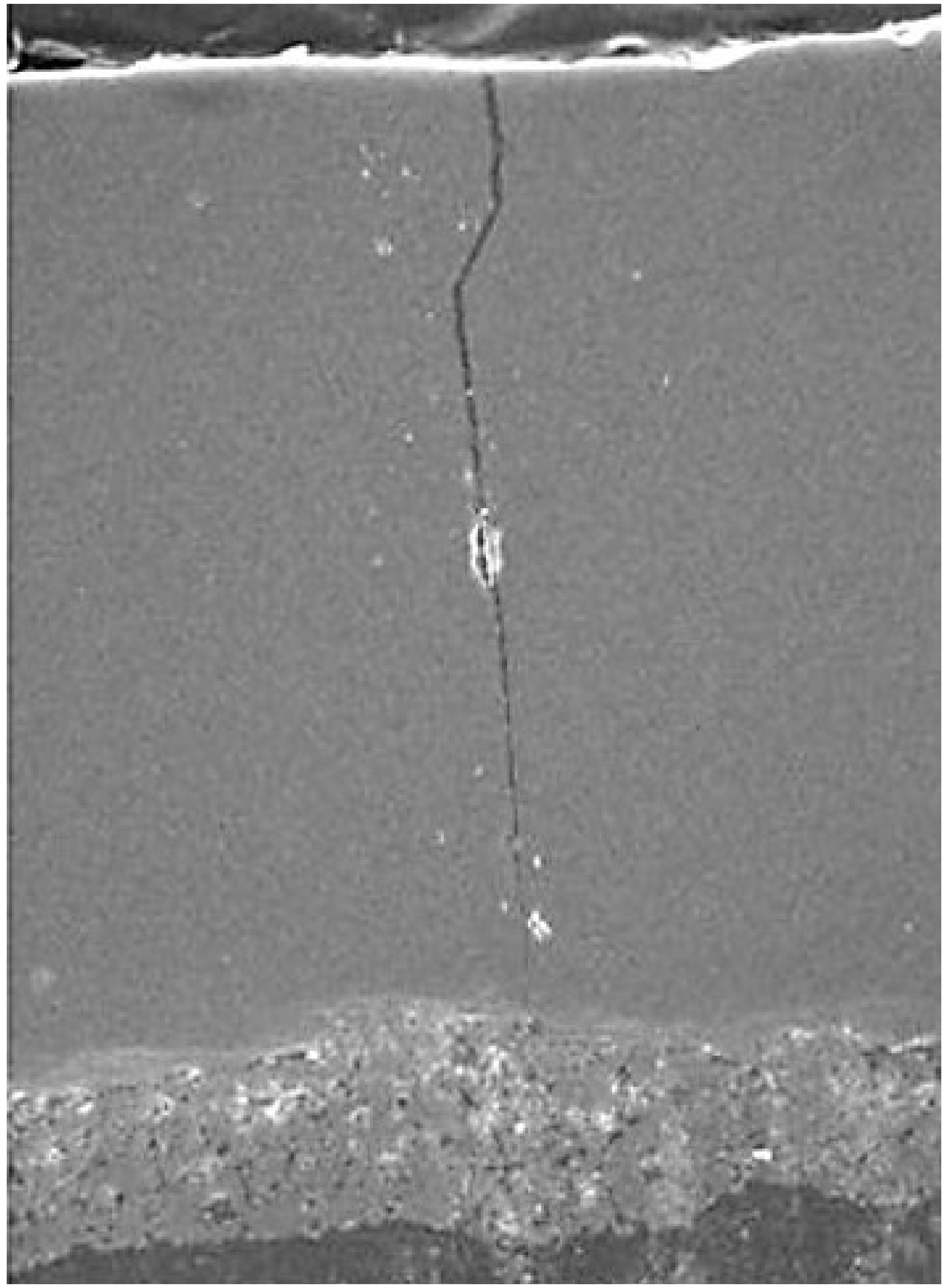

IMAGE CREDIT: KENT KERNAHAN AND PETER CURZON

Progressive Technology

Of course, it's safe to say that module technology has moved on significantly over the last few years, and the continual development of thicker wafers and stronger glass/laminate fronted modules is encouraging. I've seen more video clips of people jumping up and down on modules in the last 12 months than ever before; so perhaps they've cracked it? (excuse the pun). No more micro-cracks… Well, not quite.

Being aware of the manufacturing methods, materials and design is necessary, but young cracks remain prevalent in brand new, contemporary modules and even more in the field following installation. So, it hasn't gone away, but more-so improved by a significant factor. The operational fleet which has the thinner more susceptible to micro-cracks modules has not gone away, and there are still pro-active measures that can be taken to further reduce micro-cracked modules on new build sites.

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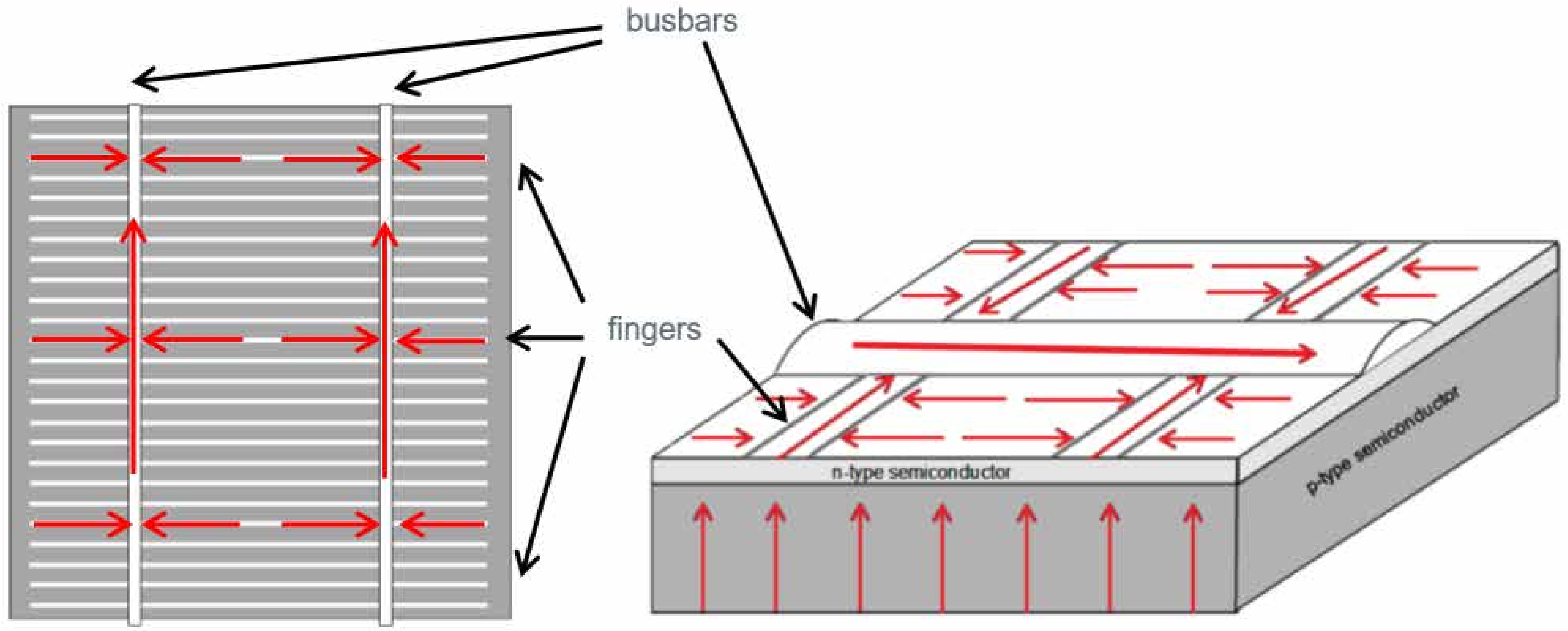
How do Micro-cracks affect the power output of a module?

