Maximum power estimation through injection dependent electroluminescence imaging

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Funding information
South African Department of Science and Innovation; Nelson Mandela University; PVinsight.

Abstract
The mathematical models applied to photovoltaic (PV) modules are typically oversimplified. In general, the models applied to individual PV cells are modified to obtain the “cell” voltage by dividing the module voltage by number of cells in the module. Due to the complexity of the current–voltage (IV) relation and the presence of bypass diodes in commercial PV modules this approach is inappropriate and can lead to incorrect conclusions about the electrical response of a module. This paper provides a method of determining each cell’s electrical response using a combination of the Dark IV response of the entire module and injection dependent electroluminescence (EL) imaging. This combination of characterization techniques makes use of equipment that is readily available in commercial facilities as well as regular PV characterization laboratories. This method can be used as an alternative to lock-in thermography (LIT) based methods, as the equipment required is not always present in standard PV characterization laboratories. In this study, Evolutionary Algorithms are used to optimize the individual cells' electrical parameters. This advanced characterization method can be utilized in commercial facilities, to investigate atypical module electrical response and in research laboratories to investigate the degradation in individual cells within a module.

KEYWORDS
electroluminescence, Genetic Algorithm, parameter optimization, photovoltaic

1 | INTRODUCTION

The deployment of Photovoltaics (PV) within global grid-scale electricity production is gaining traction,¹ as it is a clean power source that is rapidly becoming more economical. As this is the case, characterization of PV modules is becoming more important as part of quality control and constant research and development off newer technologies.

The characterization of degradation mechanisms of new (and current) PV technologies allows manufacturers to correctly predict power performance over the operational years of the modules. Although it is useful to characterize complete modules, the effects of degradation can occur on the individual cell level. Therefore, the ability to characterize individual cells within a module in a non-destructive manner is beneficial. Individual cell characterization has been performed before by Bauer et al.; however, this technique makes use of a lock-in Thermography (LIT) system which is not always available in laboratories as the equipment can be expensive.
or not readily available. The method employed in this work makes use of electroluminescence (EL) imaging and Dark current–voltage (IV) measurement equipment that is available in many PV characterization laboratories.

An injection dependent EL method was developed by Pothoff et al.\(^3\) to determine individual cell voltages of a PV module where the injection current (I) is greater than 10% of the short-circuit current (I\(_{\text{SC}}\)). The method developed and presented in this paper expands the method developed by Pothoff. In a previous study,\(^4\) we developed a Genetic Algorithm (GA) that was used for the parameter optimization of Dark IVs of Si PV cells. Similarly, in this paper, a GA is applied on each cell’s Dark IV data. The electrical parameters for each cell, except the shunt resistance and the photocurrent, can be determined (as it is Dark IV data where I \(>\) 0.1 I\(_{\text{SC}}\)). Combining the obtained electrical parameters with the Dark IV curve of the entire module, the shunt resistances of each cell can then be determined using a different GA. This is an improvement on our previous work on this method,\(^5\) where it was assumed that the IV data determined through injection dependent EL was enough to determine shunt resistance. However, it became apparent in the development of this method that the IV curve is insensitive to changes in the shunt resistance at injection levels \(\geq 0.1\) I\(_{\text{SC}}\). Combining electrical properties of the bypass diodes and each cell and assuming the short-circuit current is the photocurrent for each cell it is possible to estimate the power output of the module. The exact parameter optimization method is not important at this point as this paper focuses on the development of the method rather than a completely optimized procedure. This is an appropriate approximation for commercial modules due to the cell binning procedures in PV module manufacturing.

This method also allows for the estimation of the maximum power point across different irradiances. Combining this with irradiance data for specific locations can provide more accurate yearly energy yield estimates for PV systems.

