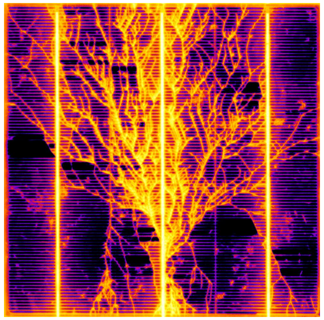
Faculty of Engineering
School of Photovoltaic and Renewable Energy Engineering

UNSW SYDNEY | Australia's Global University



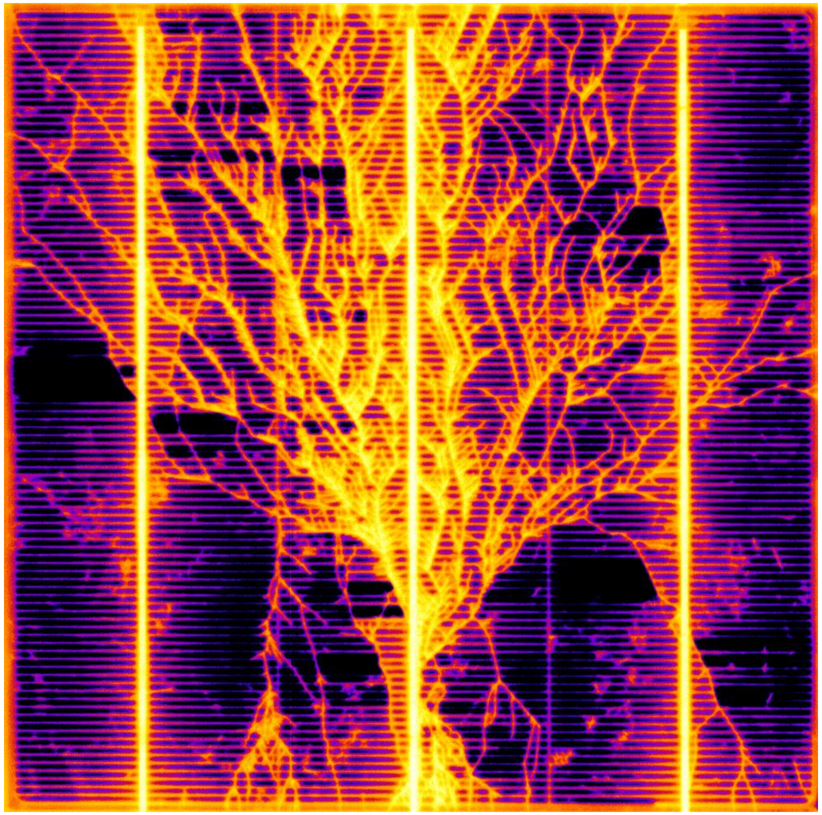
Thorsten Trupke

PL imaging going downstream: Outdoor Module Inspection in Full Daylight

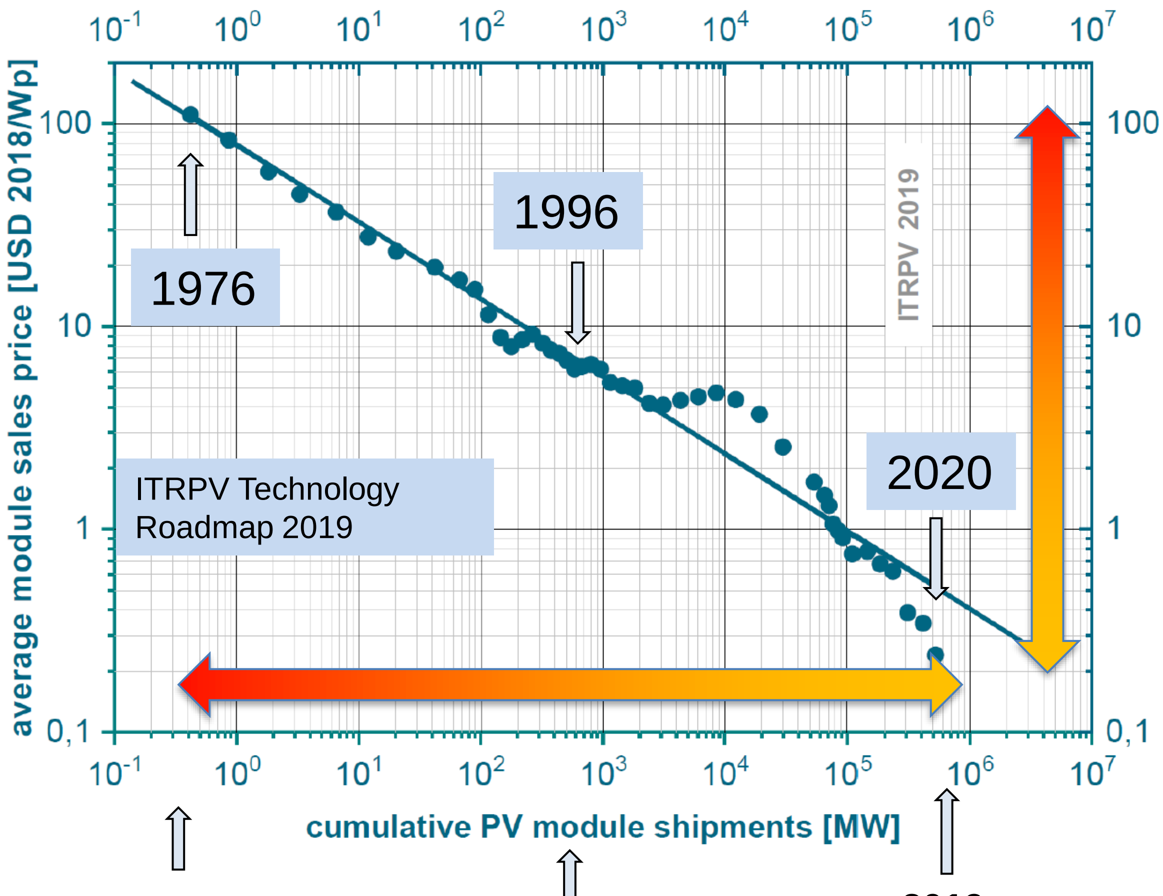
SPREE Seminar 20 May 2021

Contents

- **Photovoltaics - The big picture**
  - The past
  - The present
  - The future
- **Photoluminescence imaging**
- **PL imaging on PV modules**
  - Laboratory applications
  - UNSW projects on field inspection in full daylight
- **Summary and conclusions**



Big Picture
– The Past



Photovoltaic Learning Curve:

Prices dropped **almost 1,000x over 45 years**

Installed capacity increased **1,000,000 times!**

Rapidly approaching **1TW$_p$** (expected in 2022)

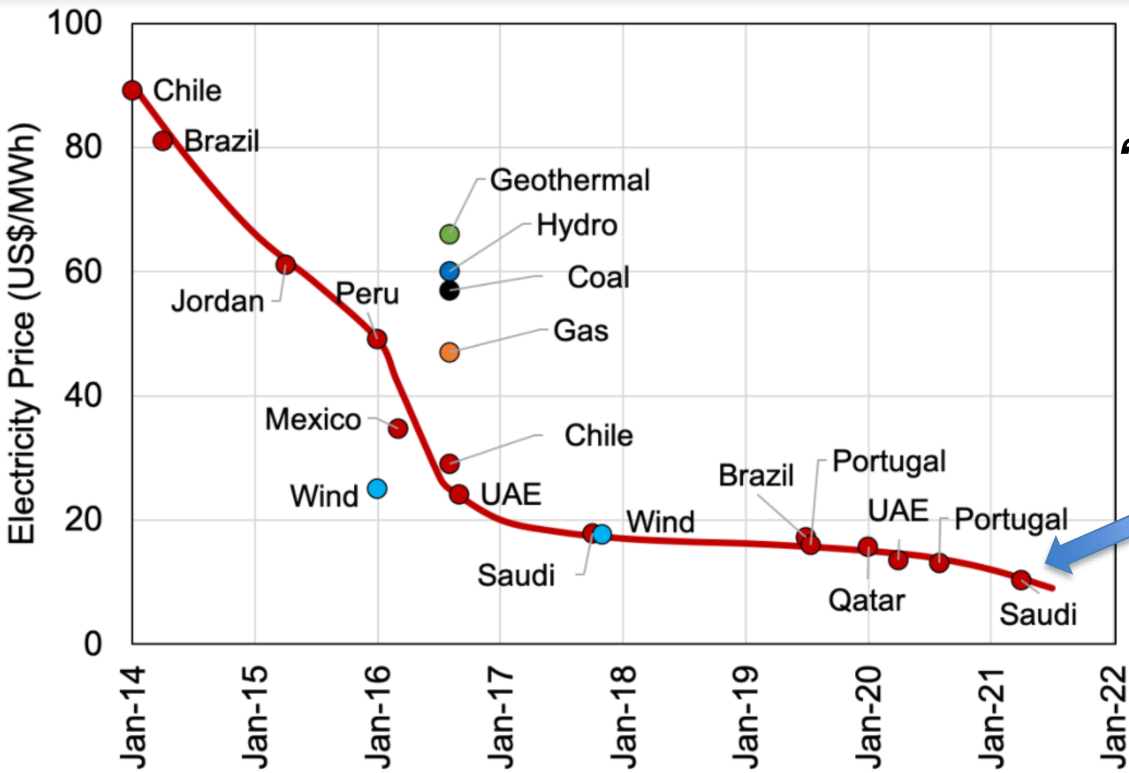
1976:
600 kW$_p$:
Few 100 rooftop systems

1996:
600 MW$_p$: generating far less than one coal fired station

2019:
600 GW$_p$

Big Picture
– The Present

For comparison, retail price:
A$ 0.30 / kWh ~ US$ 220 / MWh



"PV is now the cheapest form of generating electricity!"

Saudi Arabia's second PV tender draws world record low bid of $0.0104/kWh

$10 / MWh = 1c / kWh

https://www.pv-magazine.com/2021/04/08/saudi-arabias-second-pv-tender-draws-world-record-low-bid-of-0104-kwh/

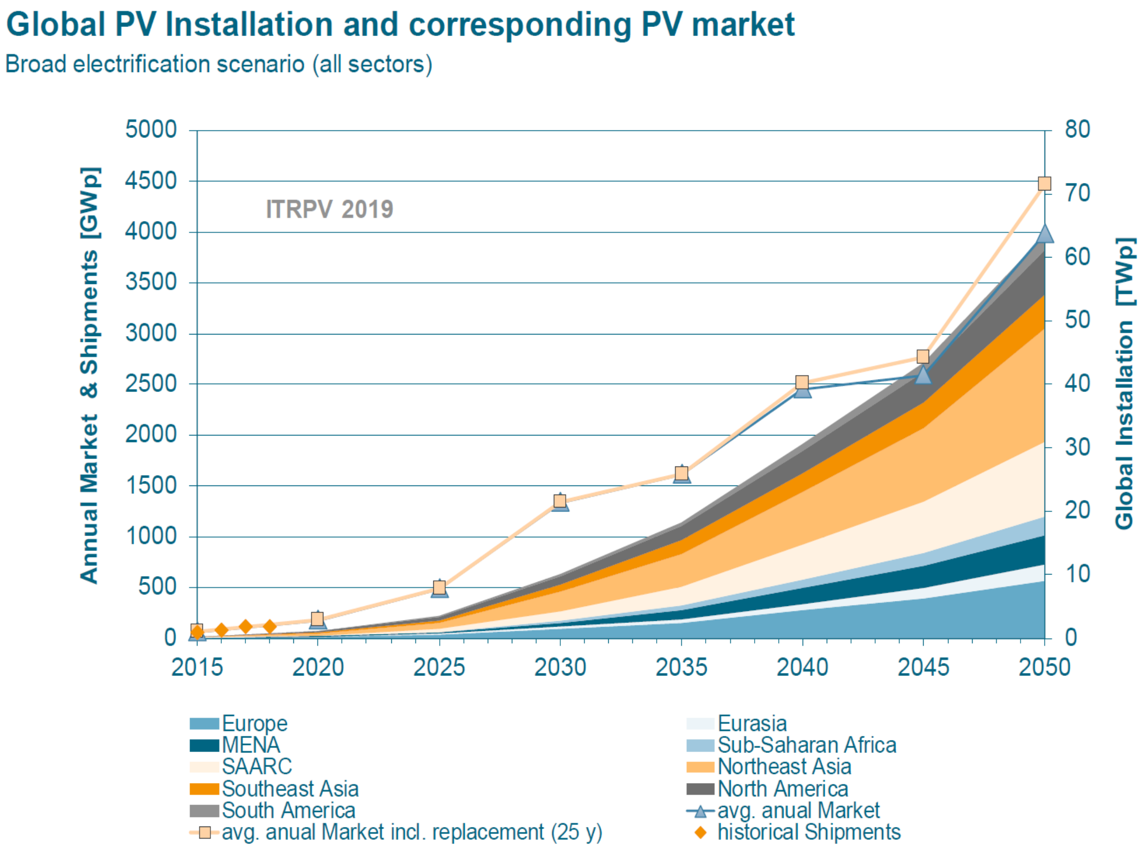
Big Picture
– The Present

Big Picture – The Present

- Utility scale solar farms with solar panels as far as the eye can see
- Now reach GWp scale with up to several million panels in one PV power plant!