Micro-cracks themselves will not cause a current flow interruption as long as the grid finger is still intact. But in instances where a microcrack exists, it doesn't take long before the grid finger breaks. In the early stages of a recent grid finger break or tear, the current flow may still be able to flow when the cell is cold; it will only be interrupted when the cell heats up, and creates a void. As the cell cycles over time, this void will open up until it is wide enough for a current flow interruption. This will be permanent and irreversible.

Visualize the current being created in the blue crystalline areas of the cell; it flows to the grid fingers, passes through to the bus bars, and travels on to the next cell in series. Any interruption in these grid fingers can restrict the flow of current and power output of the cell & module, but only if the crack/fracture is in a particular area, orientation and length in relation to the cell.

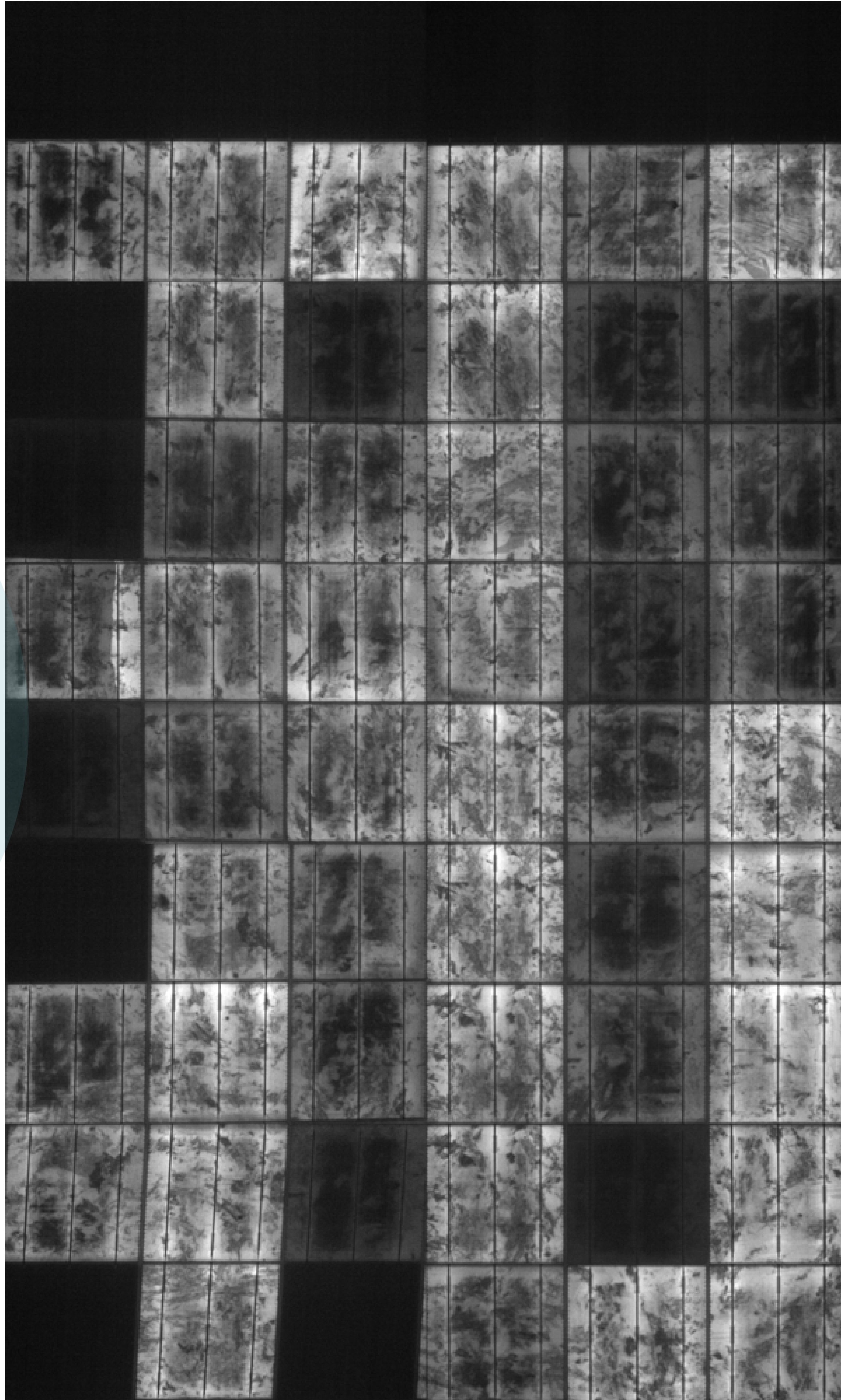


Solar Cell Top Contact

Current flow in a solar cell

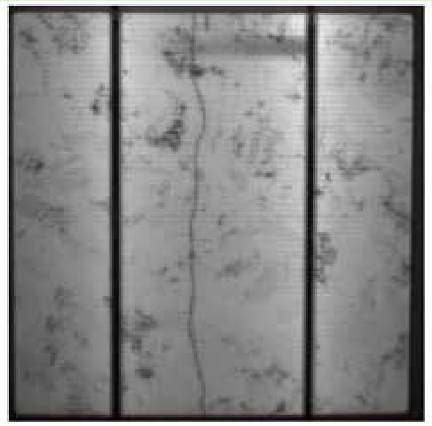
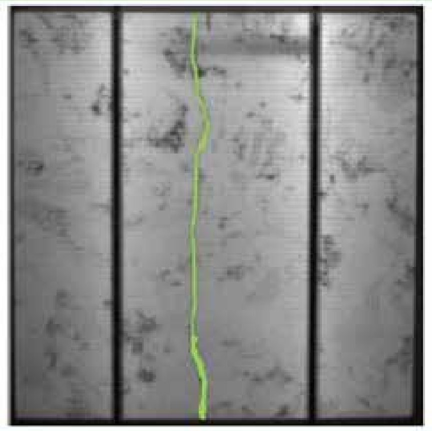
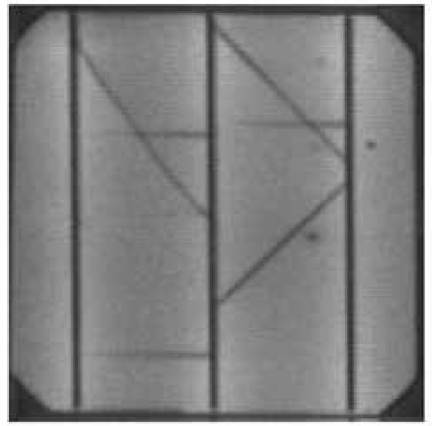
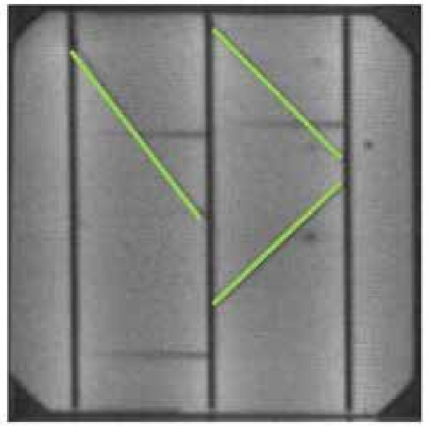
The Importance of Electroluminescence

In some cases, these types of micro-cracks will create ‘hot-spots’ on the affected cells. These can be identified using infrared thermography (IR), as well as other anomalies and conditions causing hotspots.
