Interpreting module EL images for quality control

Rhett Evans[1,2], Adeline Sugianto[3,4], Weiwei Mao[4]

[1]Suntech R&D Australia, Sydney Olympic Park, NSW, 2127, Australia
[2]Australian Centre for Advanced Photovoltaics, The University of New South Wales, Sydney, NSW, 2052, Australia
[3]Now with school of Photovoltaic and Renewable Energy Engineering, The University of New South Wales, Sydney, NSW 2052, Australia.
[4]Wuxi Suntech Power Co Ltd, New District Wuxi, Jiangsu, 214028, China

email address: rhett.evans@suntech-power.com.au

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Abstract

A strong supply-side photovoltaic market coupled with increasing customer awareness of the importance of quality module manufacturing is resulting in customers increasingly dictating supply terms with manufacturers. With customers focusing on quality metrics, this in general becomes a positive development which is of benefit for high quality manufacturers. In Australia, with Australian Consumer Law leaving ultimate warranty responsibility in the hands of the local service providers, the need for these service providers to have confidence in the quality of the manufactured product is higher still.

A quality control technique that is becoming increasingly important is electro-luminescence (EL) testing. EL testing is useful for identifying variations in wafer quality, wafer impurities and dislocations, microcracks, front grid finger breaks, poor solder joints and shunted cells. There is a wealth of scientific literature dealing with most of these issues. Some of this information is useful for manufacturing process control and some of it is useful to customers. For example, features such as microcracks can impact a module's durability in the field and this information is important. But other features of the EL image – such as the uniformity of EL response from the cells – has no reliable relationship to module performance. By reviewing the theory and application of module scale EL testing, interpretation of the images can be improved and areas where further work is required can be highlighted.

1. Introduction

Electroluminescence (EL) imaging is a measurement technique used to analyse solar cells and solar modules, the original exposition of which is commonly accredited to Fuyuki et al [1]. An external power supply is connected to the cell / module and a current is passed into the positive terminal and out the negative terminal (see figure 1), causing the solar cell to emit light in the non-visible range around 1100nm. This light can be captured using a special type of charge-couple device (CCD) camera (see sample images in figure 2). Since these cameras are usually sensitive to light of a range of wavelengths, the cameras are usually filtered and the measurements are often performed in the dark or in near-dark conditions. A simple way to think of an EL test is that it is like the solar cell operating in reverse. A current is passed through the cell and it emits a form of light, whereas in normal operation, light on the cell will cause it to generate a current.

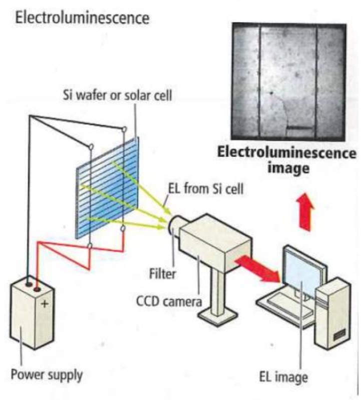
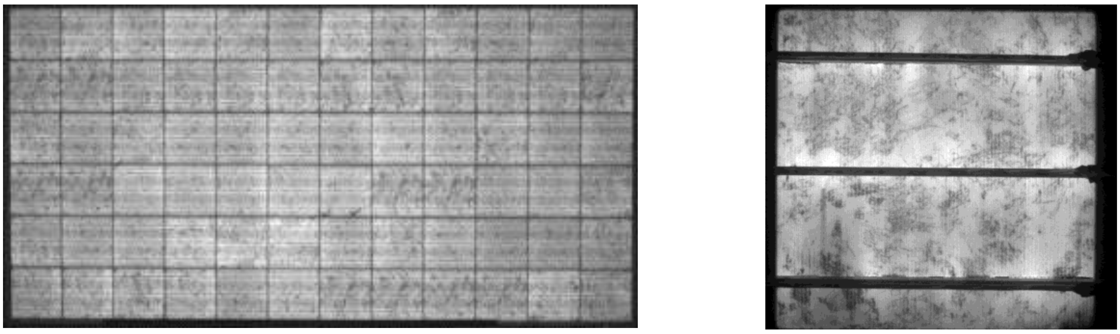


Figure 1 - Basic EL imaging setup for a cell or module

EL testing provides information about the voltage and resistance in a cell [2-4] and detailed material properties such as diffusion length [5, 6]. The test is also very sensitive to particular faults and variations within a cell [7-12]. Some understanding of this method is required to make good interpretations of the images.