Big Picture
– The Present

Big Picture
– The Future



- **50 TWp** of installed PV by 2050
- **Outrageous growth** expected for 30 years
- 50TWp would generate about 3 times the entire global 2020 electricity consumption
- Up to 50% of world's predicted 2050 primary energy demand from PV
- Significant acceleration in electricity demand due to electrification of transport

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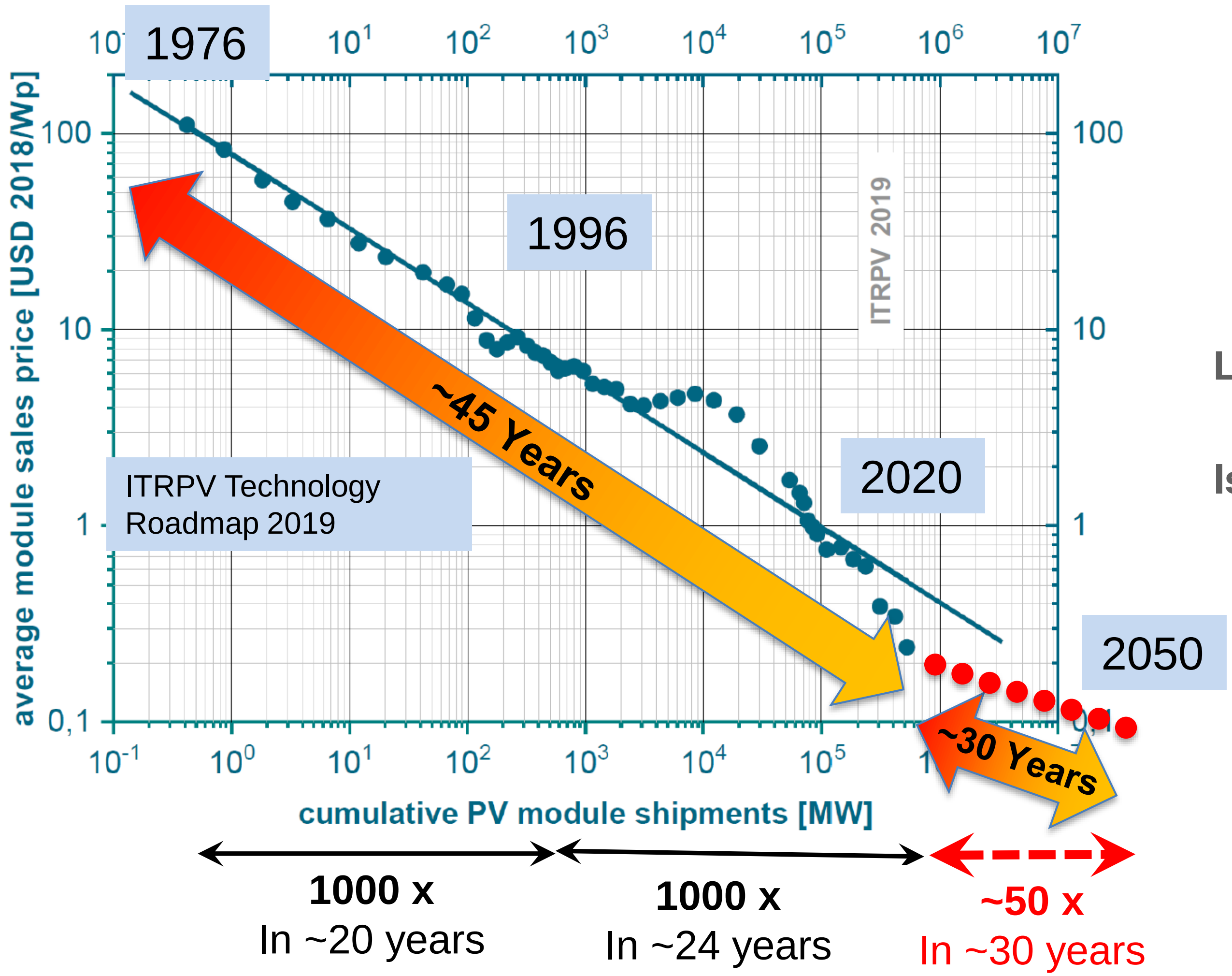
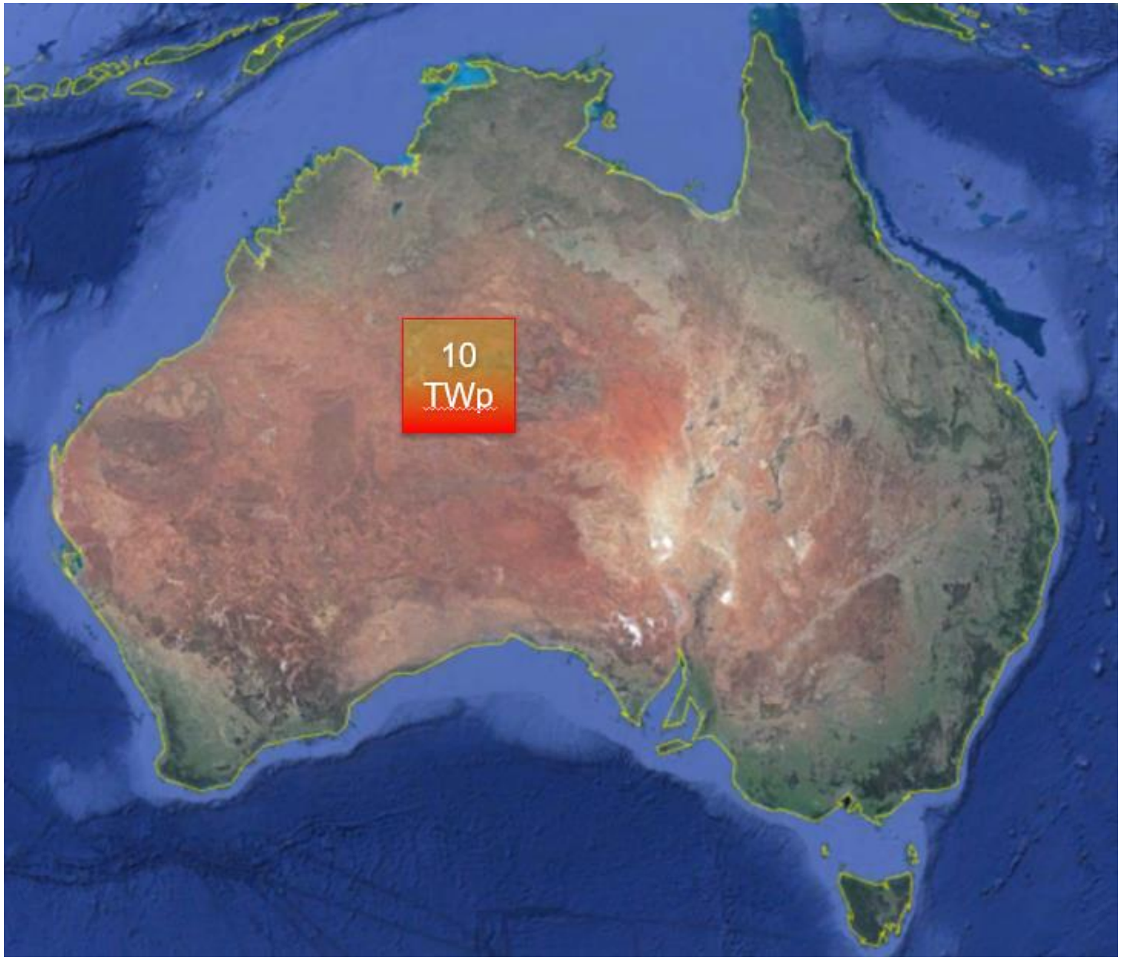
Big Picture
– The Future



Learning curve in 2050

Is this doable…?

Big Picture
– The Future



Land area requirements:

- 10 TWp installed in Australia
- Requires ~ 200,000 km^2 (450km x 450 km)
  - Conservative estimate
- 2.5% of Australian land mass
- Vision for a future Australia as net exporter of energy

Module quality matters!

Modules must last in the field for > 25 years:

- Manufacturing issues
- Degradation during operation
- Damage during transport, installation or operation
- Severe weather events

→ Quality testing imperative

Most defects cannot be detected with the naked eye!

→ Luminescence imaging

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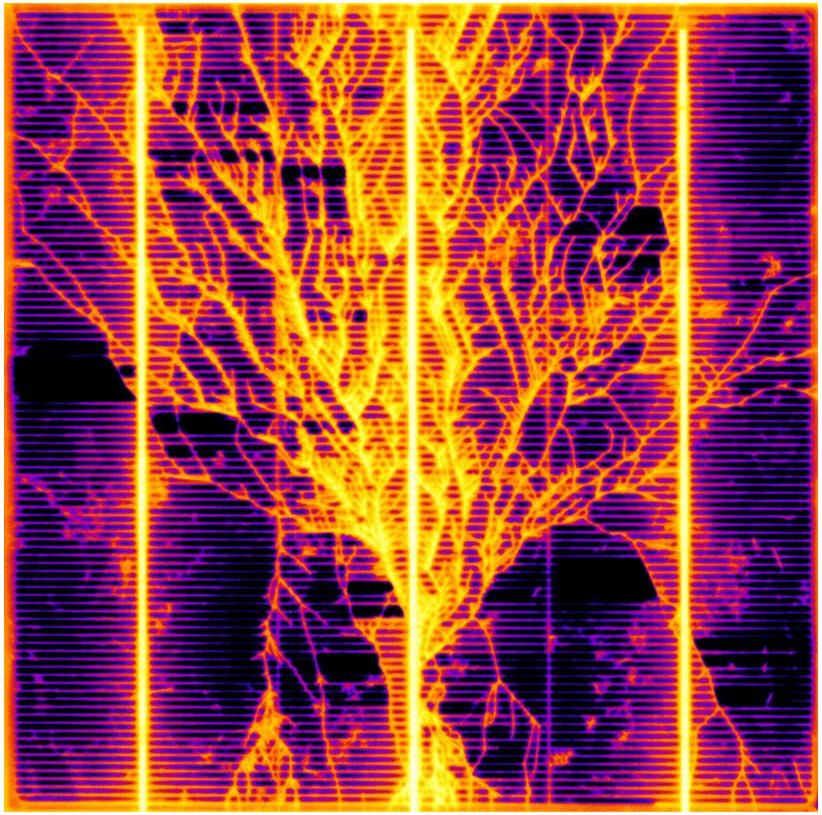
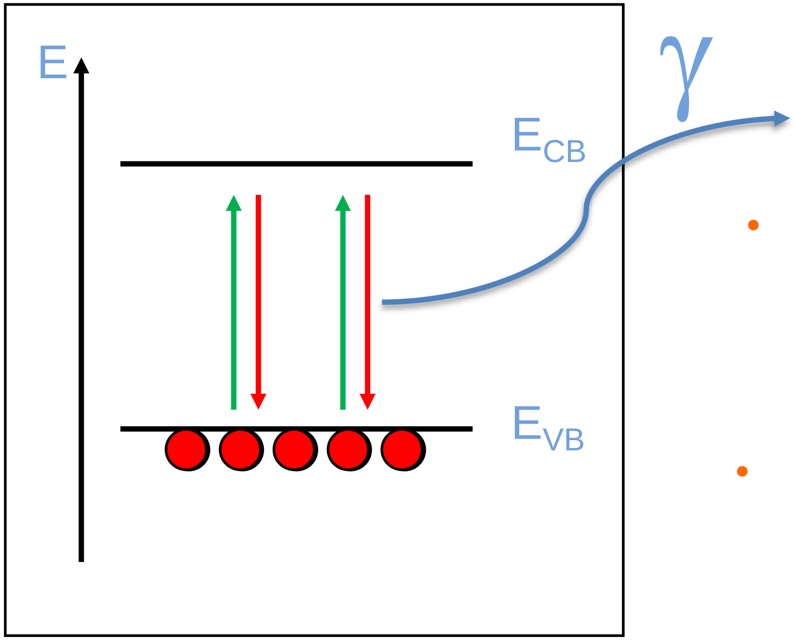


What is luminescence

"Luminescence is the emission of light, that is observed from some materials under external excitation."



- *In semiconductors luminescence (γ) is emitted when electrons relax from a high energy state to a lower energy state*

- *The amount of luminescence (intensity) tells us a lot about the quality of the material for solar cell applications!*

What is luminescence

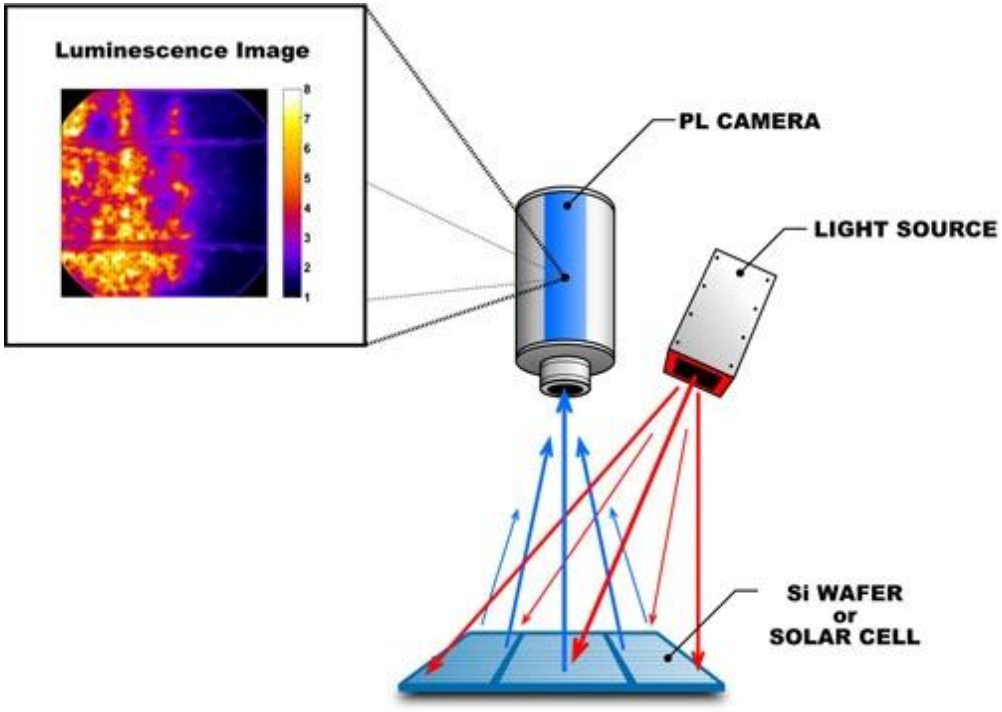
Photoluminescence

"Luminescence is the emission of light, that is observed from some materials under external excitation."

Electroluminescence (LEDs)

Chemiluminescence

Photoluminescence imaging



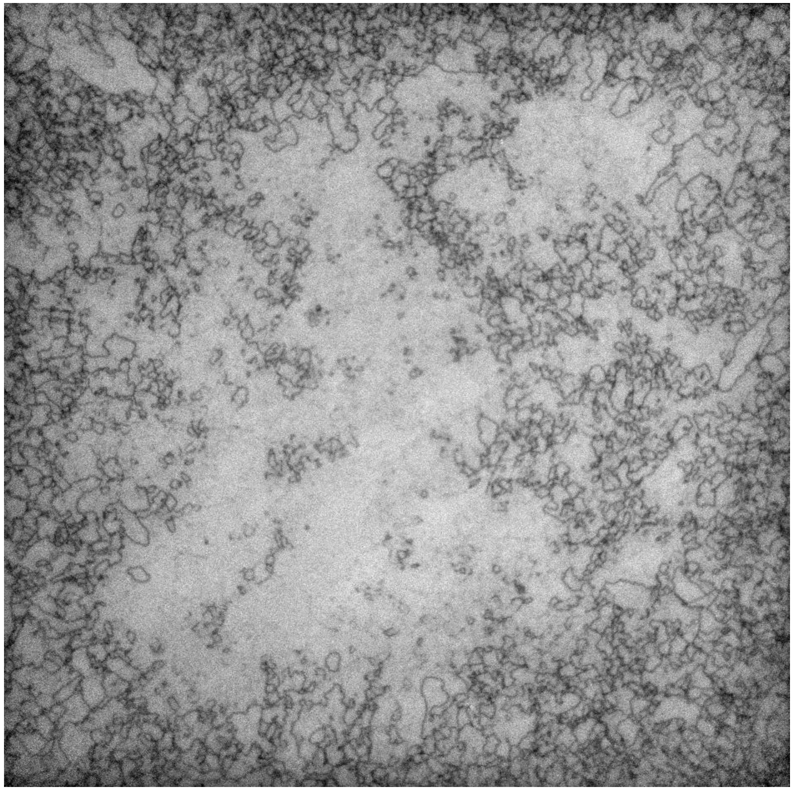
- Silicon is a poor light emitter
- Separation of luminescence from reflected laser light challenging due to low luminescence quantum yield (e.g. $\mathbf{10^{-10}}$ for as-cut wafers)
- Introduced at UNSW in 2005
- Wide range of applications in R&D for ingots, wafers, solar cells

T. Trupke, R. A. Bardos, M. C. Schubert, and W. Warta, "*Photoluminescence imaging of silicon wafers*," Appl. Phys. Lett., vol. 89, no. 4, p. 044107, Jul. 2006

Photoluminescence imaging

Example: Cast mono silicon wafer

What you see with the naked eye



PL Image

General rule: "*Dark patterns represent defects*"