\section{Theory}

\subsection{PV device IV modeling}

In this paper, the two-diode model is used and is described in Equations (1) and (2).\(^6\) Equation (1) describes the Dark IV response while Equation (2) describes the light IV response of an individual cell. Diode 1 is associated with bulk recombination current while diode 2 is associated with the junction recombination current.

\begin{equation}
I = I_{01} \left[ \exp \left( \frac{q (V - IR_{\text{SE}})}{n_1 k_B T} \right) - 1 \right] + I_{02} \left[ \exp \left( \frac{q (V - IR_{\text{SE}})}{n_2 k_B T} \right) - 1 \right] + \frac{V - IR_{\text{SE}}}{R_{\text{SH}}} - I_L \tag{2}
\end{equation}

\begin{equation}
I_{01} \text{, the saturation current, and } n_1 \text{, the ideality factor, are typically associated with } R_{\text{SH}} \text{, the shunt resistance, and } I_L \text{, the photocurrent. It is generally erroneously assumed that it is appropriate to use a representative/average cell to model the light IV response of a complete module,}\(^7\) \text{ and that the voltage is equally distributed across the } N \text{ series connected cells as described by Equation (3). This is an erroneous assumption as shown in the results and can lead to inappropriate conclusions. The superscript } * \text{ indicated a representative parameter value.}

\begin{equation}
I_{\text{mod}} = \frac{V^* - IR_{\text{SE}}}{R_{\text{SH}}} - I_L \tag{3}
\end{equation}

where \(V^*\) is the module voltage divided by the number of cells.

It is possible to realistically model the IV response of a complete module based upon the module’s individual cell IV characteristics. The method for determining these characteristics using voltage dependent EL is described in the next subsection. The module’s IV response is described by Equations (4) and (5) below.

\begin{equation}
I_{\text{mod}} = I_1 = I_2 = \ldots = I_i = \ldots = I_N \tag{4}
\end{equation}

\begin{equation}
V_{\text{mod}} = V_1 + V_2 + \ldots + V_i + \ldots + V_N \tag{5}
\end{equation}

where \(I_{\text{mod}}\) is the module current, \(I_i\) is the \(i\)th cell’s current, \(V_{\text{mod}}\) is the module voltage and \(V_i\) is the \(i\)th cell’s voltage.

\subsection{EL imaging and how injection dependent EL is used for individual IV characterization}

In EL imaging, the emission detected for each local position \(\phi_{\text{EL}}^x, y\) on a PV device is dependent on the local material properties, camera’s CCD detector’s quantum efficiency and local junction voltage. The determination of individual cell voltages can be attributed to the equation that describes the relationship of EL signal with local junction voltage\(^3,\) as
described by Equation (6). It can be reasonably assumed that the local junction voltage \((V_{x,y})\) is generally lower than the applied voltage.

\[
\phi_{EL}^{x,y} = C^{x,y} \exp \left( \frac{qV_{x,y}}{V_T} \right) \tag{6}
\]

where the \(x\) and \(y\) describe the local position on the PV cell surface, \((V_T)\) is the thermal voltage and \(C^{x,y}\) is the local calibration constant.

In the study by Pothoff, et al (2010),\(^3\) the authors discovered a method for determining the individual cell voltages in a module using injection dependent EL imaging. It is assumed that the brightest pixel \(\phi_{cell}^{max}\) in each cell in the images are well connected and must have approximately the same calibration constant due to very similar local properties. It was confirmed in the same work, that the calibration constant for \(\phi_{cell}^{max}\) of each cell was within 1.08% of the average calibration constant. As described in\(^3\) at low currents, the potential drop \((I_{mod}R_{mod})\) due to the series resistance term is negligible. Therefore, the following approximation can be made:

\[
V_{mod} = \sum_{i=1}^{N} \left( V_T \ln \left( \frac{\phi_i^{max}}{C} \right) \right) + I_{mod}R_{mod} \approx \sum_{i=1}^{N} \left( V_T \ln \left( \frac{\phi_i^{max}}{C} \right) \right) \tag{7}
\]

where \(V_{mod}\) is the applied voltage across the module, \(N\) is the number of cells in the module, \(\phi_i^{max}\) is the photon count of the brightest pixel of the \(i\)th cell, \(I_{mod}\) is the current through the module, \(R_{mod}\) the non-cell related resistances within the circuit of the module and \(C\) is the calibration constant for the brightest pixel. Therefore, to determine the calibration constant, Equation (8) may be used with the data from a low current (<=0.2 Isc) EL image.