Electroluminescence (EL) is the most advanced and forensic inspection method to give a clear and conclusive view of the defect, or micro-crack in this case. Using EL, micro-cracks are visible as fine dark lines, usually propagating from a busbar, cell edge or impact location; when assessed in line with a reputable judgement criteria, conclusions can be made as to its criticality. This exposes the non-power producing areas of any given cell, and also gives an indication of the crack’s length, position and orientation. The likelihood of future non-power producing areas can also be determined.



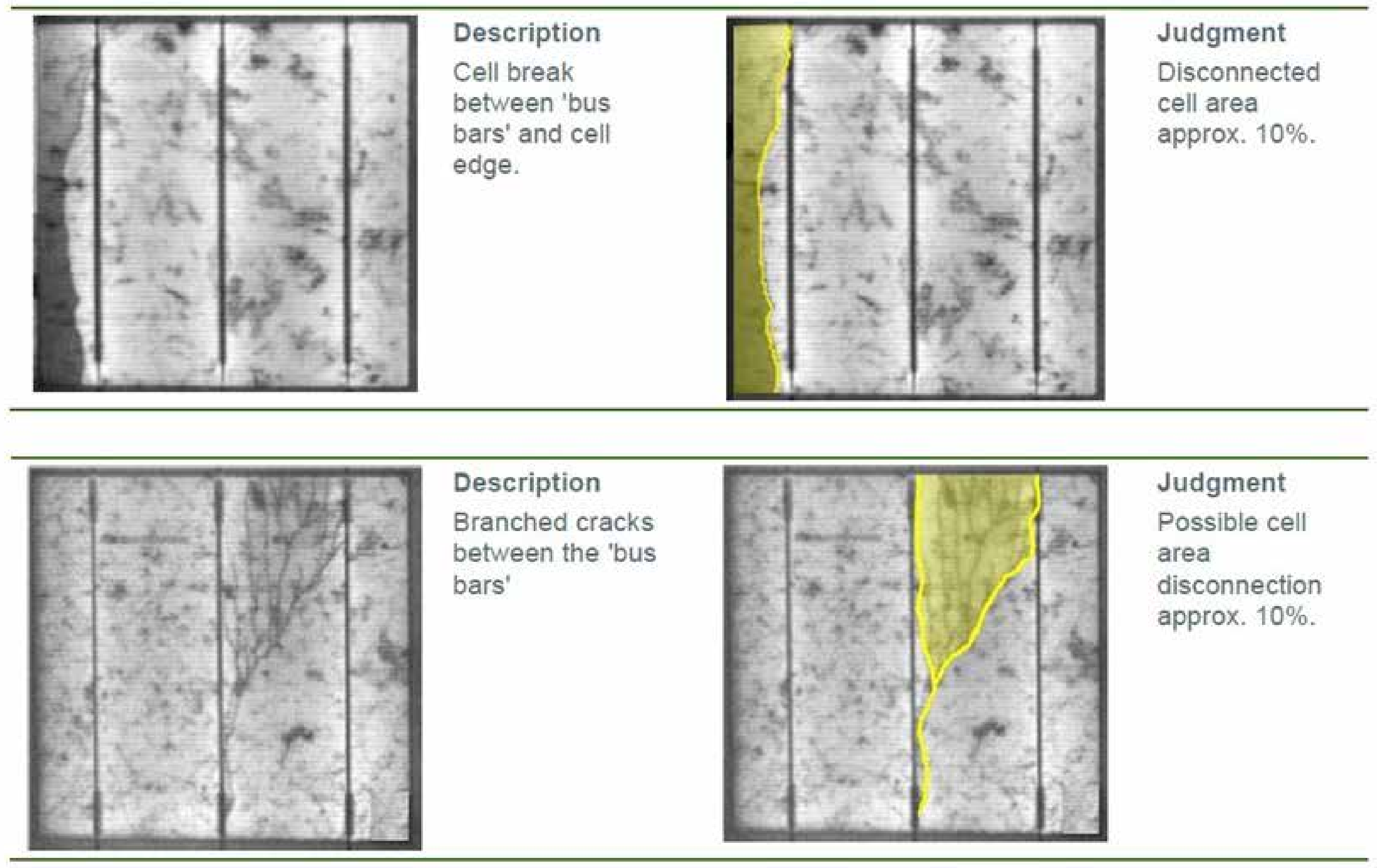
Classification: Non-Critical

The example given here, which is taken from the MBJ Services Judgement Criteria, shows cracks within the inner zone of the cell meaning that, even if these cracks separated all of the grid fingers, current would still be able to flow to the adjacent busbar; there would be negligible effect on power output. In this case, this cell would be classified as a 'Non-Critical Crack.'

	**Description** Cell break runs parallel between the 'bus bars'.		**Judgment** A further expansion of the cell break is not expected. Possible cell area disconnection 0%.
	**Description** Various cell break run in a straight line between the 'bus bars'.		**Judgment** A further expansion of the cell breaks is not expected. Possible cell area disconnection 0%.