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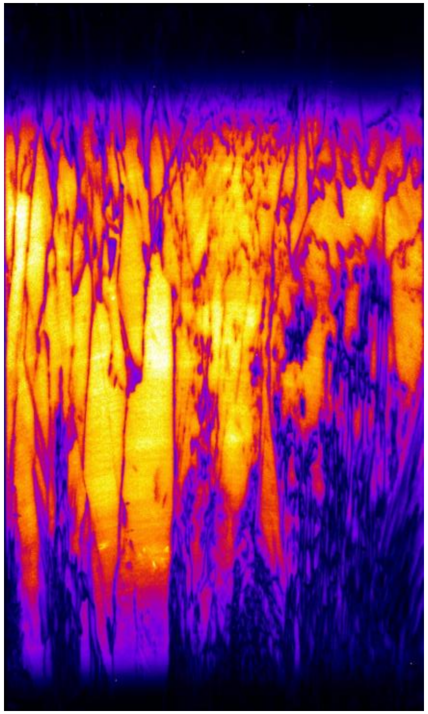
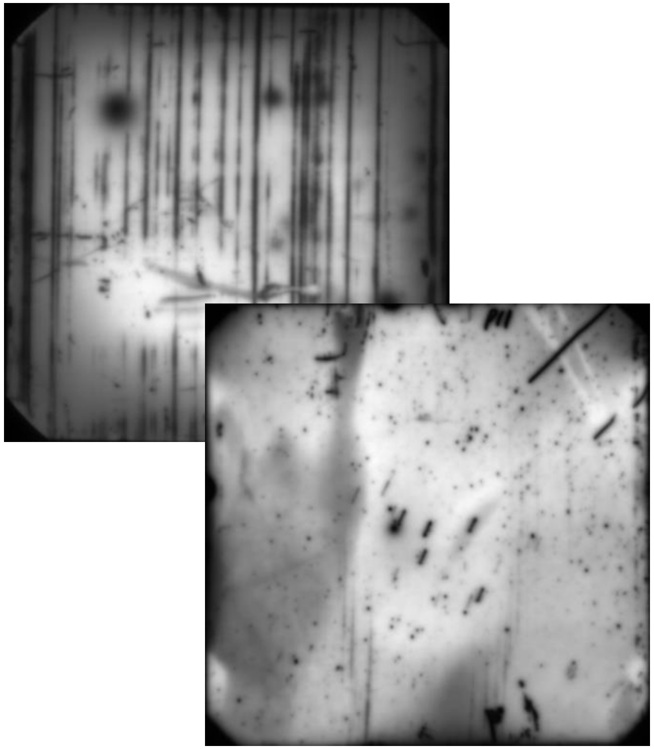
Photoluminescence imaging

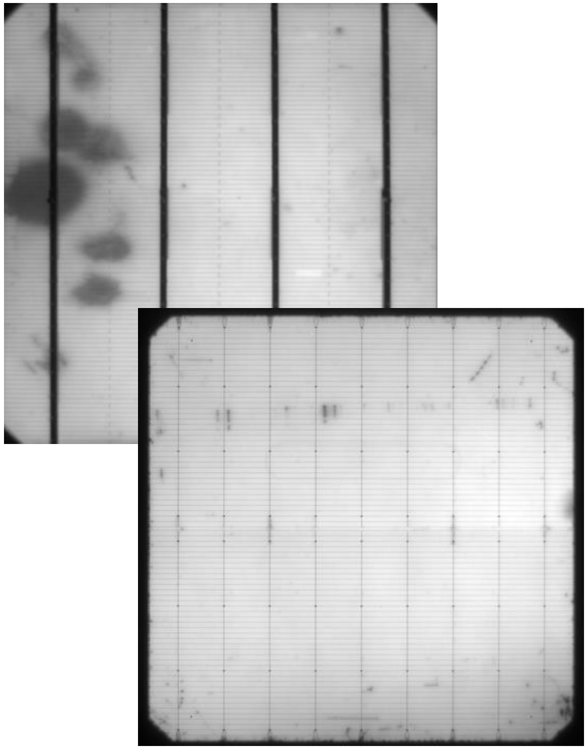
Applications across the value chain



Ingots and bricks



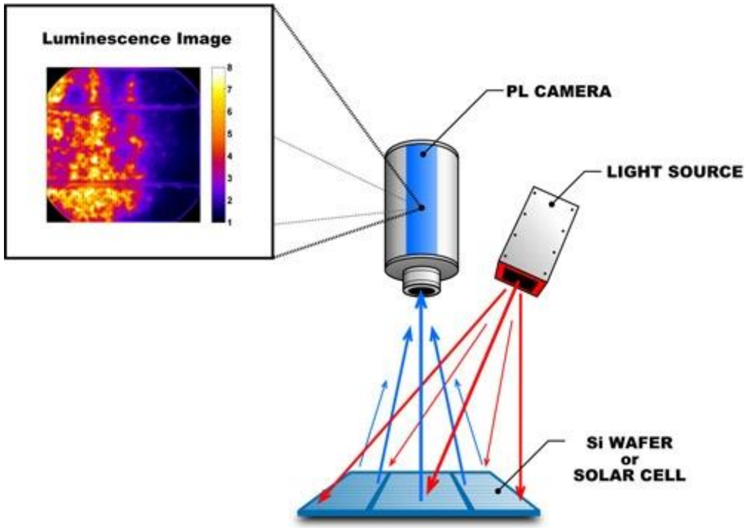
Wafers (As cut and partially processed)



Cells

Modules?

Photoluminescence imaging on modules



JA Solar launches 800 W solar panel

The new product, currently the most powerful panel on the market, was showcased at the SNEC PV Power Expo in Shanghai. Also presented at the fair was a 780 W product from Tongwei and a 660 W module from Trina.

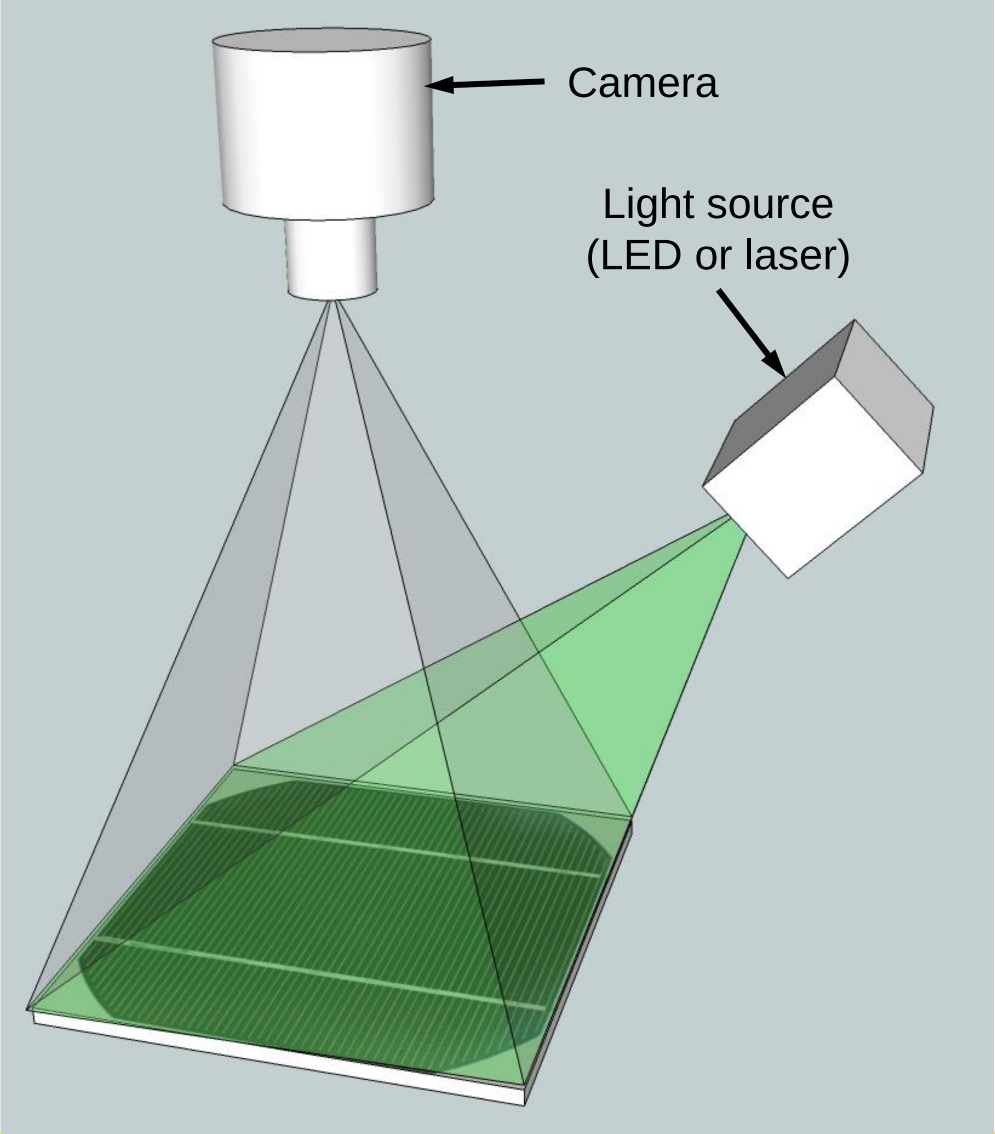
AUGUST 14, 2020 VINCENT SHAW

MARKETS MARKETS & POLICY CHINA

- PV panels are large (now up to 2.4m x 1.6m…!)
- Uniform laser illumination difficult / impractical to achieve

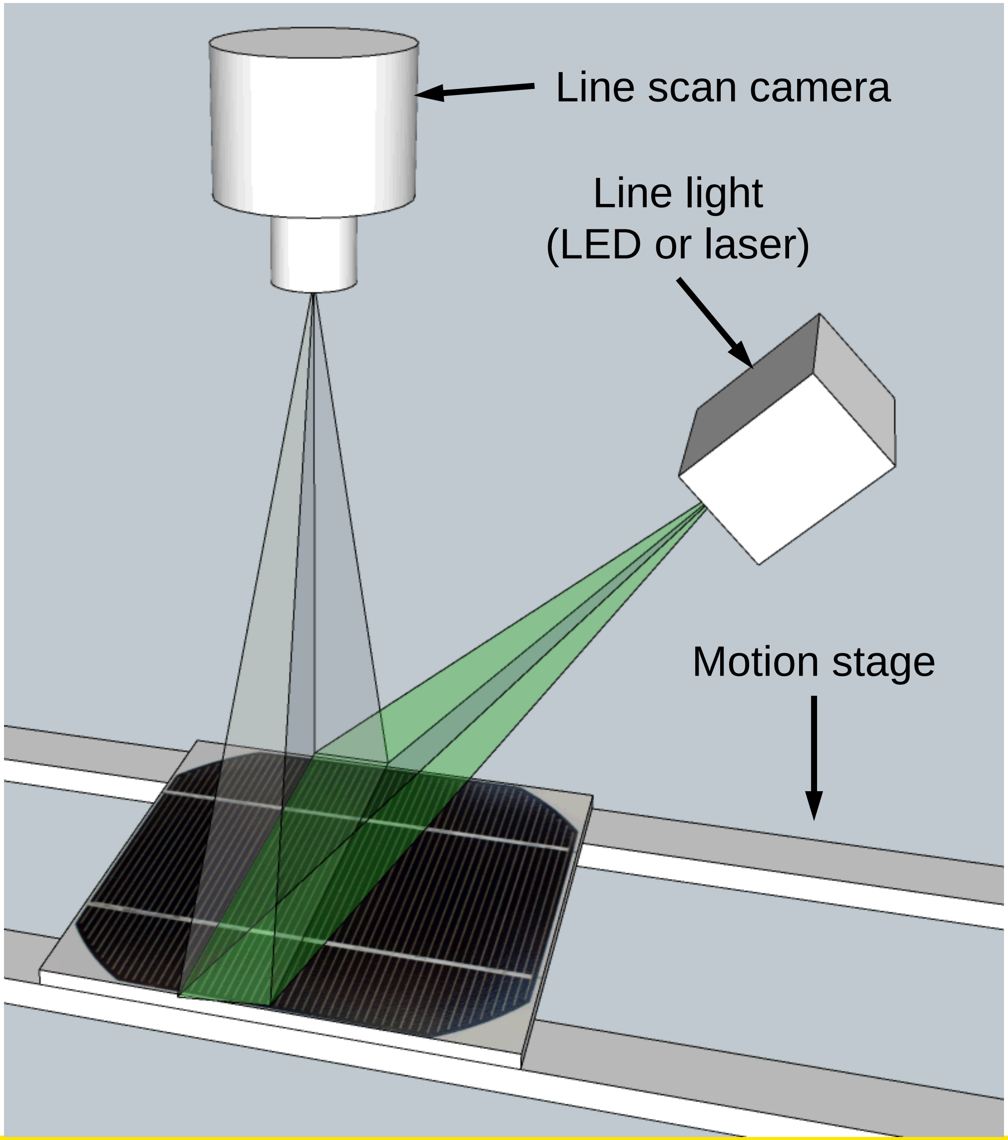
→ **Line scan PL imaging**

Conventional PL imaging



- Full area illumination
- Simultaneous image acquisition using “*conventional*” camera
- Sample stationary

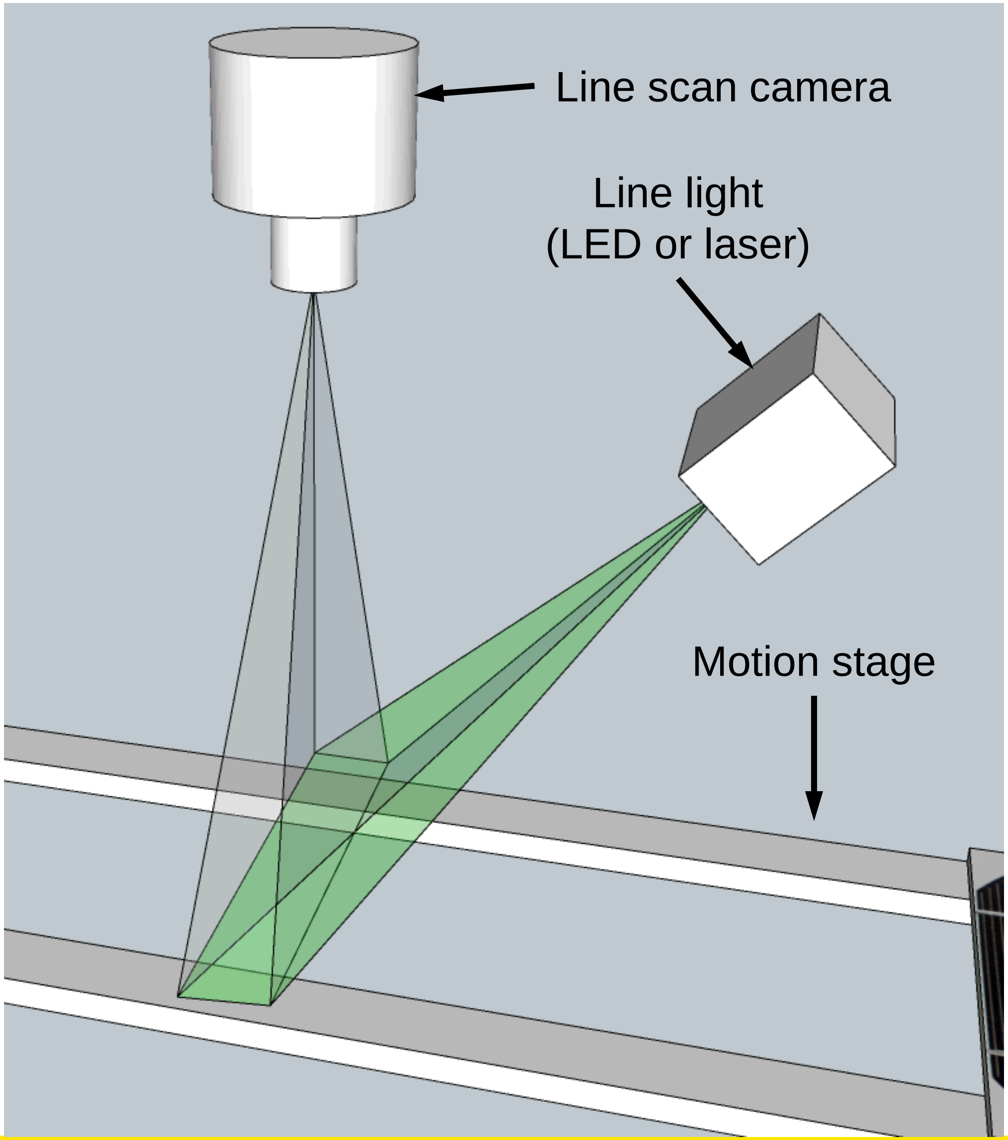
Line scan PL imaging



- **Only a narrow line is illuminated**
- Sample (e.g. module) moves at constant speed (up to 500mm/s)
- Line camera captures image lines in sync with sample motion
- Full image is assembled from individual lines
- Applicable to ingots, wafers, cells **and modules**!