(a) (b)

Figure 2 – Typical EL images of a module (a) and a more detailed image of a cell (b)

2. Background

A review of theory of EL testing and cell and module performance is useful in order to be able to more confidently interpret EL images at a module level.

2.1. EL testing and Cell Performance.

The intensity of the EL signal, $\Phi(x)$, relates to the voltage V(x) at any point by the following equation [2, 3]

$$\Phi(x) = C(x) exp\left(\frac{V(x)}{V_T}\right) \text{ for } V(x) \gg V_T \quad (1)$$

Where C(x) is a constant for a given cell and V_T is the thermal voltage. In an EL image, there will be a difference between the voltage at any point on the cell, and the net external voltage due to the voltage drops across the series resistance elements. This is fully expanded elsewhere [2, 3], but the key point is that the brightness of the image is conveying information about the voltage AND the resistance within the cell. The constant C can be empirically calculated from EL images at low current levels where these series resistance effects are negligible and can be ignored [2, 3]. Some investigators have used these relationships to derive information about cell electrical behaviour from EL images [4].

2.2. Cell and Module Performance.

In most commercial modules, individual solar cells are connected in series. The cells are measured and then grouped with other cells according to their suitability to be made into modules together. Every solar cell will be slightly different from the other cells due to variations in manufacturing processes. Each cell's properties can be usefully described by their Current-Voltage (IV) curve and their Power-Voltage (PV) curve (see figure 3). From these curves, it can be seen that each cell has some maximum power (P_{mp}), and a maximum power current (I_{mp}) and maximum power voltage (V_{mp}) for which this occurs.

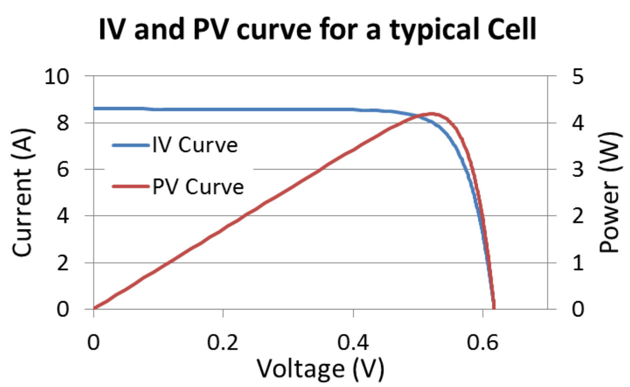


Figure 3 – Typical IV and PV curves for a solar cell

When these cells are connected in series to make a module, all of the cells are constrained to operate at *the same current value*. Therefore, many of the cells will not be operating precisely at their P_{mp}. The difference between the sum of the maximum power possible from all the cells individually, and the total maximum power of the module is sometimes referred to as the mismatch loss. While in the past mismatch loss has been a significant issue for module design [13], the mismatch loss related to standard cell grouping rules in a modern solar module is immeasurably low [14]. Theoretical studies using variance values typical of modern manufacturing suggesting the loss is < 0.1% [15] if we used no special mixing of the cells whatsoever and less than half that again for any reasonable mixing methodology.

2.3. Experimental Results: EL signal intensity as a function of cell performance

As a demonstration of the relationship between EL intensity and cell performance, a study of 50 production cells was done at a Suntech manufacturing facility in Wuxi China in early 2013. All the cells are multi-crystalline (mc) silicon, with a broadly standard production sequence of acidic etch / belt diffusion / SiN ARC / screen print contacts / IV measurement on a Halm in-line cell tester. All cells were removed from the production line and EL tested at 4 different current settings – the Isc and Imp of the individual cells, and then the average Isc and Imp of the cell group. The latter two measurements are more reflective of measurements that would happen in a module where all cells are constrained to operate at the same current level.