Classification: Critical Crack

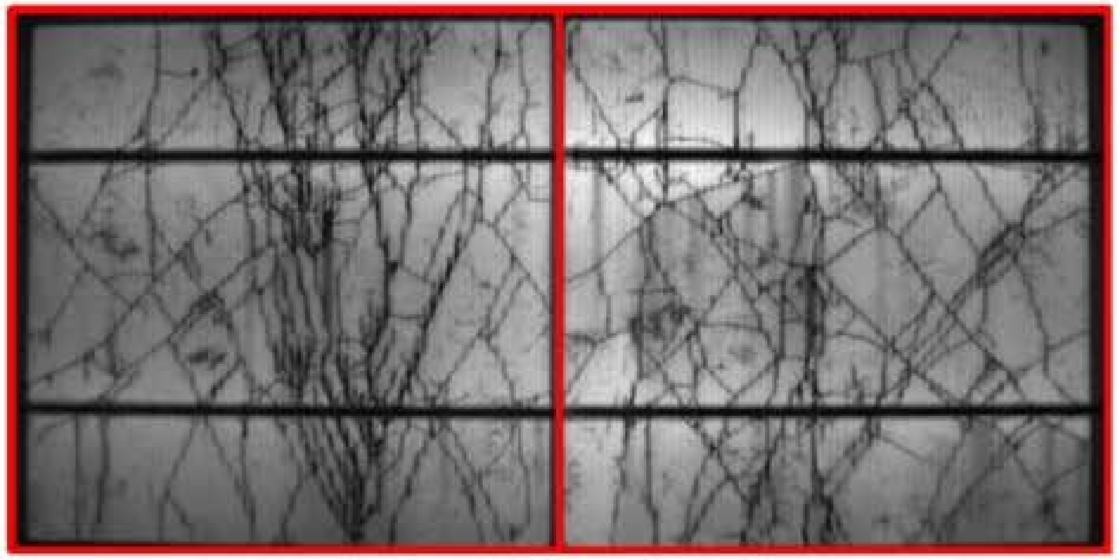
This example shows cracks positioned within the two outer zones of the cell and an isolated region within the inner zone of the bus bars. When the grid fingers separate, the areas isolated will not be able to generate power. This would be classified as 'Critical Cracks', as they are >0%<20% of non-power producing cell area. If it was over 20%, the cell would warrant a 'Very Critical' classification.



Classification: Very Critical

The example shows a 'Very Critical' cracked cell when it was found on a 2012 vintage module; it experienced 1 year of operation. This module was subsequently sent to an accredited laboratory, where it was put into an environmentally controlled climatic acceleration chamber. This chamber exposes the module to the temperature and humidity cycles which would replicate its operational conditions in the field. This standardised testing is used by module manufacturers and laboratories for measuring performance, and ensures that the product will last the guaranteed design life period. Following this test procedure, the module was aged to the 25-year mark; the results highlight non-power producing areas which would have a catastrophic impact on the power output of the cell. The point is that this didn't happen at year 25, it happened somewhere in between and currently asset owners are not only aware of how cracked their sites are, but they don't know when cell-level catastrophic power loss will occur.

Multiple cells, on multiple modules, on multiple strings with losses will creep up on most sites, and the most impactful effects will be on sites which had earlier module technology installed and where the most micro-cracks were introduced in their early days of construction and operation.



Critical fan-like breaks (before aging)

Critical fan-like breaks (after aging)

Classification: Action

A module with one isolated 'Very Critical' cracked cell may not have a noticeable power impact. However, when multiple very critical and/or critical cracks are present within the same module, there is a compounding effect on the power output of the module. Judgement criteria will have module classification thresholds for different numbers and combinations of cell defects; these will dictate the classification of a given module. The classification of a given module will then, in most cases, determine the resulting action to take with that module (i.e. monitor, replace, escalate to test more modules etc).

The darkness of an isolated area within a cell usually indicates the age or completeness of the crack, and in particular, the complete separation of the grid fingers. Even if a newly cracked cell/module is classified as 'Very Critical', it may have little to no impact on the power output. When it ages through thermal and environmental cycling and stresses, grid finger separation will worsen until areas of complete isolation occur. Each cell, batch, module and manufacturer are unique, so they will all deteriorate at different rates; irrespective of speed, they will all deteriorate to significantly within their 25 year design life (and product warranty). Each will show measurable losses in power output experienced.

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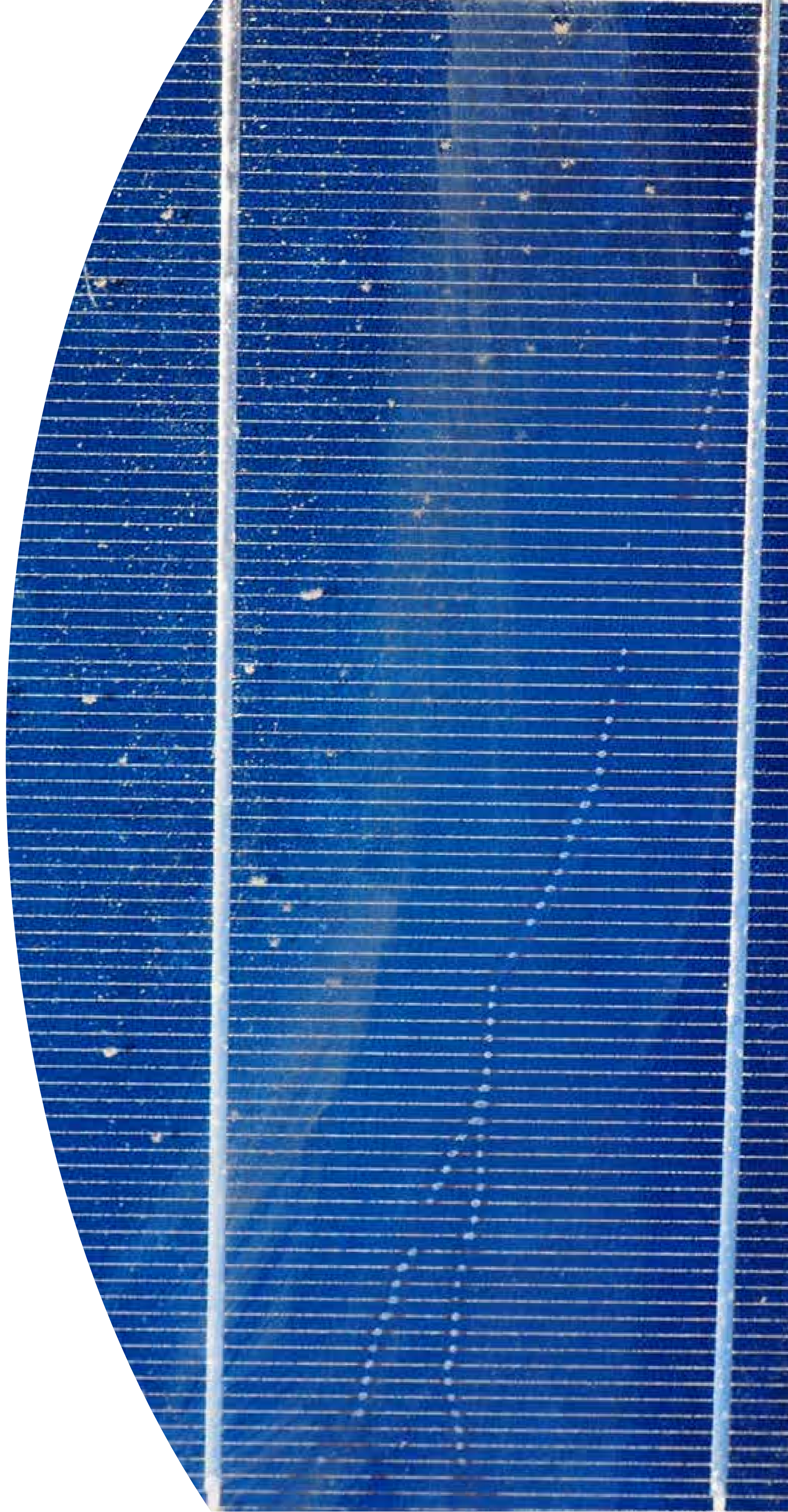
Methods of Micro-Crack Detection