Courtesy I. Zafirofska

Line scan PL imaging



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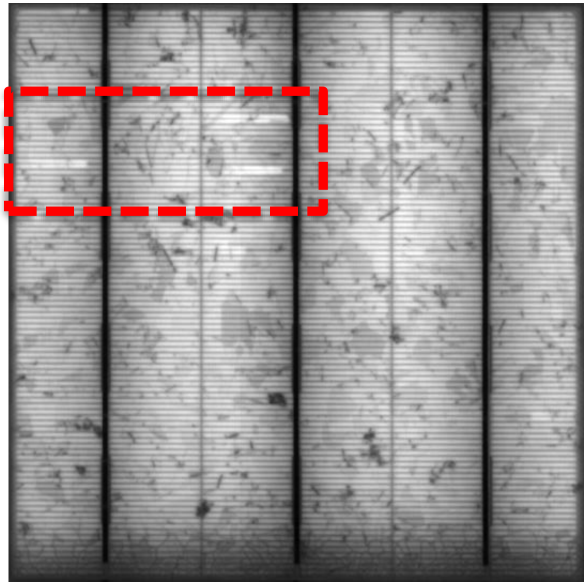
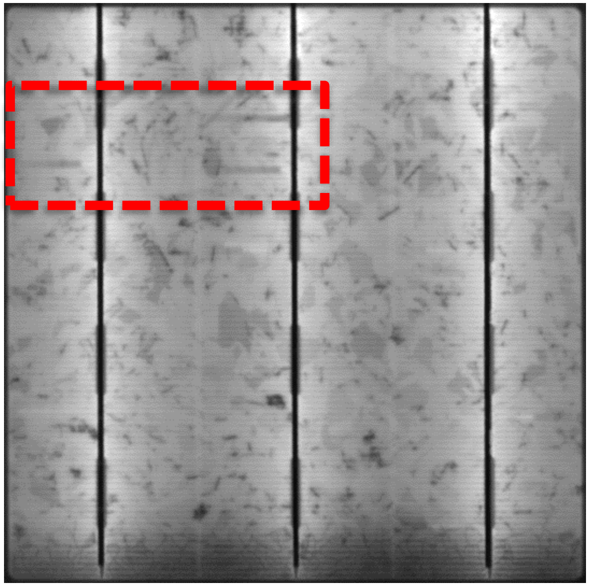
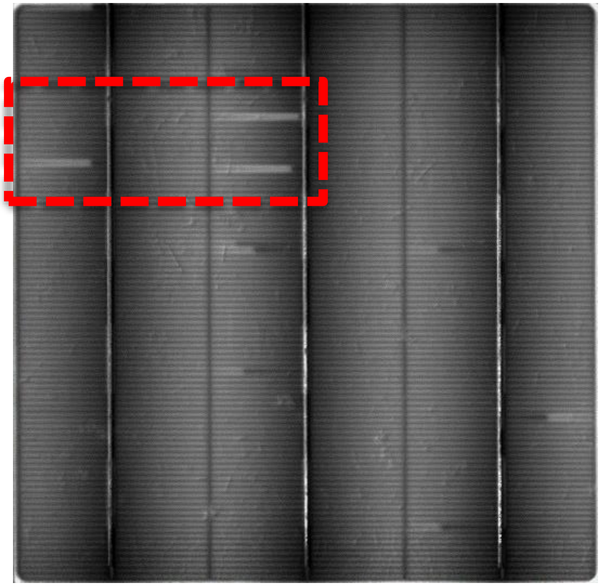
Photoluminescence imaging on modules



PL_{LS} image



EL image

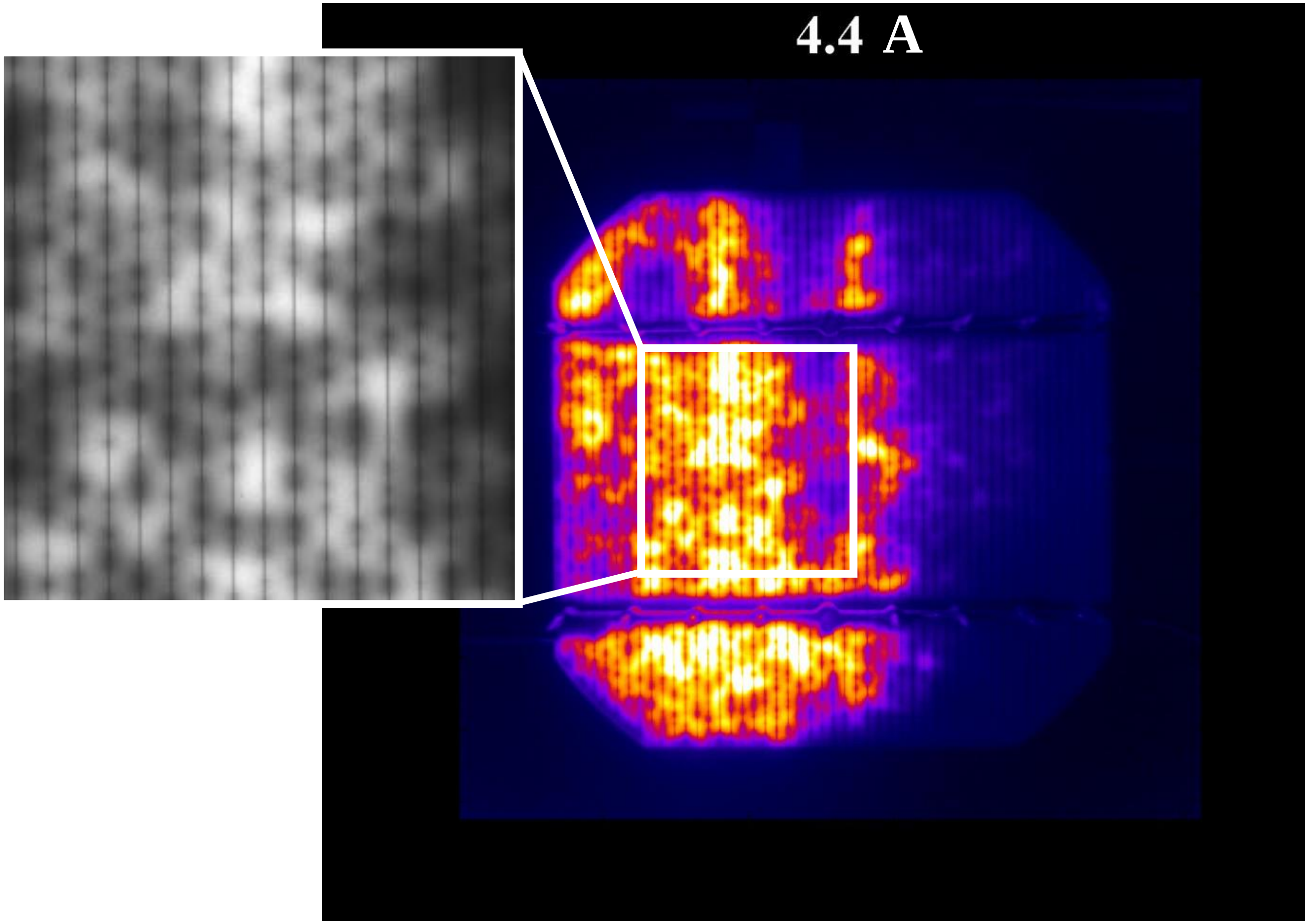


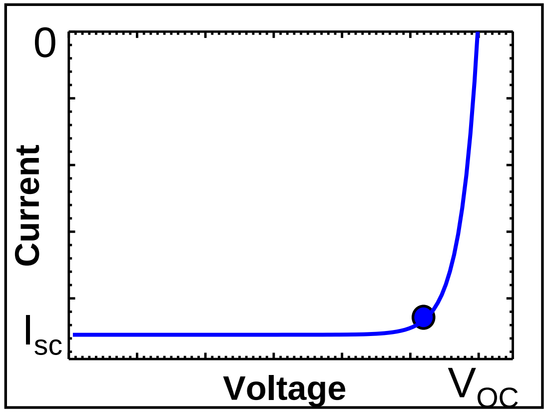
Ratio image

- Areas of enhanced Rs (e.g. broken fingers) show increased PL
- What is causing that?

One luminescence image is not like the other!

PL images with uniform illumination and simultaneous current extraction



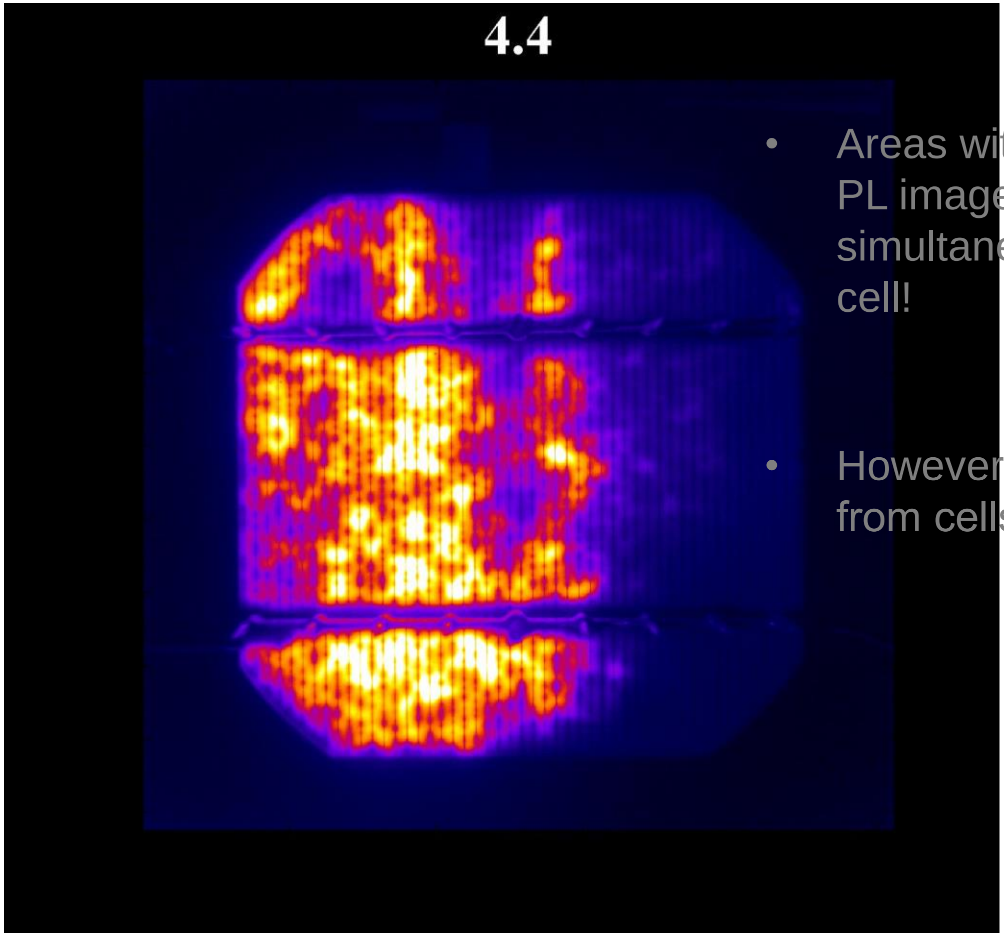


Rs imaging!

T. Trupke, E. Pink, R.A. Bardos and M.D. Abbott, *Spatially resolved series resistance of silicon solar cells obtained from luminescence imaging*, Applied Physics Letters **90**, 093506 (2007).

One luminescence image is not like the other!

PL images with uniform illumination and simultaneous current extraction

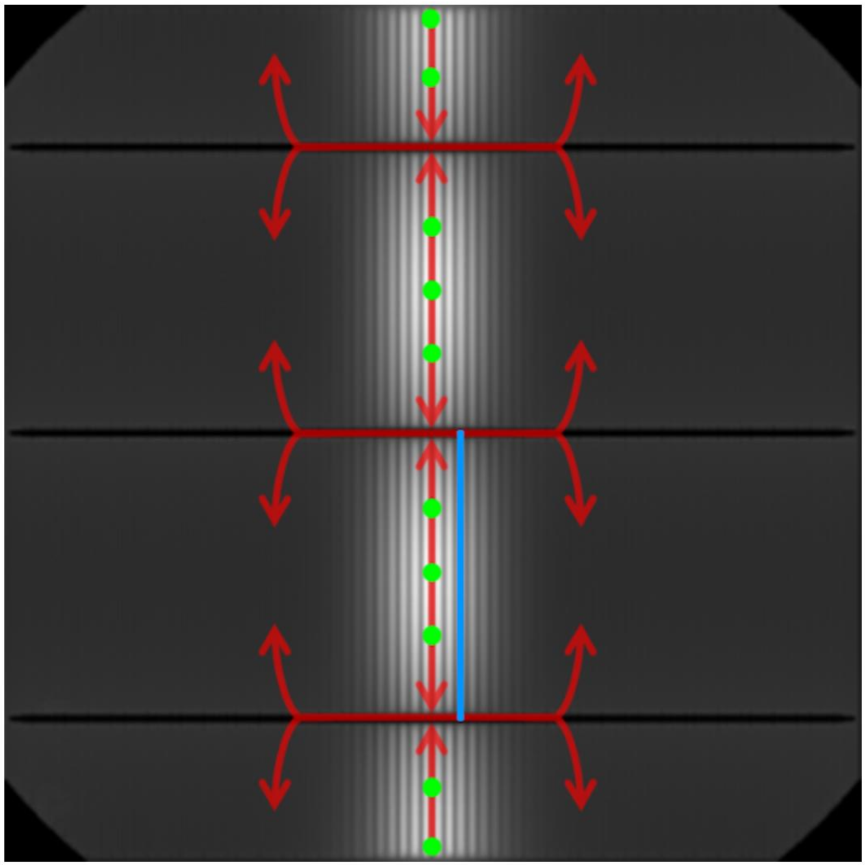


- Areas with high Rs appear bright in PL images, when current is simultaneously extracted from the cell!
- However, no current is extracted from cells in line scan images…

T. Trupke, E. Pink, R.A. Bardos and M.D. Abbott, *Spatially resolved series resistance of silicon solar cells obtained from luminescence imaging*, Applied Physics Letters **90**, 093506 (2007).