\[
C = \exp \left( \frac{N}{\sum_{i=1}^{N} \sqrt{\prod_{i=1}^{N} \phi_i^{max}}} \frac{V_{mod}}{V_T} \right) \tag{8}
\]

Once calibrated, it is possible to determine the individual cell voltages. Equation (9) describes the relationship between brightest pixel signal and the individual cell voltage \((V_i)\).

\[
V_i = V_T \ln \left( \frac{\phi_i^{max}}{C} \right) \tag{9}
\]

### 2.3 Parameter optimization

The IV relation of PV devices is a relatively complex implicit function inhibiting analytical approaches to accurately calculate the IV parameters. Parameter optimization algorithms pose an effective solution to this problem. In this paper, a GA algorithm was utilized as GAs have a proven track record regarding resolving this problem.\(^4,9,10\)

However, other parameter optimization algorithms do exist that can effectively optimize IV curve parameters including Particle swarm optimization\(^11\); Harmony Search algorithm\(^12\); Differential Evolution.\(^13\) The GA algorithms used within this paper were coded in such a way to effectively make use of GPU processing to minimize on computing time. However, this paper’s focus is the method of utilizing a combination of injection dependent EL imaging of the module, the Dark IV of the module and parameter optimization algorithms to accurately model the PV modules performance by analyzing the cells individually. Further refinement of this method could be to determine the most effective parameter optimization algorithm.

### 2.4 Device simulation

To highlight the importance of this method, as well as the importance of the appropriate models applied to PV modules, two separate devices were simulated. The devices were simulated were based off of the module studied within this paper, that is two 36 half-cell modules were simulated. One of the devices will be simulated with cells with precisely the same electrical parameters (in Table 1) and the other with

| Parameter | Value |
|-----------|-------|
| \(I_01\)  | 1.664 \times 10^{-10} \text{ A} |
| \(n_1\)   | 1     |
| \(I_02\)  | 3.708 \times 10^{-6} \text{ A} |
| \(n_2\)   | 2     |
| \(R_{se}\) | 0.0015 \text{ Ω} |
| \(R_{se}\) | 50 \text{ Ω} |

**TABLE 1** Electrical parameters of “same cell” module

**FIGURE 1** Simulated high injection EL image of “same cell” module map of simulated module (0-8500 counts)
parameters varied by ±20%. The resultant Dark IV curves will be compared to each other.

To follow the methodology and the associated data flow, the EL images, Figures 1 and 2, were simulated using the EL images obtained from the device under test and the electrical characteristics of the individual cells. The assumption in simulating these images is that the simulated local junction voltages scale proportionally with the calculated relative local junction voltages from the measured EL images and the simulated cell voltages (based upon the "selected" electrical parameters). These images would form part of a set of injection dependent EL images (EL image datacube) which would then be used to determine individual cell voltages. To do this the images would then need to be calibrated using an EL image at low injection (the calibration procedure is described in the document).

Figure 3 is the Dark IV curves of the two simulated devices. This data set is important in the second step of the method presented in this paper. The complete module Dark IV curves are used to correct the optimized shunt resistance values determined in the first step of the method presented.

Figure 4 is a map of the individual cell voltages of the "varied cell" simulated module at low injection (1 A). It is apparent in this figure that the cell voltages do not vary substantially (relative standard deviation of 0.878%). Figure 5 is a map of the individual cell voltages of the "varied cell" simulated module at high injection (5.8 A). It is apparent in this figure that the cell voltages do not vary substantially (relative standard deviation of 0.815%). The map of the individual cell voltages of the "same cell" module was not included as it would simply be the same voltage for each cell. The individual cell voltages at the different injection levels are the used to optimize the electrical parameters of each cell in step one of the method presented in this paper. As mentioned previously, the shunt resistance values for the cells are corrected using the complete module's Dark IV data.