Visual Inspection

Visual inspection is one of the most under-rated inspection methods. Due to the scale of solar assets and physical size of the arrays, O&M visual inspections are not generally implemented comprehensively; image gathering is poorly captured, if practised at all. At best, an O&M technician will walk the row noting any obvious defects. Although better than doing nothing, if this was done with a little more rigour, we're positive that more defects would be found.

A visual inspection for micro-cracks also proves problematic, as these are typically invisible to the human eye. The only time that crack-like phenomena can be seen visually is in the case of the infamous 'snail-trail'. Snail trails are believed to be caused by moisture entering via the back sheet and making its way through to the cell itself; the grid finger material can later dissolve, allowing ions to migrate to the EVA (encapsulation material). They can then be seen on the front side of the module, manifesting most commonly as small silver blobs in the middle of a darker shadowed area; a browning discolouring will also be present. In many instances, the route of the snail trail follows that of a micro-crack, but the two phenomena are not intrinsically linked, and one may occur without the other.



Visual Inspection: Snail Trails

These markings can be visually seen, appearing as small dots of soldering/silver, and bleeding out from the grid fingers to form lines/patterns that resemble a familiar snails slime trail. From our experience, 'snail trails' are reasonably common, and some module manufactures have suffered from them more than others. As they are visibly seen as a defect, many owners and asset managers want them investigated and, in most cases, electrical testing & IR surveys are inconclusive; if they are EL & flash tested, however, the micro-cracks are confirmed, and in younger modules underwhelming power losses are detected. Many manufacturers have argued the case that these are a normal and common phenomenon and do not warrant exchange. Cases are closed on this basis. However, owners be warned, these snail-trails and underlying micro-cracks should be monitored as they will affect power more significantly as they mature. 2DegreesKelvin now utilise site-wide high resolution surveys to quantify the volume distribution and intensity of snail trails on a given site, which in turn justifies the requirement for further testing.

Advanced Inspection: Infrared Thermography (IR)

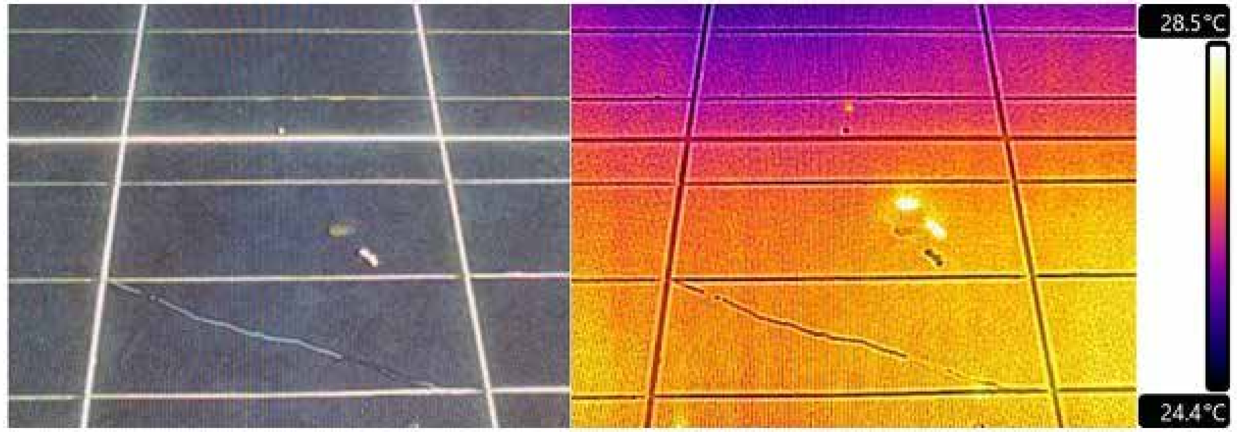
Today's most popular and cost effective advanced inspection method in detecting micro-cracks is Infrared Thermography (IR) via drone. This method is now adopted globally, and gaining a quick, cheap and high-level indication of module based operational condition has become standardised. The method involves IR images taken from the air; thermal anomalies are detected, and usually presented to the client in a report or on an online portal.