Understanding line scan PL images

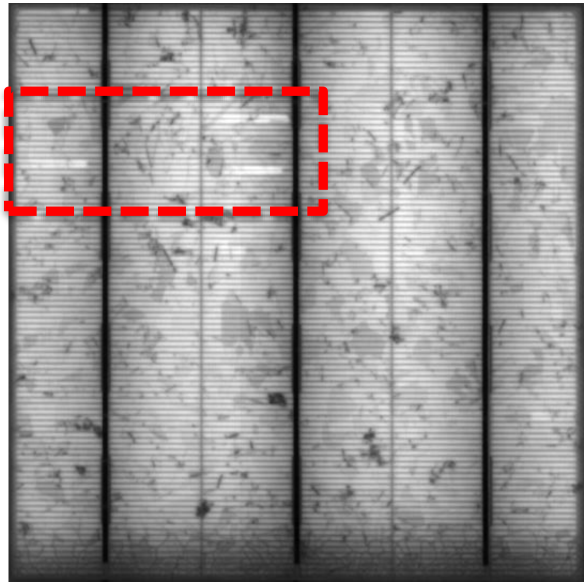
Sample motion



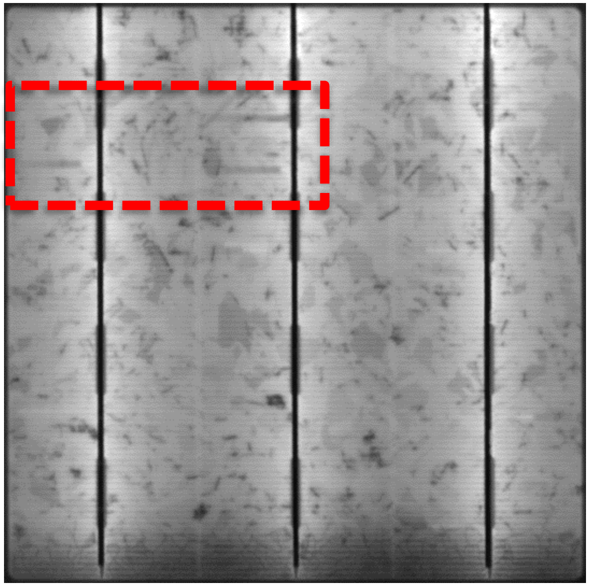
- Griddler simulation of a solar cell with line illumination
- Only a small fraction of the cell is illuminated at any time
- Current flows within the cell from illuminated to non-illuminated cell regions
- **The camera always sees a cell region under illumination and with current extraction**

→ **Non contact Rs imaging**

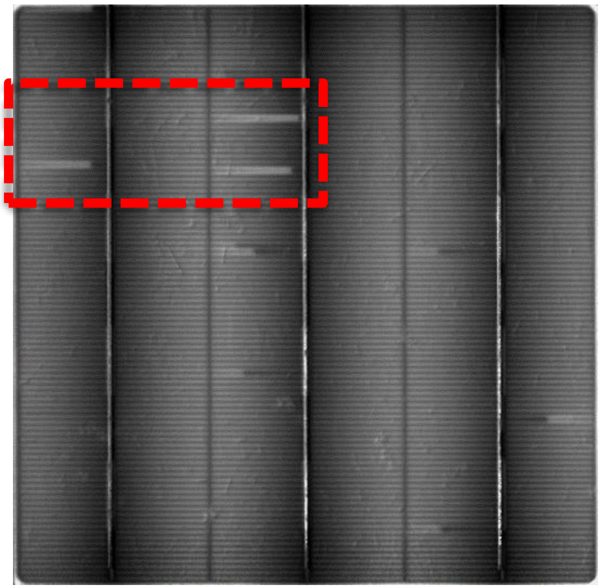
Photoluminescence imaging on modules



PL_{LS} image



EL image



Ratio image

- Areas of enhanced Rs (e.g. broken fingers) show increased PL
- **Non-contact Rs imaging!**

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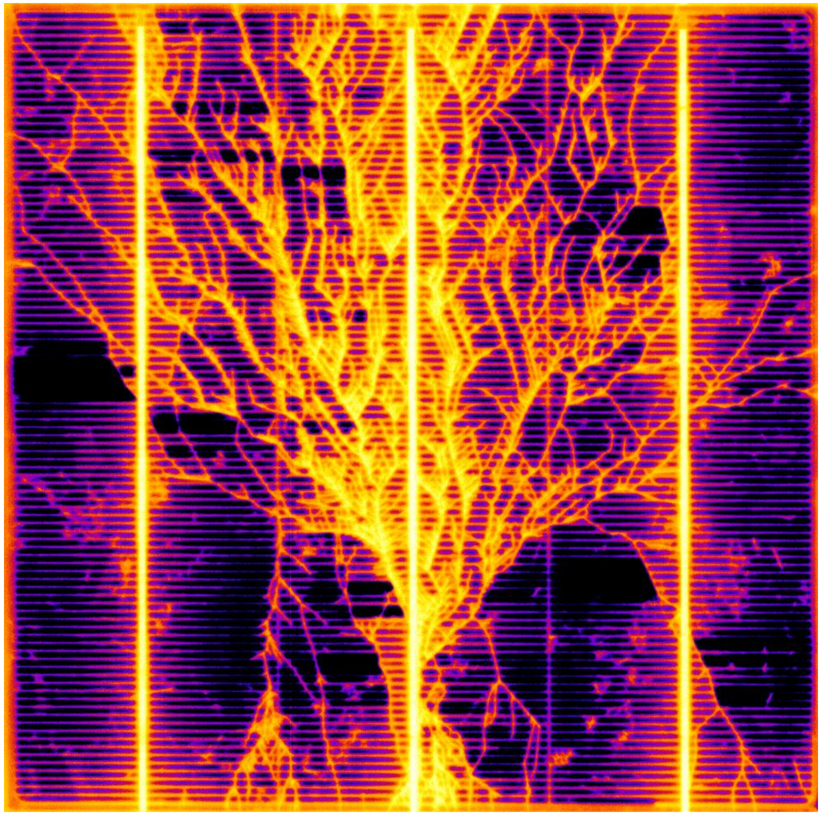
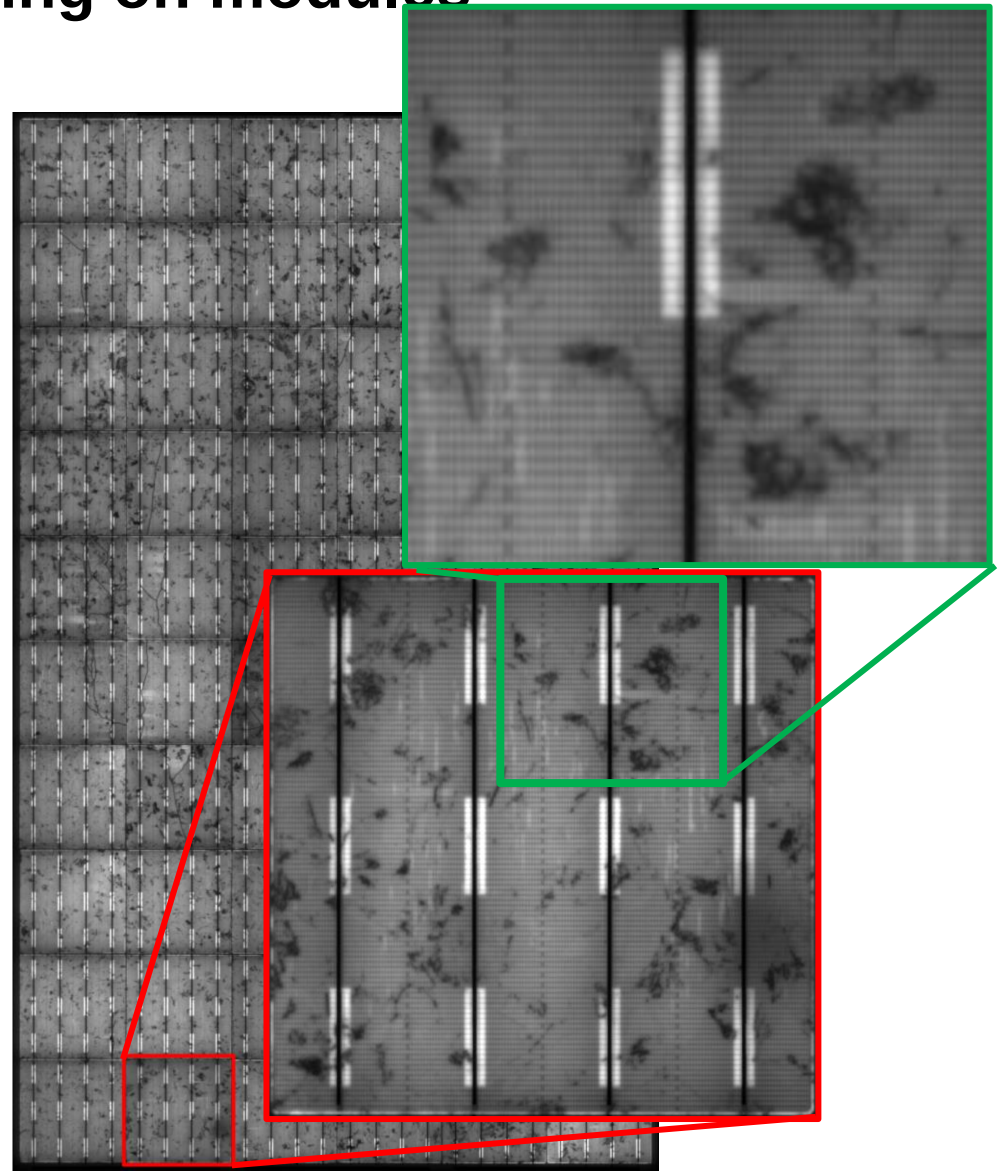
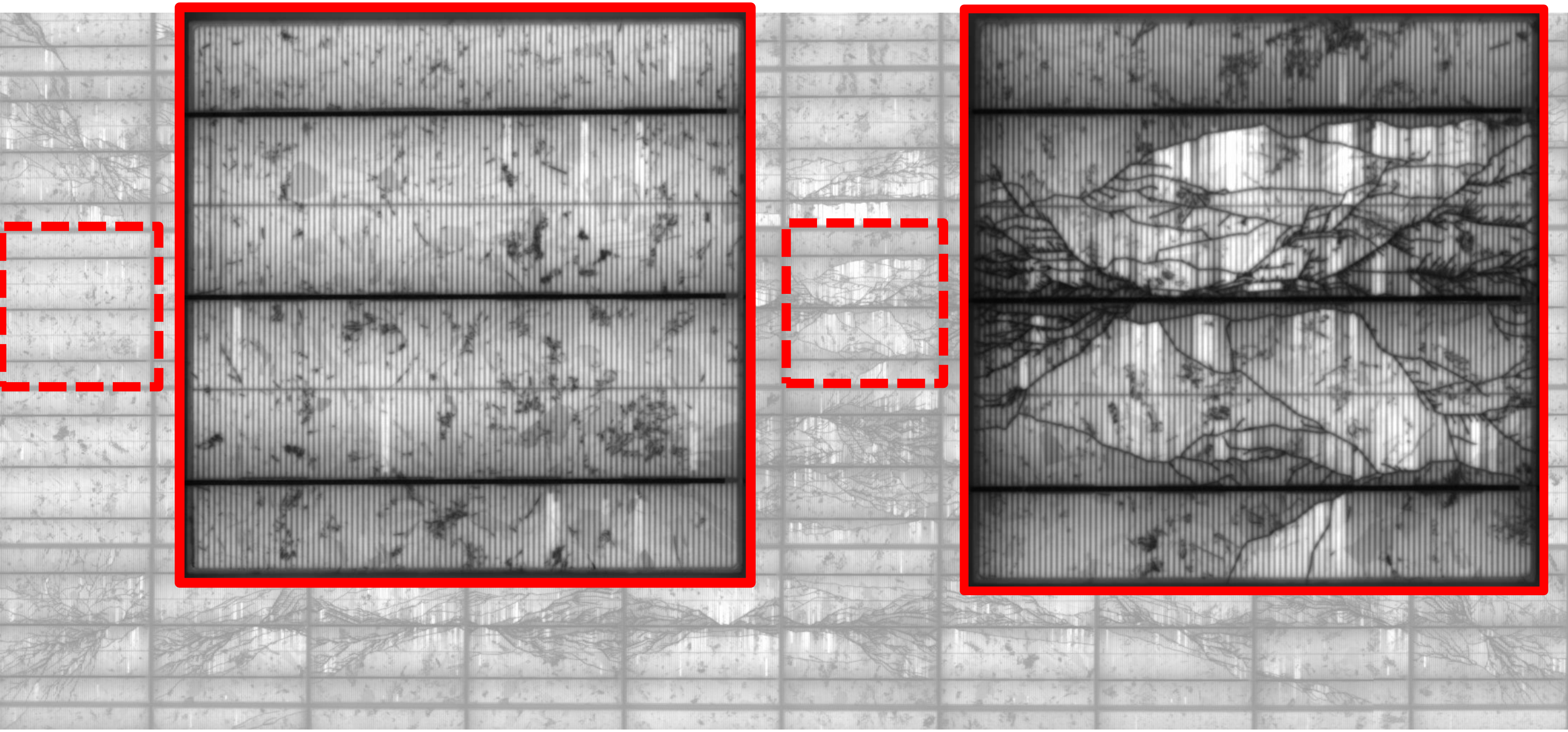