### 3 | EXPERIMENTAL PROCEDURE

#### 3.1 | EL procedure and equipment for light and Dark IV

Table 2 summarizes the experimental details including PV module details, and experimental setup. A multi-crystalline Si PV module with 36 cells (half-cell module, 15.6 cm × 7.8 cm) was chosen as the device under test to demonstrate the principle of the developed method. This device was chosen as it was modified to directly measure some of the individual cell voltages to confirm that the injection dependent EL image technique were accurately estimating cell voltages. This module was chosen out of convenience and availability rather than for a specific device technology reason. This data was not included as previous studies have presented similar data. The device was powered by a programmable DC power supply while imaged by a Si CCD camera. The DC power supply was set to constant current mode allowing for the set of images to be acquired under current conditions from 0.2 A to 10.0 A. For each resultant image taken, a dark image was...
also acquired and subtracted from the light image to remove stray light, thermal noise and defective pixels. Measurement noise was then reduced by the application of a median filter to each image. The Dark IV data of the module was collected from the same DC power supply, where the current injection was varied from 0.05 A to 10 A. For verification of the estimated power output of the module, an A + A+ A + MBJ solar simulator was used at multiple injection levels. The five light injection levels were from 200 W/m² to 1000 W/m² in increments of 200 W/m².

3.2 | Implementation of GAs to determine individual IV characteristics

Two separate, yet similar Genetic Algorithms were used to determine the electrical parameters of the cells within a module. However, other parameter optimization algorithms could be used. EL signals are typically only detectable in the region of more than 10% of the short-circuit current of the module. This inhibits an accurate shunt resistance determination from the cell Dark IV data obtained using the EL data. To mitigate this fact, the following process was developed, the overall process flow diagram is shown in Figure 6.

- The EL data cube is the set of injection dependent EL images, this data cube is then used to determine individual cell Dark IV curves. This is done in accordance to the method described in the theory section.
- The first genetic algorithm is then applied to the individual cell IV data calculated in the previous step to optimize the cells’ electrical parameters (including a preliminary $R_{SH}$ value for each cell).
- The second GA is then applied to the combination of these individual IV parameters and the complete module’s Dark IV data. The $R_{SH}$ values are then re-optimized using this extended data set using the preliminary $R_{SH}$ values as a starting point.
- With a complete Dark IV characterization of the module down to the cell level, the light IV data of the module (different injection levels) is simulated under the assumption that each individual cell will have the same photocurrent. This assumption is not ideal; however, based on binning procedures of module manufacturers, it is not completely unfounded.

The first GA algorithm makes use of the Dark IV data for each cell acquired through the injection dependent EL. The fitness for this GA is determined using the relative error for the estimated IV against the measured cell IV data. In this case, the lower the error, the higher the fitness. That is, each cell’s parameter values are determined individually. The second GA makes use of the entire Dark IV curve of the module, so the entire module’s IV curve is simulated using the previously determined IV parameters; therefore, the fitness of this GA is based upon the relative error (RE) for the estimated module IV data against the module’s IV data, the lower the error the higher the fitness.

![Figure 5](image)

**FIGURE 5** High injection cell voltage map of simulated module (0.621-0.639 V)

| TABLE 2 Summary of experimental details |
|------------------------------------------|
| **Module**                               |
| Technology | Multi-crystalline Si | Cell area | 15.6 cm × 7.8 cm |
| Number of cells | 36 (3 × 12) | Power | 100 W |
| Isc | 5.95 A | Voc | 22.30 V |
| Imp | 5.56 A | Vmp | 18.0 V |
| **EL camera**                             |
| Resolution | 1023 × 1024 px | Gain | 0.65 counts/e⁻ |
| **Solar simulator**                        |
| Current uncertainty | ≈ 2% | Voltage uncertainty | ≈ 0.8% |
| Spectrum | Class A + | Long term stability | Class A + (< 0.25 %) |
| Homogeneity | Class A + (< 0.25 %) | Power repeatably | Class A + (< 0.2 %) |
where $M$ is the number of IV data points, $\hat{V}_i$ is the $i$th estimated voltage at a given injection and $V_i$ is the equivalent measured voltage.