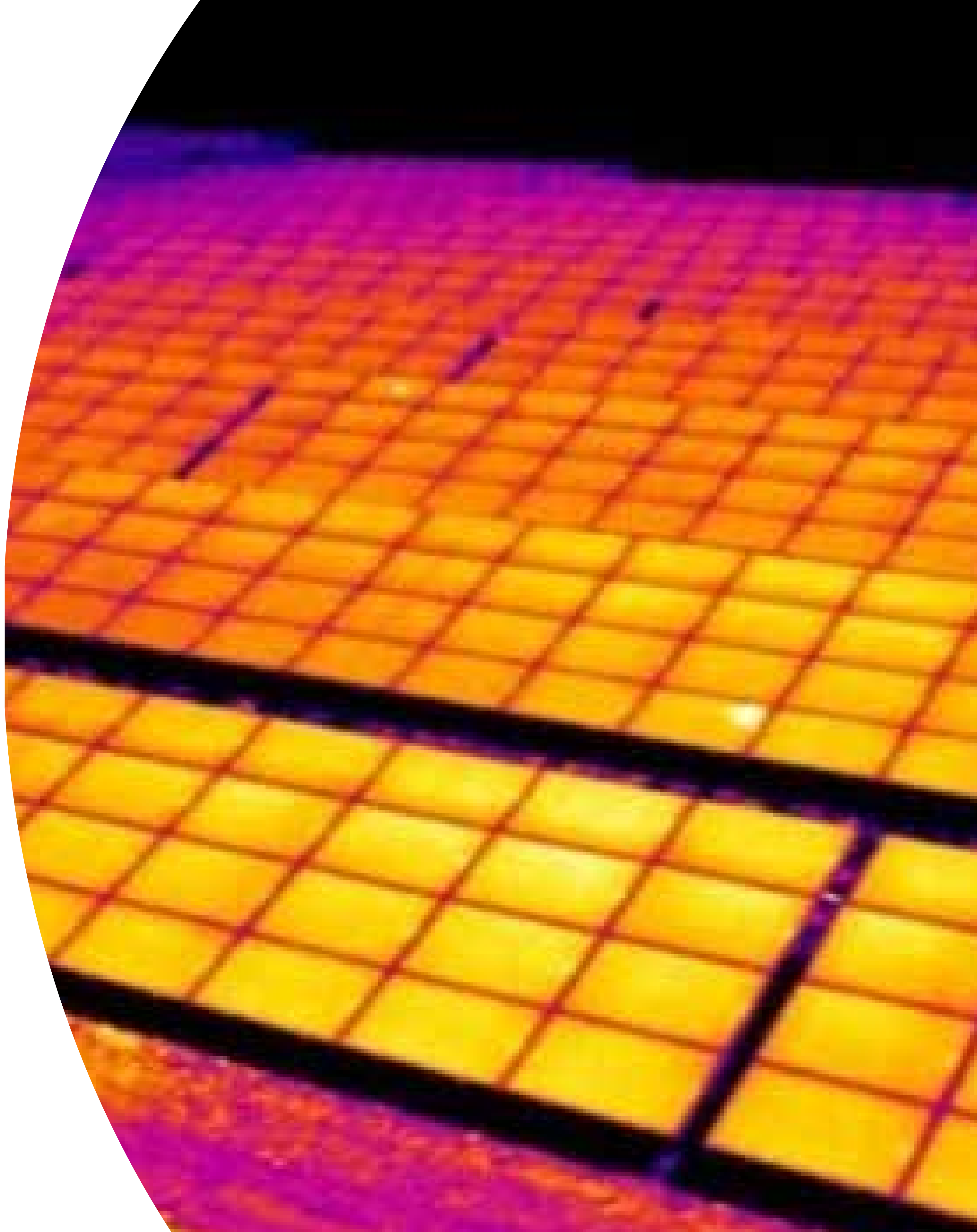
The challenge is that there is always a compromise between the minimum level of image resolution and the height, speed and subsequent cost of the given survey. This balance usually means that for standard (off the shelf) IR surveys, the level of detail visible is usually limited to:

- Disconnected strings
- Disconnected modules
- Short-circuited modules / Faulty by-pass diodes
- Shading/Soiling and....
- Hot spots

The Problematic Hotspots

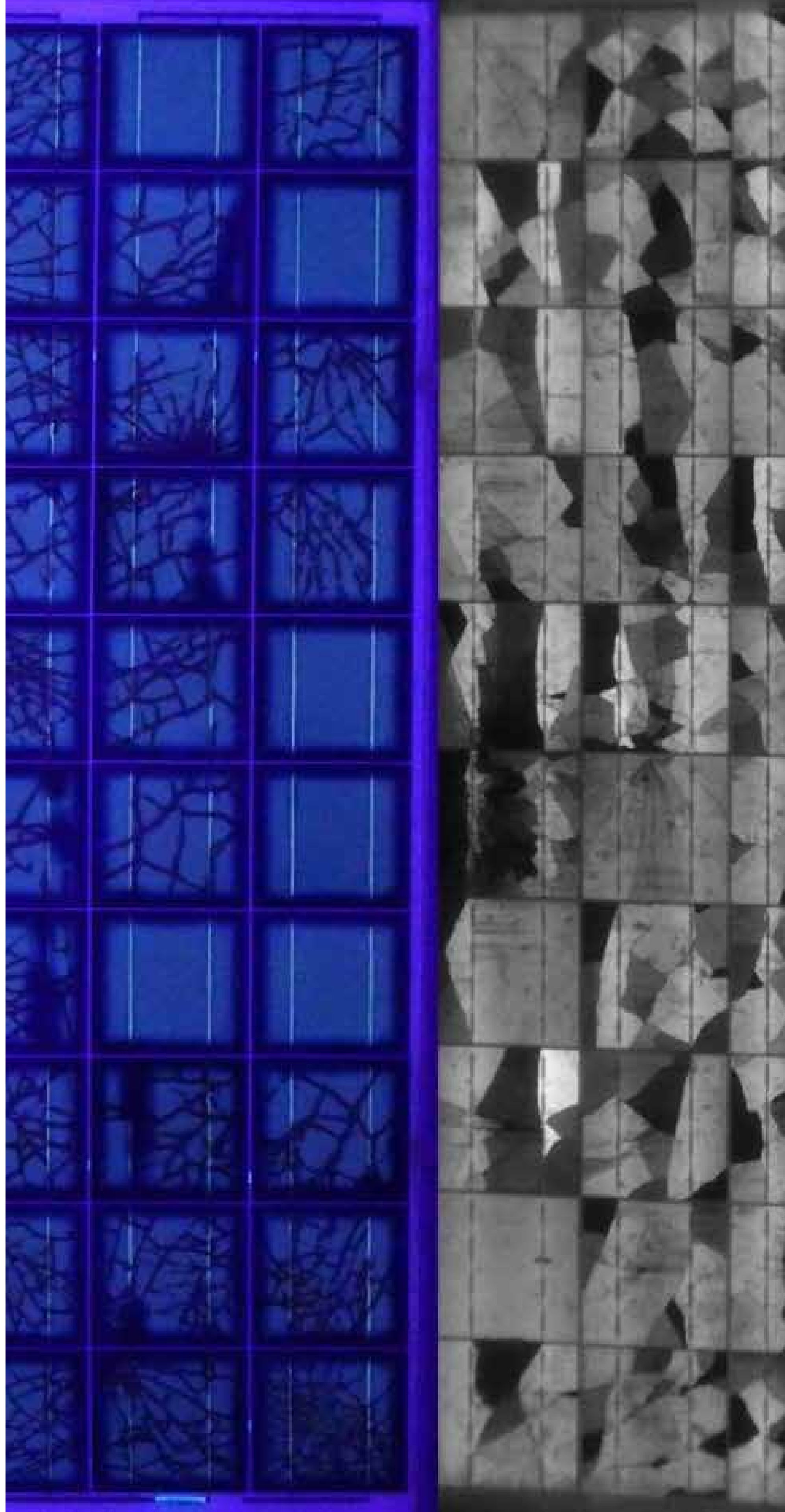
Hotspots can sometimes be identified due to shape and intensity of colour, typical of bird droppings or shading. Most thermal hot spots will need deeper investigation if the asset owner or operator wants to know exactly what they are, what is the likely cause, and what is their impact on production. The other issue is that young cracks which are not generating hotspots will not be detected, like this example below. Equally, of course, is the pixelated relative low resolution of thermography, which doesn't lend itself well to detailed cell analysis.