Photoluminescence imaging on modules



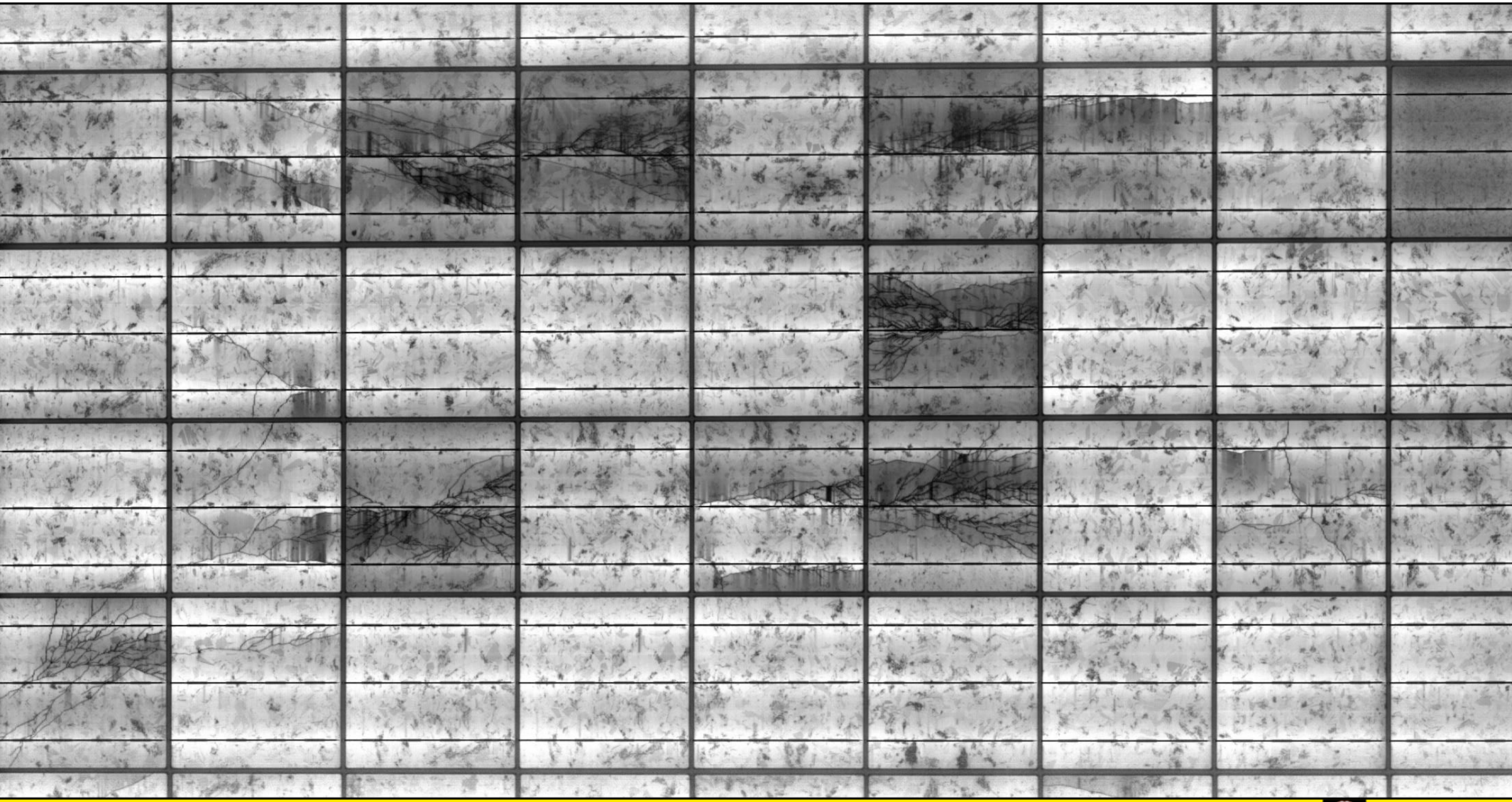
Line scan PL on modules

Line scan PL image of an industrial c-Si module **after mechanical load testing**



Line scan PL on modules

EL

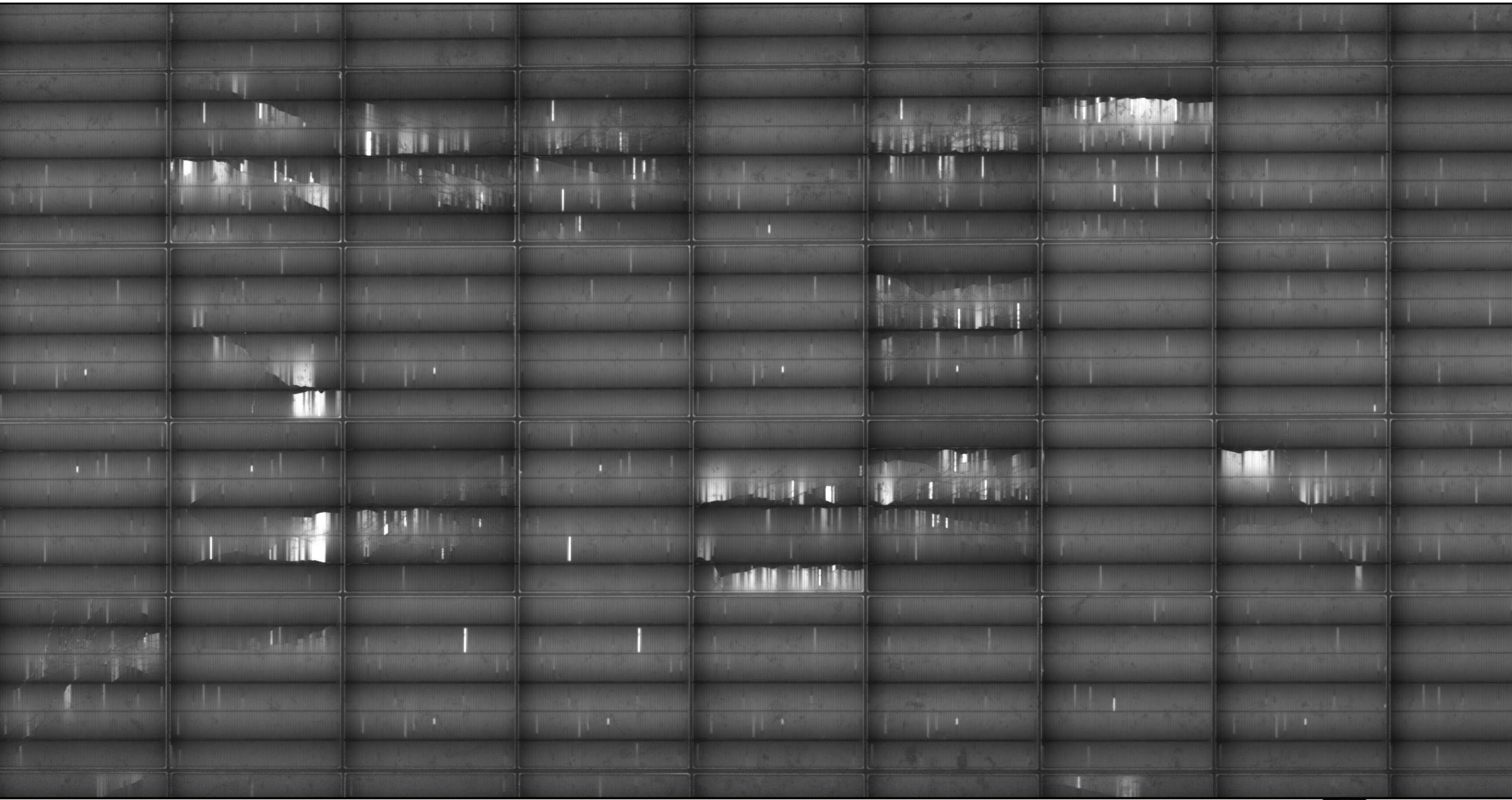


Line scan PL on modules

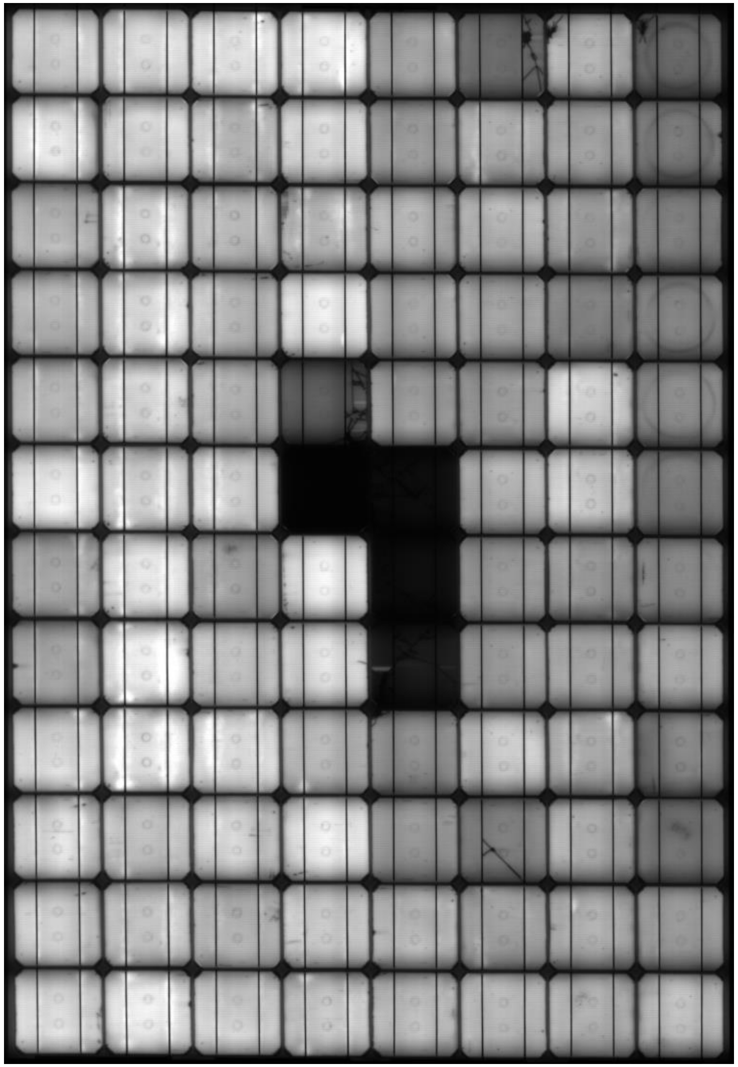
Line scan PL

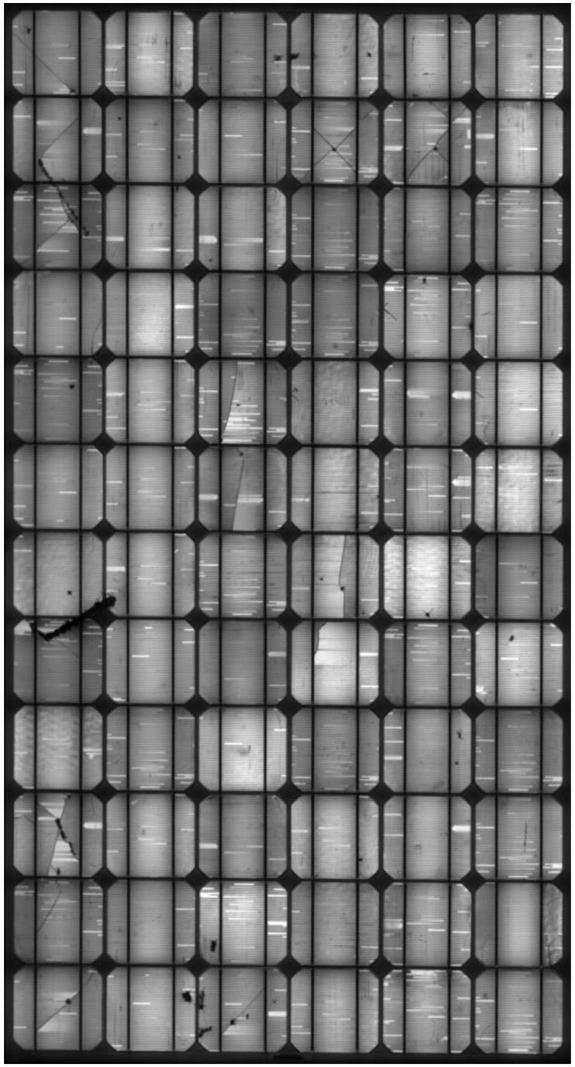
Line scan PL on modules

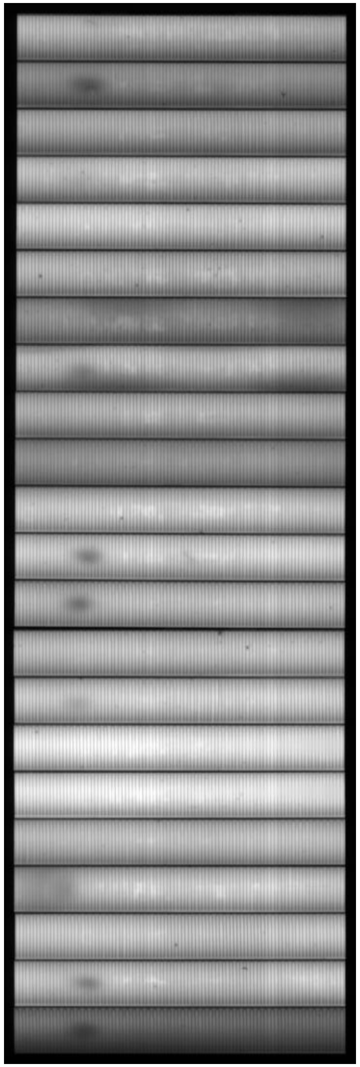
Rs enhanced



Line scan PL on modules



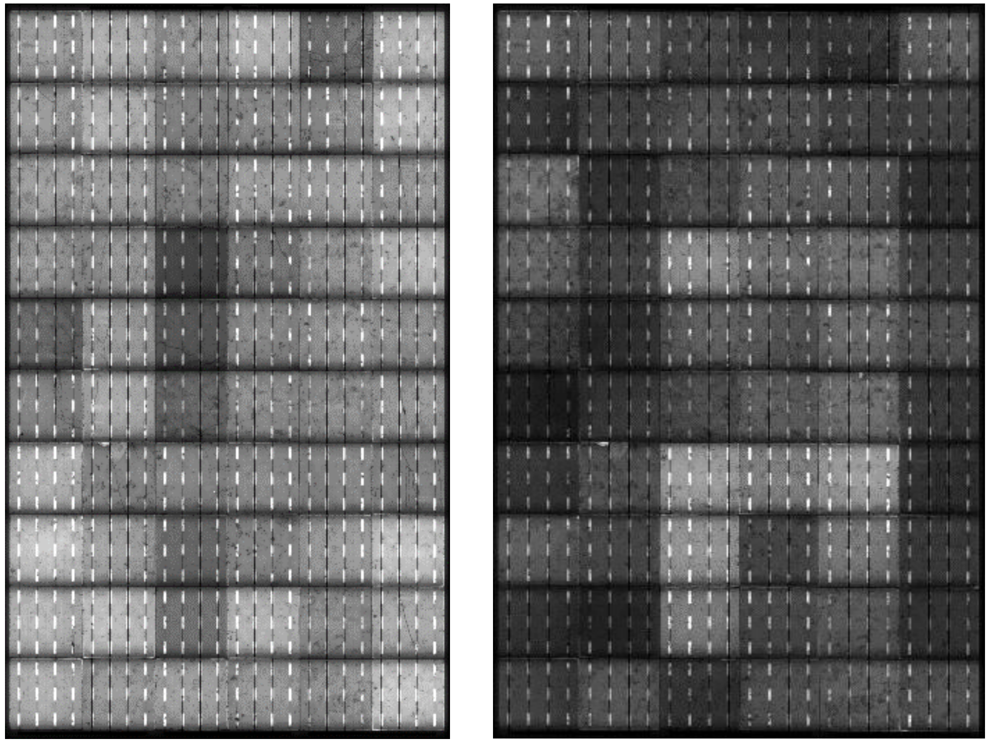




Luminescence imaging –

powerful tool for **degradation studies**

Line scan PL



0 hours light soaking — 83 hours light soaking

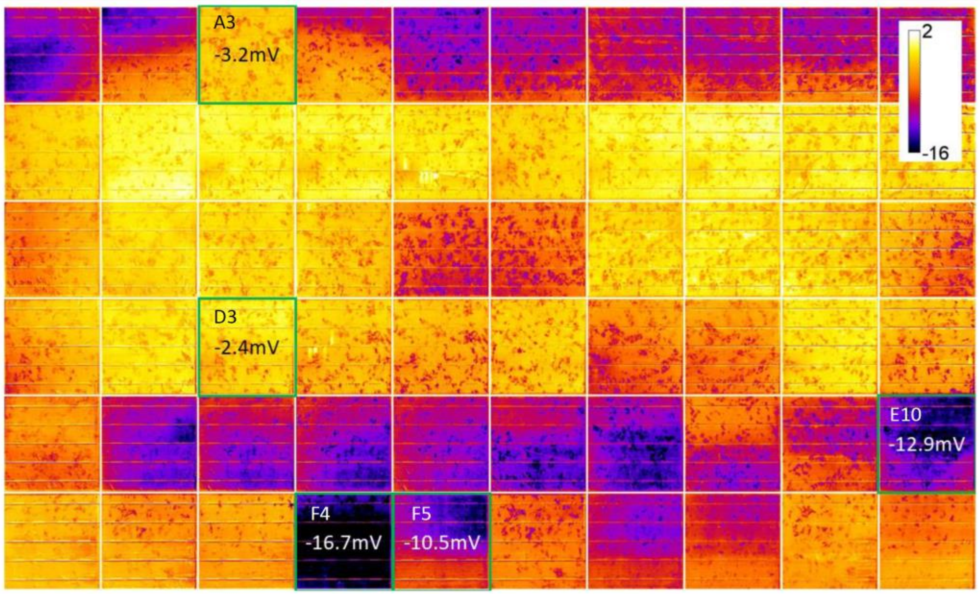
- Luminescence is an excellent probe for cell / module quality
- Less sensitive to Temperature variations, compared to terminal voltage