Table 3 is a summary of the operational parameters of the GAs used in the parameter optimization used in the method described above.

The models used within this study for light and Dark IV relations are described by Equations (1) and (2). That is, the two-diode model was used. This selection was based upon accuracy of the simulations and the curve fitting when applied to this module. The ideality factors for both the diodes were set to 1 and 2 respectively, as the varied ideality factors in the case of this sample provided no increase in accuracy with physically realizable solutions. It could be argued that there exists regions on this sample with non-ideal characteristics; however, to correctly characterize such regions a localized cell characterization technique would need to be employed to do this. This is indeed possible as described in2; however, considering the fact that the method presented in this paper is intended for use in laboratories without access to such equipment, this is not necessary. The contributions to the electrical characteristics of these non-ideal regions are not significant, otherwise, the varied ideality factor model would have provided significant accuracy over the model applied in this study. Generic bypass diodes were assumed for this study and were not measured directly. Direct measurement of the bypass diodes largely depends on accessibility to the diodes. Some more recent modules make use of individual cell bypass diodes, the diodes are contained within the panel and have no direct access. By assuming generic diodes, it is possible to achieve reasonable accuracy without being reliant on direct measurements.

4 | RESULTS

4.1 | Basic EL and IV data

As described in the Experimental Procedure, the multiple EL images were acquired at different injection levels. Including all of these EL images would not contribute to the discussion of the presented results, therefore two images were selected to effectively represent the EL data. Figures 7 and 8 show the EL images of the module at injection levels of 10% $I_{sc}$ and $I_{sc}$ respectively. The low injection image (10% $I_{sc}$) is used to determine the calibration factor for the technique. Low injection level EL images are typically used to identify cells affected by PID as the increased recombination/shunting will result in a darker appearance for the affected cell (due to lower cell voltage).14 High injection images (such as the $I_{sc}$ EL image) are typically used to identify cracks and other defects due to the higher contrast.15 The cells are numbered as indicated in the figures. In the low injection image, it is possible to see some defect in C1; however, it is substantially more apparent in the high injection image. Two of the four busbars in C1 are disconnected. B3 appears darker in the low injection image due to a lower shunt resistance or higher junction carrier recombination rate and may be attributed to the onset of early stage PID.
4.2 Determination of individual IV characteristics

Figure 9 is the voltage map of individual cell voltages within the module while at Isc current injection. This voltage map was included mainly to show the step from the EL images to the voltage mapping at different injection levels to individual cells’ Dark IV curves as discussed below. In this figure, the variation of the voltage between the cells becomes more noticeable than in a regular EL image. C1 is at a higher voltage than most of the other cells, and this is due to an increased effective series resistance as a result of the disconnected bus bars. The fact that A1 has a low voltage at this high injection indicates that either the cell has low resistance or is severely shunted. However, as observed in Figure 3, this cell shows no indication of low shunt resistance (or increased defect recombination). This implies that cell A1 has low series resistance. To highlight the effectiveness of this technique, the three cells exhibiting different characteristics were further investigated for their electrical properties. These are a good cell (A1), and cells exhibiting low shunt resistance (B3) and partial disconnection (C1).

Figure 10 shows the extracted Dark IV curves using the injection dependent EL technique. The data shown in black crosses is that of a good cell (A1), as indicated by high shunt resistance, low junction recombination, and low series resistance. The IV data in black solid diamonds is that of a cell with lower shunt resistance or higher junction recombination (B3). The IV data in gray hollow diamonds is that of a partially disconnected cell (C1) which can be seen by the higher effective series resistance (indicated by the slope of the Dark IV curve in high voltage region).