The relationship between the cell properties and the average EL intensity across the cell is shown in Figure 4. The data has been normalised by converting the variance to be a percentage of the mean and then mean centring the data. This protects data sensitivity, but it also means all of the units of Voc, FF, Isc and Eff are directly comparable. The relationship between voltage and EL intensity looks linear but equation 1 is telling us the fundamental relation is exponential, which can be fitted equally well in this case. Other empirical studies also show that the voltage has the strongest relationship to EL brightness [2].

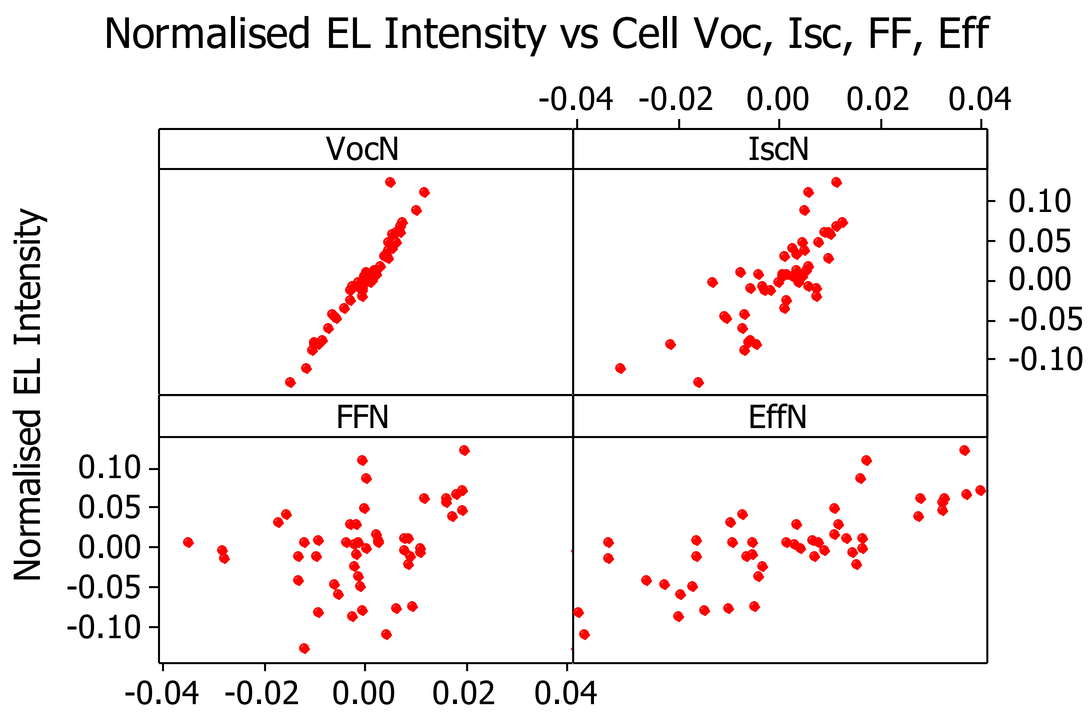


Figure 4 – Normalised EL intensity vs normalised cell characteristics. The EL vs Voc relationship is very strong, with an R-squared of 93.4%. The El vs Isc can be entirely explained by the underlying Voc vs Isc and El vs Voc relationship, so no there is no fundamental causality. FF is entirely uncorrelated with EL intensity, leaving the efficiency with a relatively weak relationship.

3. Interpreting EL images for module quality control

EL imaging setups can be purchased cheaply and provide a lot of information. This testing is now commonplace in manufacturing and it is increasingly common for customers to check all, or some significant sample of, incoming modules. It is also common for module supply contracts to have some quality requirements based upon the interpretation of EL images. When making these arrangements it is very important to have a good understanding of EL imaging and a good technical justification for the requirements. Some common requirements and their interpretations are discussed in this section.