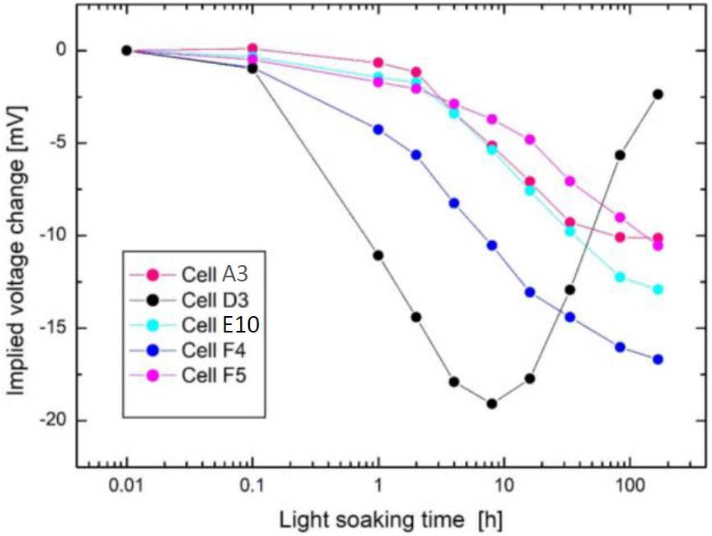
[1] I. Zafirovska, M.K. Juhl, A. Ciesla, R. Evans, T. Trupke, *Low temperature sensitivity of implied voltages from luminescence measured on crystalline silicon solar cells*, Sol.Energy Mat.Sol.Cells **199**, 50-58 (2019).

Luminescence imaging –

powerful tool for **degradation studies**

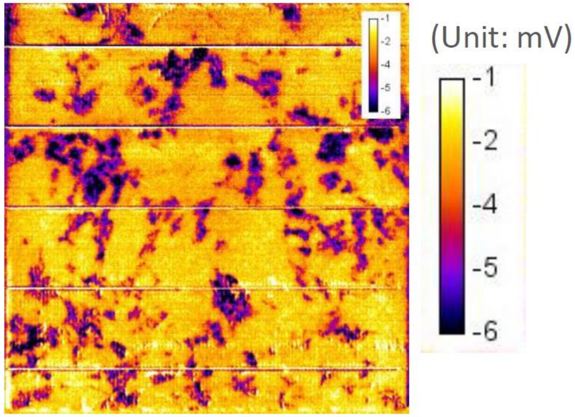
Individual cells are at different stages of degradation





Quantitative voltage loss analysis

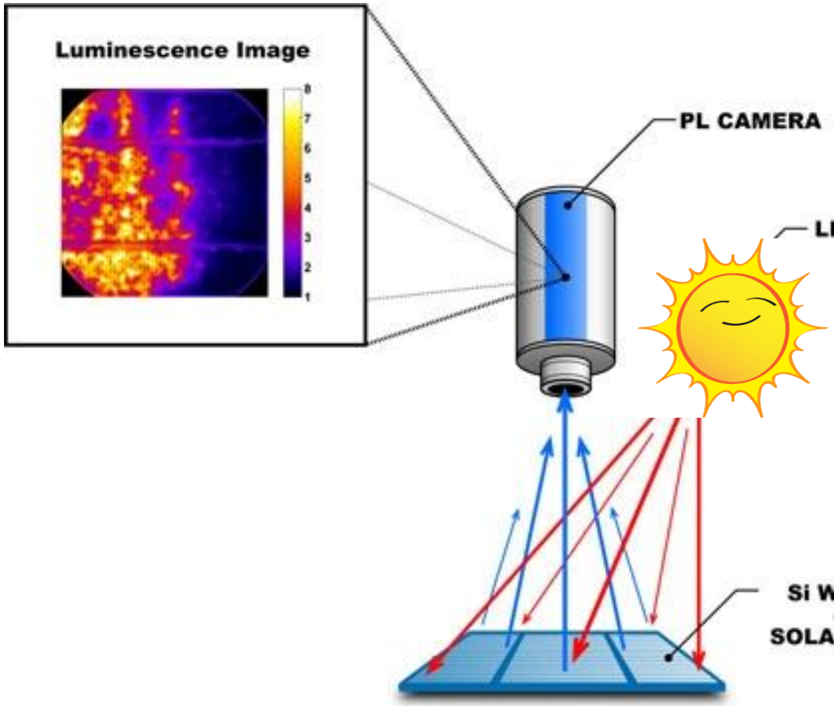
Local voltage loss analysis



Photoluminescence imaging on modules

- Try it: BT imaging LIS-M1 at SIRF
- Image acquisition in a specially designed **dark chamber** to **avoid image artefacts from ambient light**!

Photoluminescence imaging using the sun as sole illumination source

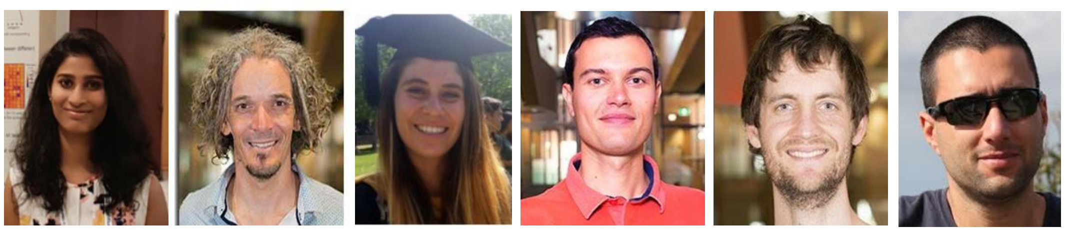


"PL imaging in full sunlight, ***impossible…?"***

Is it possible to acquire Photoluminescence images in full sunlight**?**

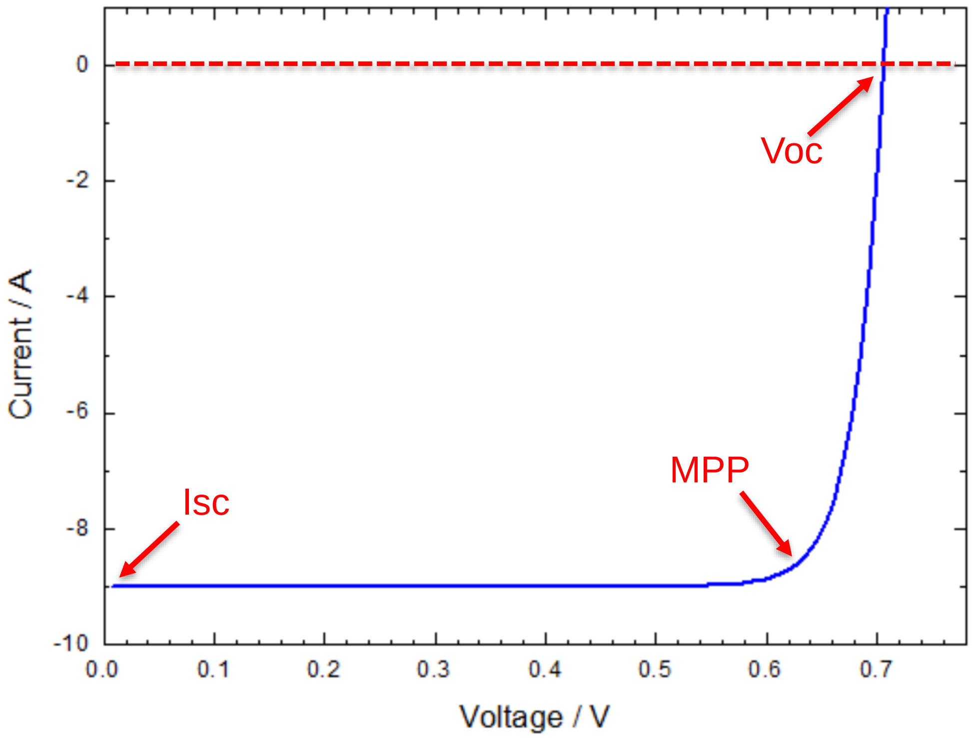
With the PL Team at UNSW SYDNEY

ANYTHING is POSSIBLE!



Background

IV curve of an illuminated solar cell



$$I_{PL} = C * exp\left(\frac{eU}{kT}\right)$$

- Voltage increase by 60mV equivalent to ~10x increase in PL intensity
- **PL intensity at MPP is about 20 times lower than at Voc**

Luminescence imaging for field inspection

The Challenge:

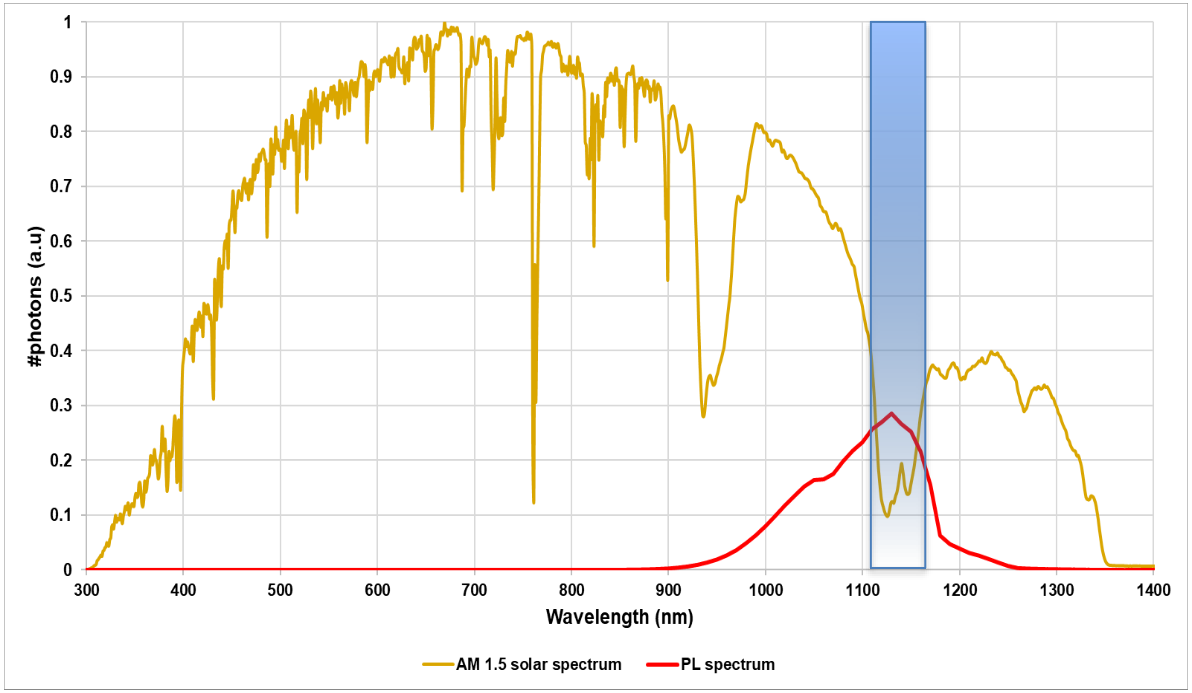
PL spectrum scaled by **1,000x**

- Broad solar spectrum
- Low luminescence yield

Any outdoor camera images are dominated by reflected ambient sunlight

Luminescence imaging for field inspection

The Challenge:

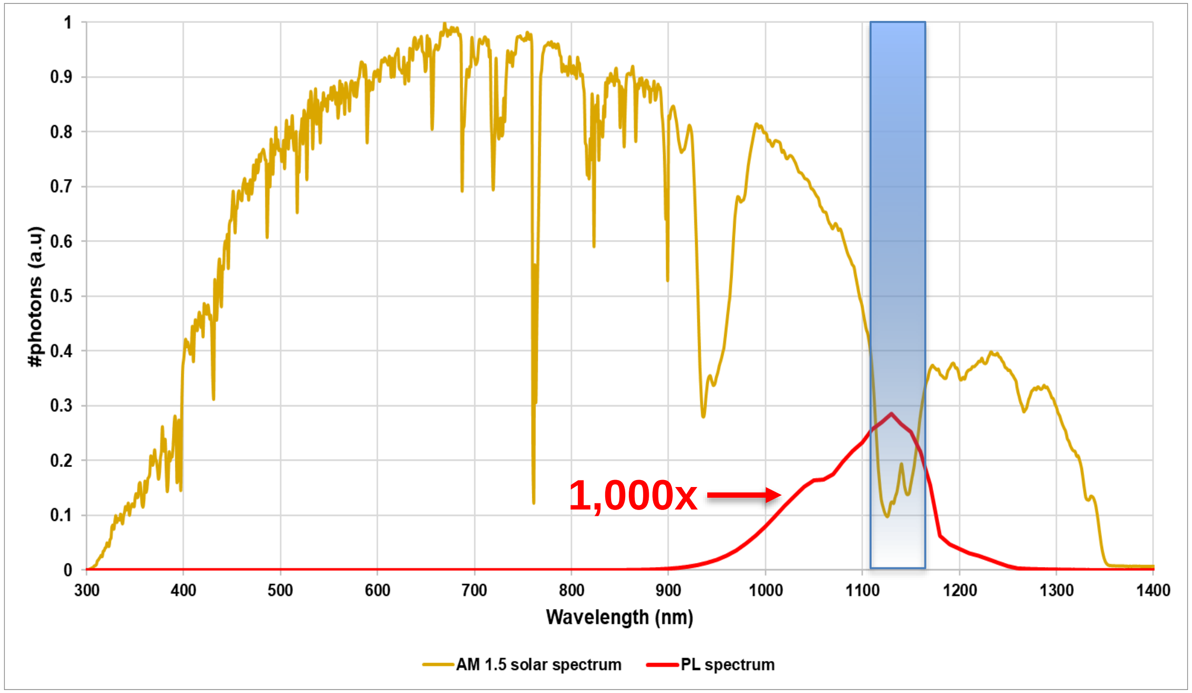


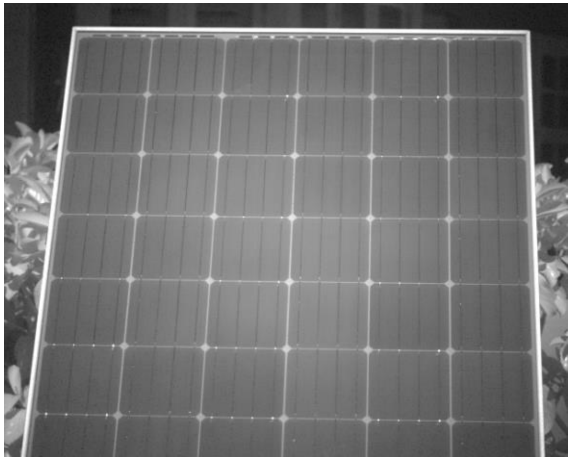
- Dip in the solar spectrum around 1,130nm, caused by atmospheric vapor absorption
- Coincides with the spectral peak of the luminescence from c-Si
- InGaAs camera required