Figure 11 shows the simulated light IV curves at STC of the same three cells. It must be noted, though, that the simulated curves are based upon the assumption that all the cells have the same photocurrent. A1 has the highest fill factor, while C1 and B3 show similar fill factors.

One of the key loss mechanisms within PV modules is cell mismatch caused by cells within a module not having matching IV characteristics and parameters. The results of the parameters of the three cells investigated are summarized in Table 4. In this table, the cell maximum power point ($P_{Max}$) is given per PV cell and compares it to the maximum power operational point for the module. The maximum power for A1 is 2.75 W, while C1 is 2.66 W and B3 is 2.68 W, respectively. The fundamental condition of equal current for series connected mismatched cells will result in the cells operating at different voltages within a module and not at their individual maximum power points. At the module's maximum power

| Table 3 | Operational parameters of GAs used within study |
|-----------------|-----------------|-----------------|-----------------|
| **GA 1: Cell electrical parameters** | | |
| Population size | 5000 | |
| Maximum iterations | 1000 | |
| Mutation rate | 30% | |
| **GA 2: Shunt resistance correction** | | |
| Population size | 100 | |
| Maximum iterations | 200 | |
| Mutation rate | 20% | |

FIGURE 7 EL image at 10% Isc (0-740 counts)

FIGURE 8 EL image at Isc (0-14 000 counts)

FIGURE 9 Cell voltage map (0.6220-0.6357 V)
operational point, the current is 5.53 A. A1 operates at 0.50 V which equates to 2.68 W, C1 operates at 0.48 V which equates to 2.57 W, while B3 operates at 0.48 V which equates to 2.57 W. This causes a relative loss of 2.55%, 3.38% and 4.10% for each cell respectively. If each cell was at their individual maximum power point the total power equates to 8.09 W while at the maximum power point of the module the total power is 7.82 W. This is equivalent to a relative loss of 3.34%. That is, in Table 4, the columns that fall under “Individual cell Max. Power Point” are the operational points of the cells if their maximum power points were used; however, the columns under “Module Max. Power Point” are the operational points of those cells if the module is at maximum power. The final column of the table $\Delta P_{Max}^*$, this column represents the difference between the maximum power of the cell and the power produced by that specific cell at the maximum power point of the module relative to the maximum power of the cell $\Delta P_{Max}^* = \frac{P_{Max} - P_{Max}^*}{P_{Max}}$.

**FIGURE 10** Three sample Dark IV curves calculated from injection dependent EL images

**FIGURE 11** The simulated light IV curves of the three sample cells
4.3 Simulated extracted curve vs measured curve

Light IV curves of the module were simulated using individual cell IV parameters determined using the procedure described in Figure 12. The Dark IV data was measured using the same power supply and cabling setup as the EL imaging data. Since a two-probe power supply cabling system was used, a series resistance correction was included. The light IV setup made use of a four-probe cabling setup and may cause any uncertainty in the cabling series resistance to enhance the deviation from the simulated vs measured light IV curves. The simulated IV curves are shown in Figure 12 for five different irradiance levels and are compared to the equivalent measured IV curves. There is noticeable deviation within the simulations at the higher injection levels. It is hypothesized that this deviation could be a result of the approximation that each cell has the same photocurrent and/or uncertainty in the estimation of the cells’ saturation currents. If this is the case, the operational voltages would shift. The difference in effective series resistance of the setups (light and Dark IV setups respectively) also have affected the simulated curves, particularly at the higher injection levels near Voc. Table 5 summarizes the comparison of the maximum power prediction of the simulations to the measured results. The simulations show decreased accuracy at the lower irradiance levels. This can be attributed to the fact that the models were simulated upon equivalent percentages of Isc at STC. That is, at 1 sun irradiance the photocurrent is assumed to be at 100% Isc, at 0.8 suns intensity the photocurrent is assumed to be at 80% Isc and spo on. The inherent error within the simulator is 3%. Further development of the method which includes accurate estimations of Isc at different irradiance levels could yield higher accuracy.