Advanced Inspection: Ultraviolet (UV)

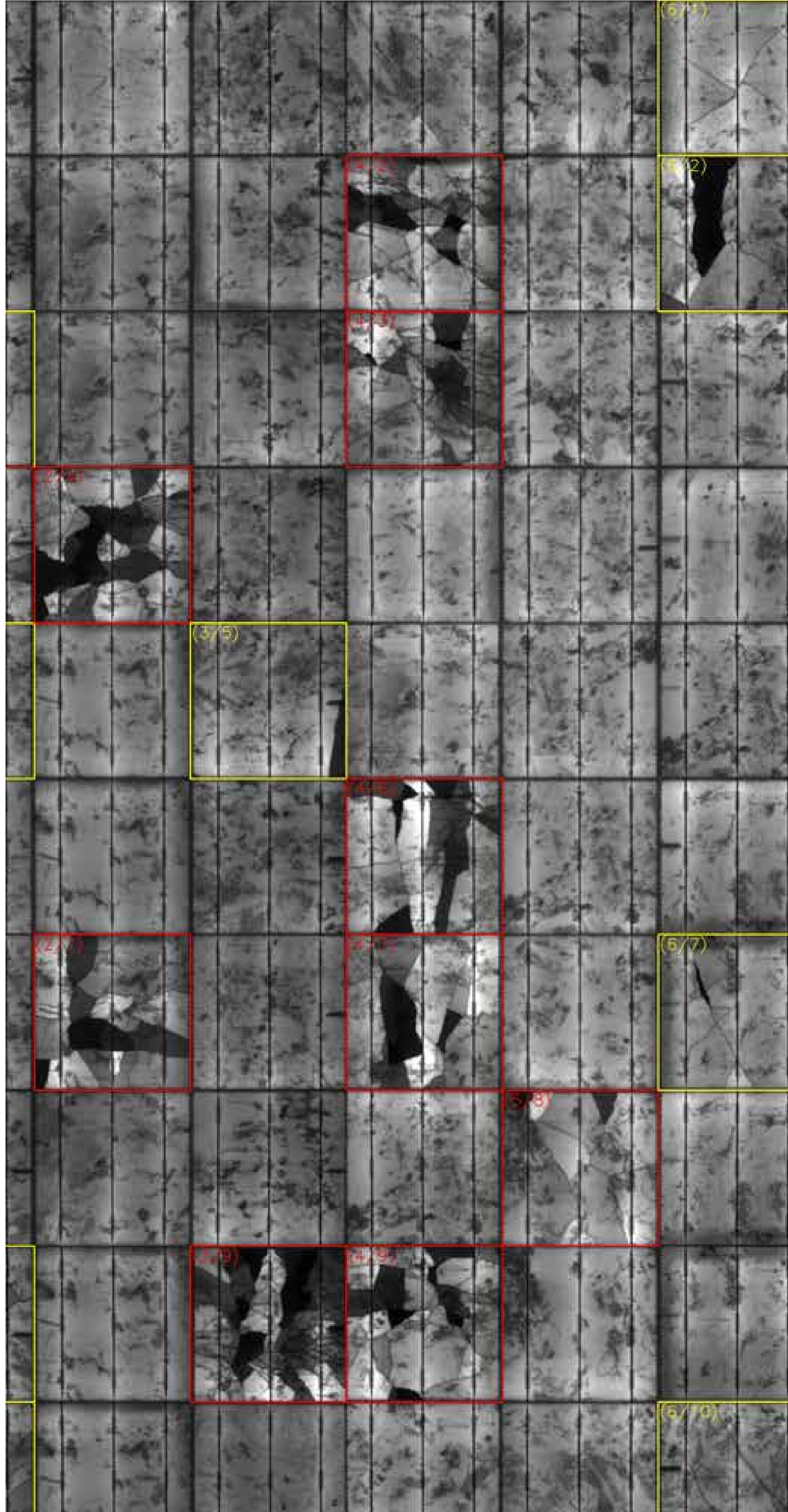
UV inspections are useful in identifying micro-cracks and indicating the age of a crack. A UV light, preferably fitted with a specialist UV filter, is simply shone on to modules at night with no interaction with the solar/electrical system; in >80% of cases, the UVA (encapsulation) ingredients emit a fluorescent effect which eliminates the healthy parts of the respective cells. Areas of the cell that have cracks do not, and instead form shadow-like areas following the lines of the cracks. Interestingly, the fatter or thicker the shadow is around a given crack, the older the crack is. There have been cases where micro-crack investigations have been carried out using UV, and it can be proved that the cracks were not caused by O&M duties; the more likely causation was installation. There are trials for scaling up manual inspections using UV, using larger/longer light configurations with cameras and even drone UV. But since the UV inspection exclusively reveals micro-cracks, the return on the investment remains subjective. And scaling up the volume of UV inspections will be of a similar order to Electroluminescence, which is by far a much more useful method. Again, this casts a less desirable shadow over UV Inspections.



Advanced Inspection: Electroluminescence (EL)

EL is the king of all inspection methods, and its popularity is on the rise for good reason. EL can detect the equivalent to 90% of all known cell-based defects, as opposed to 25% with IR. It provides very clear images of micro-cracks, and gives a detailed analysis of their orientation and length; isolated areas, and their relative darkness, suggest areas of non-power producing cells too. The extent to EL detail enables route-cause to be determined in many cases (impact points, spider cracks, cross-cracks etc). Ongoing research and testing now suggests an intrinsic link between an EL image and the power output of a given module. This is not a simple process, and has involved the assimilation of thousands of test samples; to date, the biggest variable remains the age and completeness of the cracks causing the areas of isolation.

EL equipment is now widely available which includes a power modulation unit (controlling amps and voltage to a given module or string), and an EL camera (which is essentially an D-SLR with a modified processor and lens). Many O&M companies are now having a go at 'point-and-shoot' methods to see what they can see.