3.1 Microcracks

Cell microcracks are the most significant problem that can be identified with EL imaging. Figure 5 shows an example of modules with microcracks. Microcracks typically occur due to a manufacturing fault or due to excessive mechanical stress on a finished module.

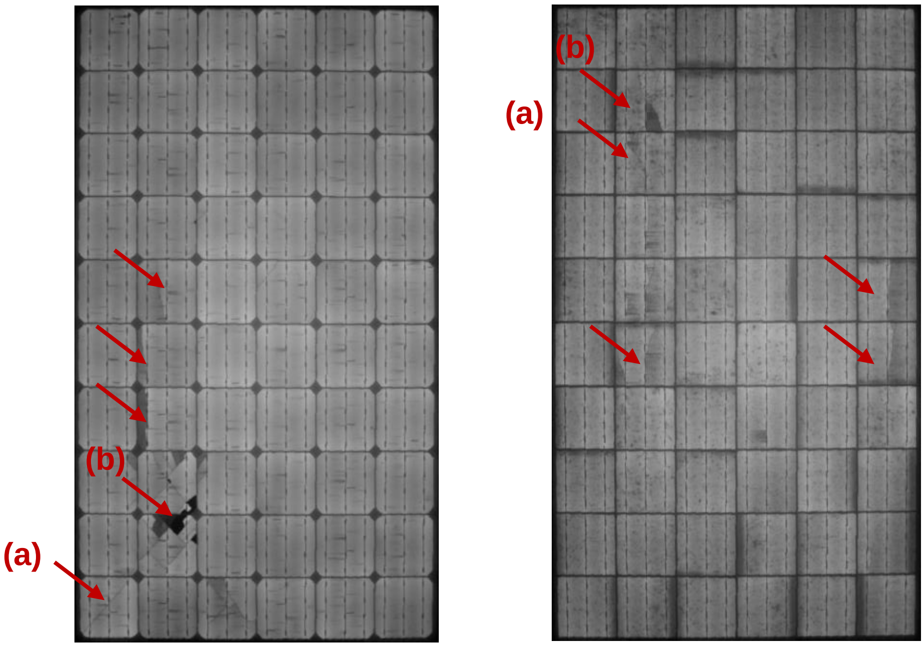


Figure 5 – Modules including cells with microcracks. Feature (a) shows a crack that does not cause any significant initial loss of power. Feature (b) is a dark area in EL, showing the region of the cell is isolated.

Excellent early work on this subject [16] dealt with crack formation and classified them in terms of their impact on module power. Further studies [17,12], have continued this and also shown that all types of cracks can get worse with humidity freeze cycling, so initial categorisation of cracks is not sufficient to address durability concerns. It should be noted that these are probabilistic effects – this means that the existence of a single crack does not mean the module will definitely fail in the field. But in the case of [17], more than 20 cracks correlates with extra loss of power after 200 humidity freeze cycles. This is a very harsh test, being 20 times the standard humidity freeze qualification test (10 cycles) [18]. It is not representative of all field situations, but it does show that large numbers of cracks can compromise module life. Microcracks impact module performance in three main ways. Firstly, any sort of crack can break cell fingers and have minor impacts on a cell's series resistance. Secondly, cracks that isolate whole sections of cells (seen as black regions on the EL image) result in a lower Isc for that cell. Thirdly, any cells with a low current will tend to operate a little hotter as they will be operating a long way from their maximum power point and so will have an extra few watts of heat dissipating within them. This problem will become severe if the short circuit current of the affected cell roughly drops below the average Imp of the rest of the cells. In this case, the affected cell will break down. The bypass diode will turn on to shunt the array current around the string that the affected cell is a part of, but the power from the other cells in that string will start to be consumed by the affected cell. How much power is consumed in the affected cell will vary depending on its current, but it can be very high. Bypass diodes are designed to protect the module in the case of transient current variations such as from shading or soiling, but they cannot protect a module in this situation where the current reduction in the cell is related to microcracks and is permanent. This situation will lead to almost certain failure in a module.