While IV curves at different irradiances are standard practice within the semiconductor and PV industry, modeling of an irradiance current–voltage parametric surface has not been done. Figure 13 shows the simulated light IV parametric surface for the module, from 0.1 Suns to 1.1 Suns. That is, each mapped color represents the light IV curve at a particular irradiance level. This allows for the determination of any operational point of the module at STC. The maximum power point of the module can then be predicted at any irradiance level at STC. These points are plotted in a black line across the light IV surface. The measured light IV curves are also plotted on the surface, highlighting the simulation’s accuracy. Further development of this method including the expansion of the method

| Cell  | Description                  | P_{Max} (W) | V_{MP} (V) | I_{MP} (A) | P^{*}_{Max} (W) | V^{*}_{MP} (V) | ΔP^{*}_{Max} (%) |
|-------|------------------------------|-------------|------------|------------|----------------|----------------|-----------------|
| A1    | Good cell                    | 2.75        | 0.49       | 5.58       | 2.68           | 0.50           | −2.55           |
| B3    | Shunted cell                 | 2.66        | 0.5        | 5.35       | 2.57           | 0.48           | −3.38           |
| C1    | Partially disconnect cell    | 2.68        | 0.49       | 5.49       | 2.57           | 0.48           | −4.10           |

**FIGURE 12** Simulated light IV curves at different irradiance levels as compared to the equivalent measured curves
to include temperature dependence will allow for complete and accurate maximum power prediction for the module across different operational conditions. This would impact the cost-benefit analysis for PV installation.

In summary, the injection dependent EL imaging method shown in this study provides a useful approximation of individual cell electrical properties, cell mismatch and resulting module performance. This information may be useful for research institutions, manufacturers, testing laboratories and PV power plants.

It is possible to provide more complete and accurate electrical characterization with the use of temperature probes or with a thermal camera. Temperature probes allow for an inexpensive temperature measurement for the individual cells. This temperature measurement can be assumed to be the average cell temperature and can be used to correct for the cells thermal voltage in the calibration process and in the process to determine individual cell voltages. A thermal camera can be used in a similar way to the temperature probes except it can correct for the local thermal voltage in each cell, providing more accurate data. This process can then be included while varying the environmental temperature that the module is present within. This can then be used to investigate the effect of temperature on the electrical parameters.

5 | CONCLUSIONS

In this paper, it has been shown that it is possible to combine injection dependent EL imaging as well as the Dark IV of the entire module to determine the individual cell characteristics within the module. It was also shown that it is possible to simulate the irradiance dependent Light IVs of each cell as well as the complete module. The greatest deviations to the approximations occur at lower irradiance levels while the precise origin of this deviation is currently unknown. It can be hypothesized to be related to the measurement accuracy of the simulator or the irradiance dependence of collection efficiency.

This method offers similar results to a recently published method developed by Blakesley et al. However, it makes use of equipment that is more readily available in laboratories. A module simulator is not required to investigate individual cell performances within a module. EL imaging
systems are used on site (large PV plants), testing laboratories and even by module manufacturers. Since module string level EL imaging has become commonplace this would enhance the potential of expanding this technique to the module string level of a large PV plant. The use of an InGaAs camera would allow for rapid analysis of modules, allowing for application of this method within testing laboratories and at PV module manufacturing plants. The current method is undergoing further development to allow for the inclusion of multi-irradiance level light IV data to determine individual cell photocurrents. This would allow for the individual cell characterization within the module during degradation studies and provide another method to determine a cell mismatch factor for a module.

ACKNOWLEDGMENTS

The authors gratefully acknowledge PVinsight (Pty) Ltd, the South African Department of Science and Innovation (DSI), ESKOM and Nelson Mandela University for the financial support and providing necessary facilities for research.

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How to cite this article: Dix-Peek RM, van Dyk EE, Vorster FJ. Maximum power estimation through injection dependent electroluminescence imaging. Energy Sci Eng. 2021;9:757–767. https://doi.org/10.1002/ese3.858