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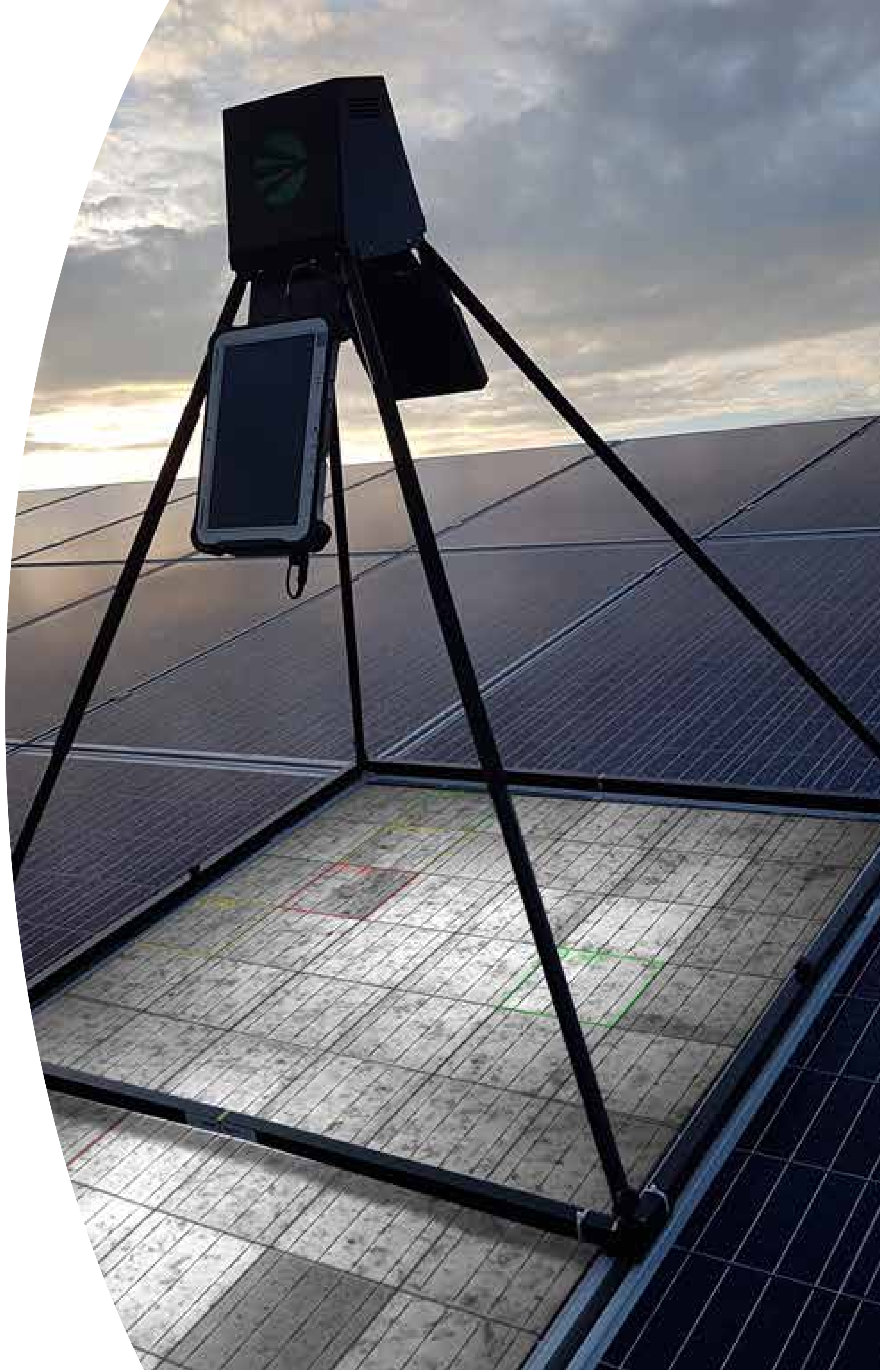
World Leaders: 2DegressKelvin

More advanced methods to gather high quality repeatable perpendicular images have been developed and are being deployed by the world leaders in this field (including 2DegreesKelvin) which include tripod systems, drones and remote power sequencing technology in order to maximise volume and bring the price point down. If EL was the same price as IR, then there would be no contest, but as you have to interact with the electrical system in a string by string or table by table manner at night, it is slower, you need more sophisticated and expensive equipment and the methodology is significantly more advanced and mature, hence the prices are a factor higher. Currently, EL images can be gathered for as cheap as £3-5/module with the optimum power setup. Regardless of the level of asset detail gathered and the increase in asset value if you had a site 100% EL'd, for mass adoption this price needs to continue to fall. In my mind the true value of EL is still to be realised.



World Leaders: 5 Top Tips

5 Things you can do to mitigate future losses in generation due to micro-cracks:

- As well as adopting site-wide professional IR surveys, incorporate EL inspections into O&M scope for operational assets
- Increase your asset knowledge to increase power production in the long run
- Adopt the philosophy, 'just because it isn't causing you pain now, doesn't mean it won't in the future'
- Get ahead of the curve, be proactive with EL inspections, identify modules to change out, identify modules to monitor and increase your sites production and your investors' confidence in you
- Adopt an end-to-end quality service for your module procurement for new build sites, to ensure maximum power production from day one of operation.

Knowledge is power, in every sense of the phrase when it comes to solar. To be in an informed position you need all the facts. Whether this be string tests, shunt resistance testing, IV-Curve tests, visual inspections, IR drone surveys or more advanced methods such as Electroluminescence and/or flash testing, the outcome of the exercise needs to be justified, needs to be useful and it needs to be stored in a more progressive way as oppose to traditional 'pdf' format reports.

World Leaders: Partnerships

The secret to gaining ultimate knowledge when it comes to micro-cracks or any other defect or deterioration phenomena, is the correct suite of advanced inspection methods that you apply, their relative quality & value and ultimately the way this information/data is presented. 2DegreesKelvin's strategy is to partner with world leaders in their respective mirco-fields and create a perfect blend of quality, expertise and data presentation.

- MBJ Services GmbH, specializes in solar module testing equipment on site using their world-famous mobile test centres. With the award-winning Mobile Lab, MBJ Services is the technology leader in the field of mobile testing laboratories with partners in all relevant markets.

- AePVI combine and automate classic and preventive inspections of solar power plants and employ a range of tripod and drone-based sensor systems through their international partners, providing a cost-effective check-up by systematic sampling or 100% screening. Specialising in high-volume EL measurement and analysis technology and services.

- Above is a market leading aerial inspection and data analytics company, focused on bringing innovation to the international solar industry. Above's flagship software product, SolarGain, enables you to bring together all types of testing and inspection data into a true digital twin, releasing previously unseen value.

World Leaders: The Conclusion

The main take away when it comes to micro-cracks are:

- Micro-cracks may not be impacting on generation if they are young but will, to varying degrees, as they mature.
- Electroluminescence is by far the best inspection method to identify micro-cracks.
- IR drone surveys will identify hot-spots, some of which will be related to micro-cracks, but similarly to micro-cracks which show no impact on power output, IR will not identify these young or early stage micro-cracks in the field as they won't be causing hot-spots.

If you have any questions about micro-cracks, advanced inspection methods or anything else relating to the assessment, improvement & optimisation of your solar asset, then please get in touch with 2DegreesKelvin.

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Where to find more

World Leaders: The Next Steps

You also may be interested in 2DegreesKelvin's YouTube channel which features our 'Technology Insights' series.

https://lnkd.in/gww96aT

Currently there are three episodes on there:

- **EP-1: Mobile Module Testing**
- **EP-2: High Volume Electroluminescence**
- **EP-3: EL Quickcheck**

These three videos provide an insight into the world-leading technology which is deployable for advanced solar PV inspection methods. Forensically diagnosing module defects & issues, enabling better production & profits and increasing longevity and sale value of the asset.

Please check them out, like and comment and if you are interested then subscribe so you can get alerted to new videos we have in the pipeline!