Cracking is also associated with another problem in modules. The discolouration of the module surface known as "snail trails" is primarily an aesthetic issue associated with microcracks accompanied by an electrochemical corrosion effect [19, 20]. Images of snail trails, reprinted from [19] are shown in figure 6. There are no significant performance problems associated with snail trails other than that associated with the microcracks themselves.

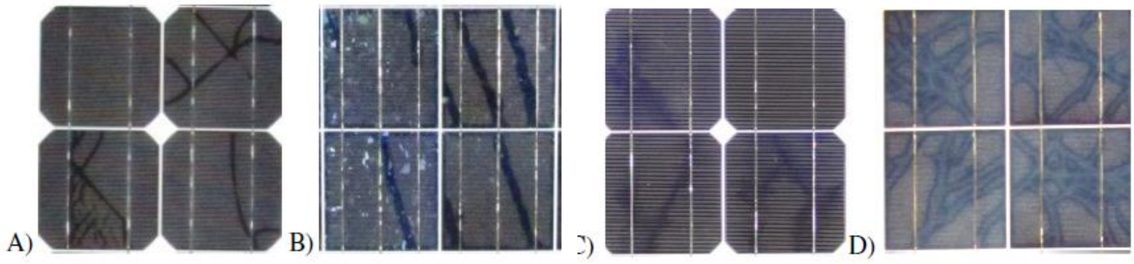


Figure 6 – Images of snail trails from [19]

3.2 Cell finger breaks

EL images are very useful for detecting breaks or discontinuities in the silver screen printed fingers that make electrical contact to the front of the cell. Figure 7 is a montage of cell EL images showing finger breaks.

Figure 7 – Breaks in the silver screen print grid on the front show up as black lines running perpendicular to the busbar in the EL image.

Finger discontinuities look dramatic in an EL image as current is prevent from travelling to parts of the cell, which then show up as black. The effect is not so severe in a solar cell operating in the light. All parts of the cell still generate current; there is just a localised area of higher series resistance as the current leaves the cell through the adjacent fingers. It takes many finger breaks on a cell to even be able to measure the impact. There is no evidence and no theoretical reason why this effect in any way compromises the fielded durability of the module. So this is mostly considered useful process control information for the manufacturer. EL imaging at a module level is often not even sufficiently detailed to capture cell finger effects.

3.3 Cell faults

Sometimes, due to a manufacturing fault or an unexpected mechanical damage, a cell may develop a serious shunting fault that shows up as a single cell being black or very dark [21]. An example of such a fault is shown below, reproduced from [21]

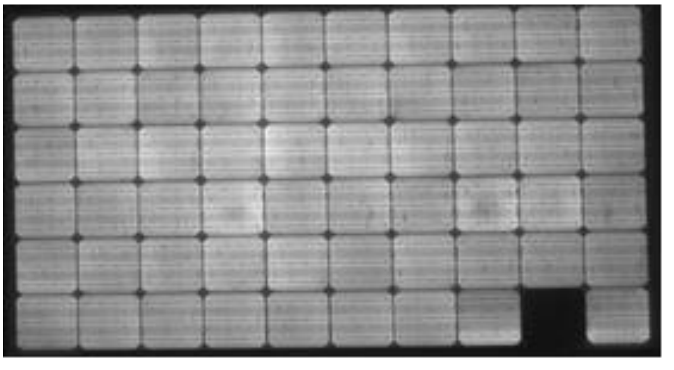


Figure 7 – EL image of a module where there is one faulted cell [21]

Such an EL image would be an immediate cause for concern and should not be used in a system. It would be expected that this would be an unusual occurrence.

3.4 Non-uniform EL response

Another area that is attracting the interest of customers is the uniformity of EL response of the cells within a module. Figure 8 shows a module where the cells have a slight variation in the EL brightness.

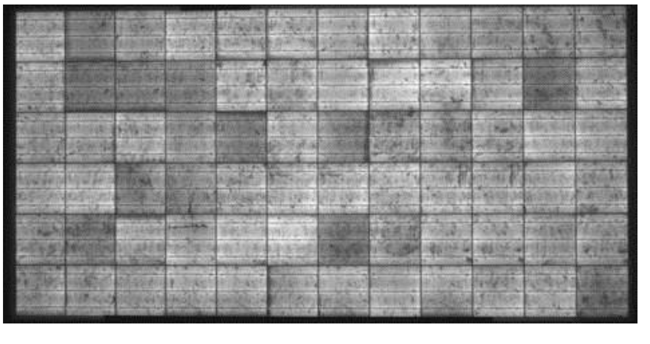


Figure 8 – EL image of a module where cells have variation in brightness

Of all the issues highlighted by EL, this is one of the more difficult to interpret and understand due to there being several underlying causes. Not the least of these problems is the qualitative nature of this metric as a quality specification. Contrast is perceived differently by people and captured differently in images. It is a much better aim to understand the key issues here and set relevant quantitative limits. As has been seen, voltage and resistance effects, together with the calibration factor C, are the key drivers for EL intensity. It is worth looking at a few issues which are important in the discussion on the meaning of non-uniform EL response.

3.4.1 Cell Sorting

At least one international industry journal [22] regularly attributes these images with a non-uniform EL response to the cells in a module being “not optimally sorted”, even attributing this to a detectable power drop. Given EL intensity is most strongly linked to voltage, which has no impact on mismatch in a series connected module, the justification for this statement is not understood. Mismatch loss is more directly related to current variation in the first instance and section 2.2 showed the cell mismatch is a very small issue for modern solar modules. There does not appear to be justifiable concerns here.

3.4.2 Low Isc

Low EL signal is often mistakenly directly linked to a low Isc. This link is weak and indirect and so not strongly predictive. The relationship between EL and Isc derives from the primary relationships between EL and Voc and the relationship between Voc and Isc, which is related to the fundamental properties of the wafer. The Isc is also linked to the EL signal level through a relationship to the calibration factor C in equation 1. Changes in texturing or SiN layer can affect the amount of the EL signal coupled out of the wafer to the camera. But there is no reason to assume the trends in C, which is dependent on light coupling *out* of the wafer at 1100nm, will always match the trend in Isc which is dependent on the entire visible spectrum coupling *into* the wafer. Other studies [11] have also noted the uncertainty of the relationship between Isc and EL intensity.

3.4.3 EL measurement at low current levels

Most of the EL images in this report were taken at a current around 8.8A, which is the short circuit current of the module. Sometimes measurements are taken at a very low current level. If the measurement current is less than 5-10% of the Isc, the voltage level will be strongly affected by the shunt resistance. So for low current measurements, non-uniform EL images are more common and are usually an indication of shunting differences. Shunt resistance does not cause non-uniform response at high current levels. The reason for this can be seen by looking at the IV curves in figure 9.

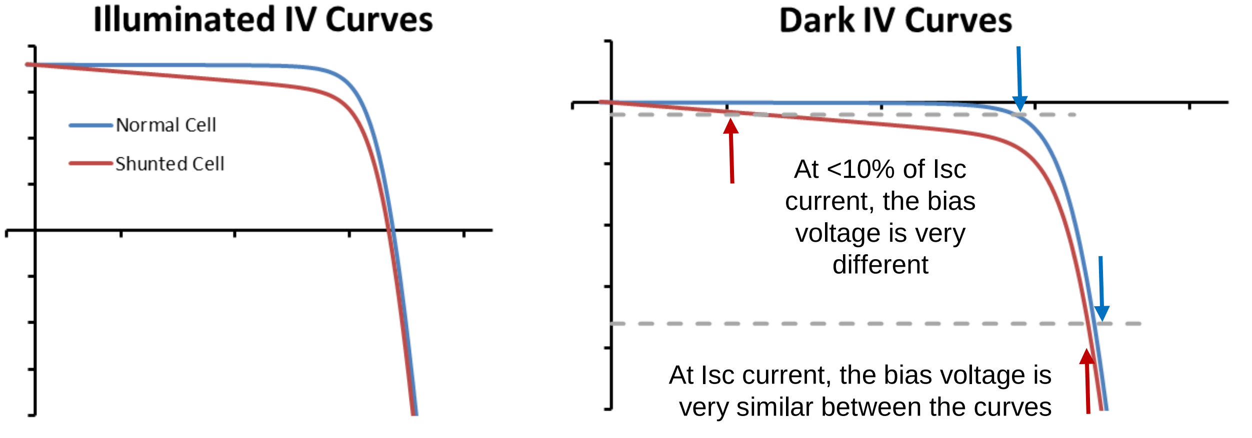


Figure 9 – The IV curves for a simulated normal and shunted cell are shown for normal illuminated conditions on the left. These same curves are shifted down for dark conditions when EL imaging is done (right). At low current levels, there is a very big difference in the cell voltage between the normal and shunted cell, which will correspond to a very big difference in EL signal levels

3.4.4 Hot Spot

Cells with a low EL signal are sometimes attributed as a hot spot risk. There are often several meanings to the phrase “hot spot risk”. It sometimes refers to the risk of cells operating in reverse bias, similar to what is described in section 3.1. This is not a serious risk for a modern solar module, unless the cells suffer some damage or soiling, because the manufacturing ranges are too tight. The phrase “hot spot risk” can sometimes refer to some cells running hotter than others in normal operation, as is tested in the various parts of IEC 61215. For reasons already discussed, EL imaging is not the best way to diagnose this issue. IR imaging [7, 11] is much more effective for looking at current non-uniformities. Importantly, these other studies [11] have shown that modules with a non-uniform EL response have little correlation between dark EL cells and hotter cells identified through IEC 61215-style tests with IR imaging. More importantly perhaps, modules with a uniform EL response still contained cells with a similar propensity to run hot. Cells run hotter than other cells almost entirely due to non-uniform current between cells, and so much of the discussion of section 3.3.2 also applies.

3.4.5 Further Discussion

Most of the potential module problems discussed in this section are related to non-uniformities in cell Jsc, and EL is not an ideal tool to detect these problems. No series issues can be diagnosed from a non-uniform cell response in a module EL image of the sort seen in figure 7. There is not even evidence it increases the probability of problems substantially over and above a module with a uniform response. Yet it is also known that extreme examples – such as where one or more cells appear very dark or completely black due to a significant cell fault [2, 21] – are cause for concern. It follows therefore that somewhere in between these two situations there is a threshold that needs to be established for acceptability of modules. More work needs to be done to establish an evidence-based case for this – particularly lacking is an investigation for variations in the constant C in a manufacturing environment. Until this work is done, a useful threshold might be to just look for very dark or black cells that are almost certainly some sort of fault. Quantitatively, intensity levels of 50% below the average might be a useful threshold for raising suspicions, although it is difficult to justify this absolutely without further work.

4. Conclusions

The fundamental theory of solar cell operation and of EL testing does need to be understood when making interpretations from EL images. It is also worth remembering that EL imaging is a solar cell working in reverse, so while it is a useful analogue to normal operation, it will not be exactly that same.

The experiments and theoretical studies discussed here show that EL is very useful for providing information regarding voltage and resistive effects. It can provide useful information to the manufacturer for improving process control in areas such as screen printing, and it can provide useful information for the customer to check delivery quality and avoid serious problems like large numbers of microcracks or serious cell faults. There is no justification to use EL for reliably establishing information about current matching between the cells and any associated effects. More work needs to be done in this area to build evidence-based criteria and confidence in using non-uniform EL response for diagnosing faults.

Acknowledgements

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