Restricting the camera detection to this spectral range substantially increases the proportion of detected PL intensity

Luminescence imaging for field inspection

The Challenge:

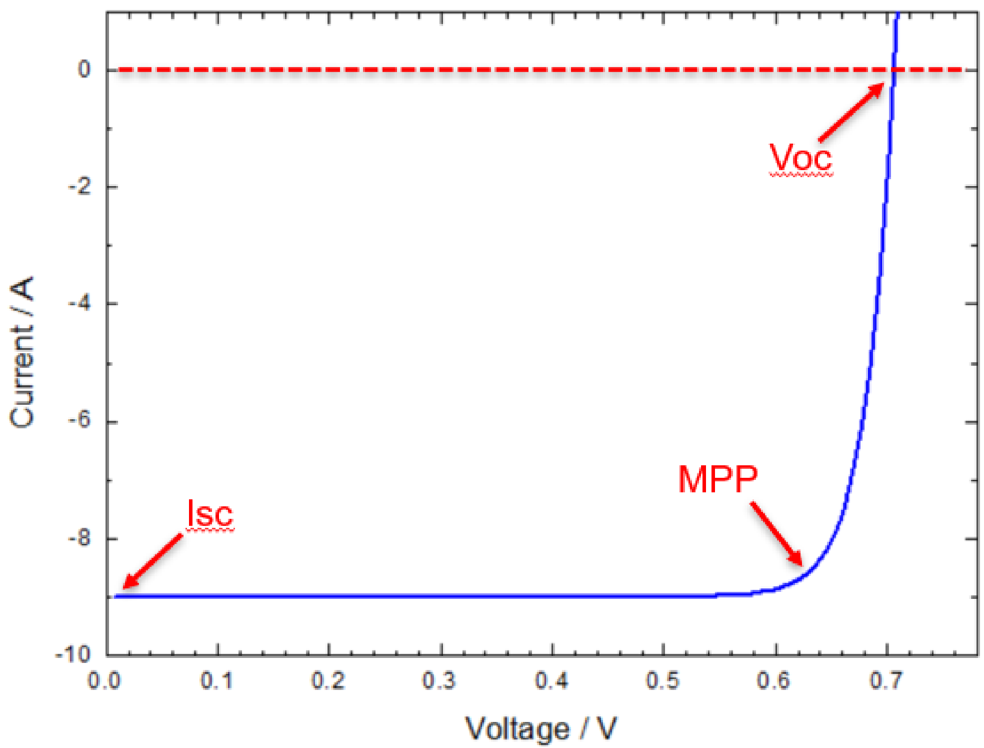




Even within this narrow spectral band, the camera signal is still strongly dominated by ambient light (typically >99%)

Background

IV curve of an illuminated solar cell



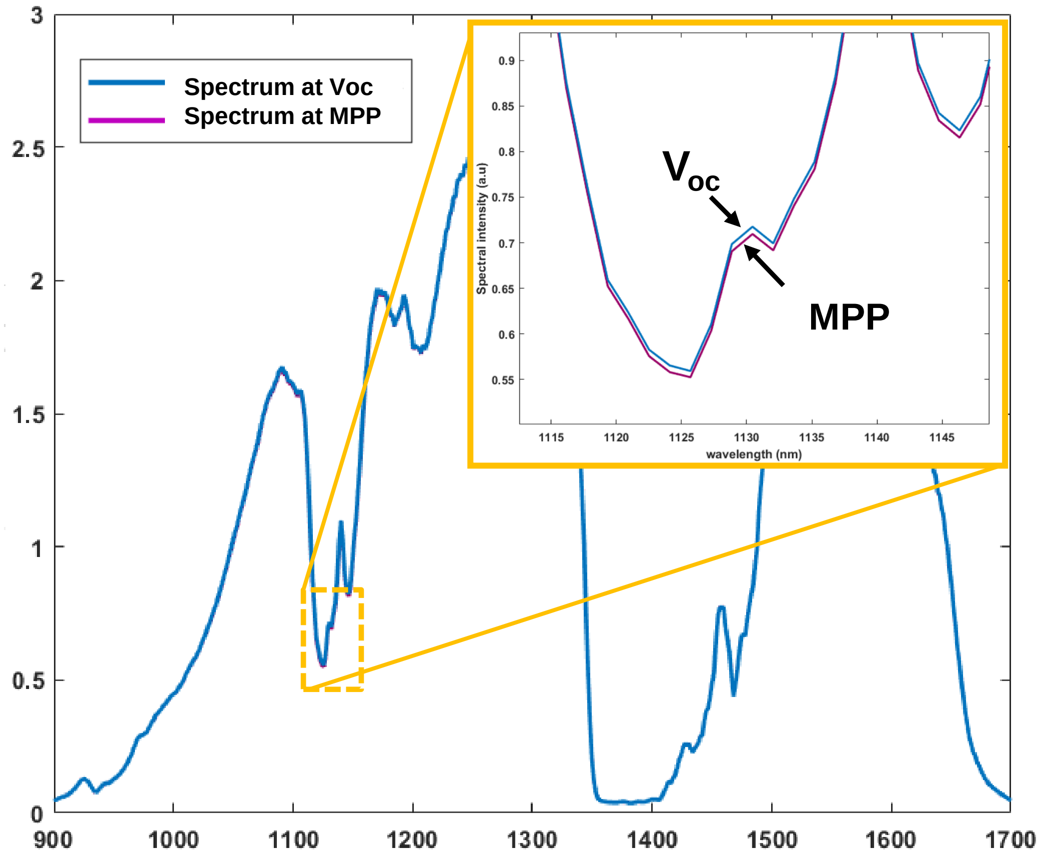
$$I_{PL} = C * exp\left(\frac{eU}{kT}\right)$$

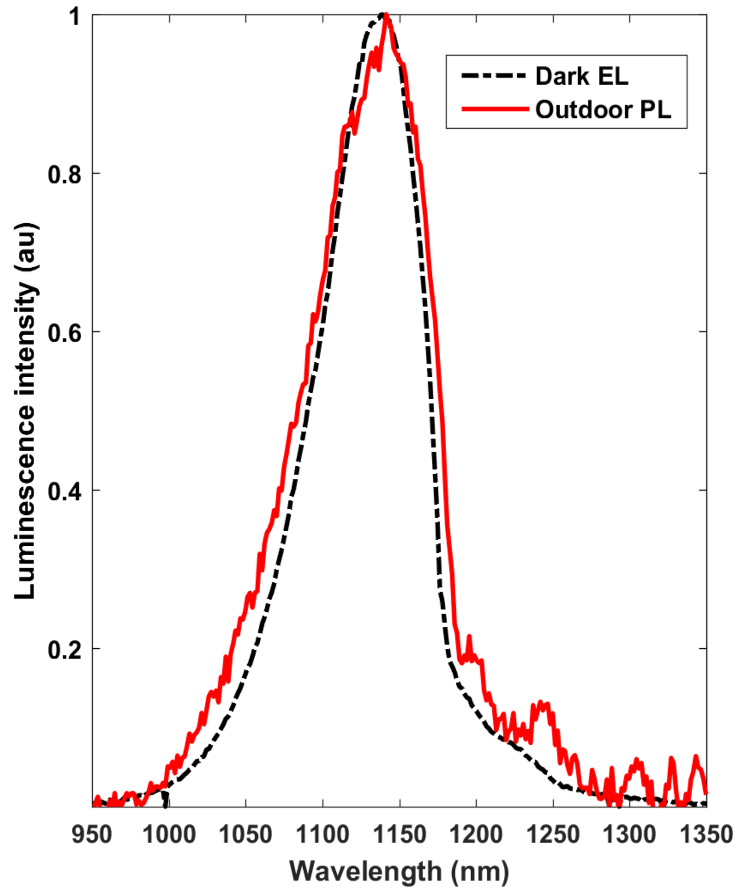
- Voltage increase by 60mV equivalent to ~10x PL intensity
- **PL intensity at MPP is about 20 times lower than at Voc**

Toggling between Voc and Mpp switches the luminescence intensity from ON to “almost OFF”

Luminescence imaging for field inspection

Spectrum from a c-Si module in full daylight





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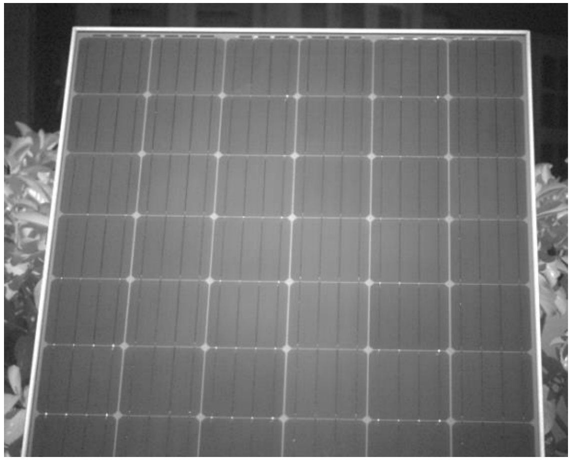
Luminescence imaging for field inspection

Principle of outdoor luminescence imaging



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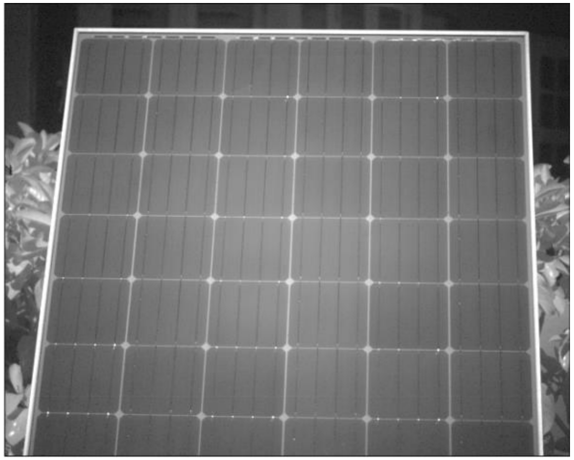

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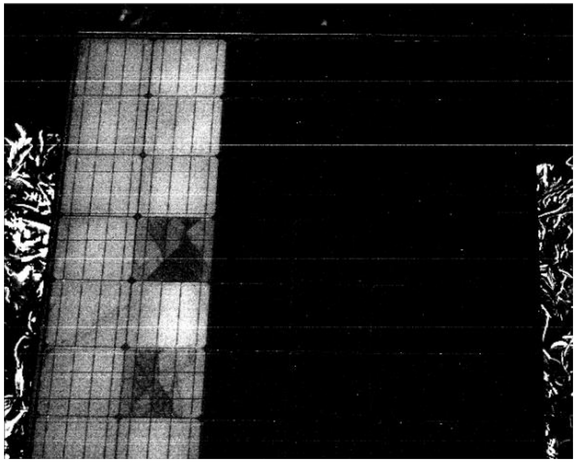


Voc
Maximum PL

MPP
Close to zero PL

Subtracted image

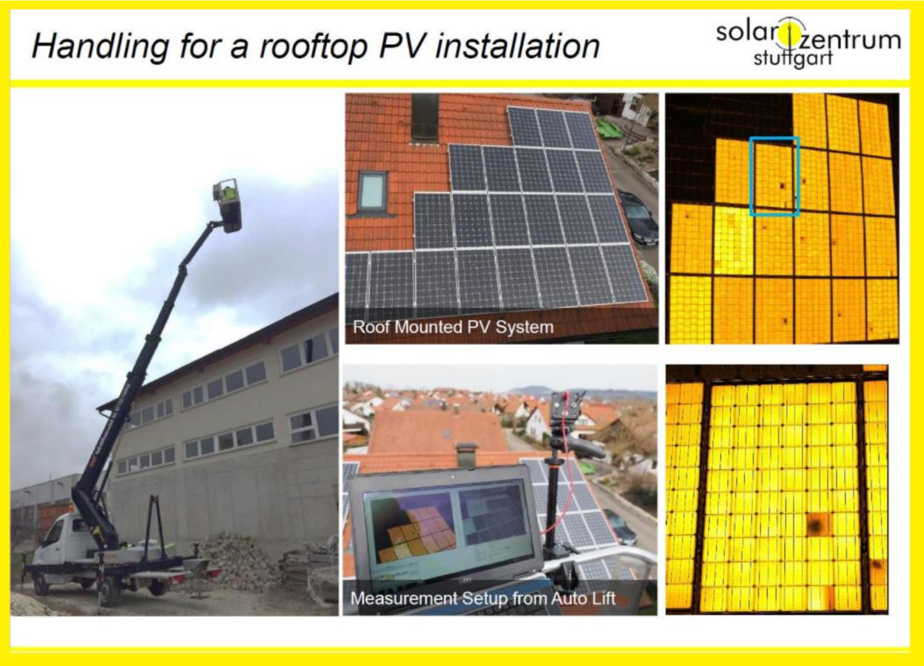
Ambient + PL (1%)

Ambient

PL

- Outdoor PL imaging in full sunlight requires **image subtraction** and **toggling of the operating point**
- Multiple image pairs required to get sufficient S/N

Luminescence imaging for field inspection



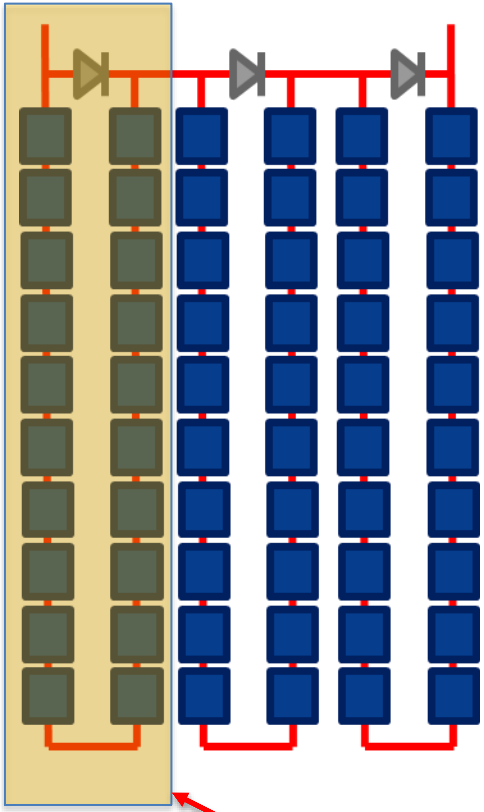
- DaySy, developed by Solarzentrum Stuttgart, uses electrical modulation
- Electrical connection to a module is often awkward, carries risks (1,000 – 1,500 V), and slows down the workflow

“How to swi[illegible] and Vo[illegible] the cables?”

https://www.solarzentrum-stuttgart.com/en/products/daysy/

Luminescence imaging for field inspection

UNSW's approach for contactless switching of the operating point
- Mattias Juhl's Eureka moment!



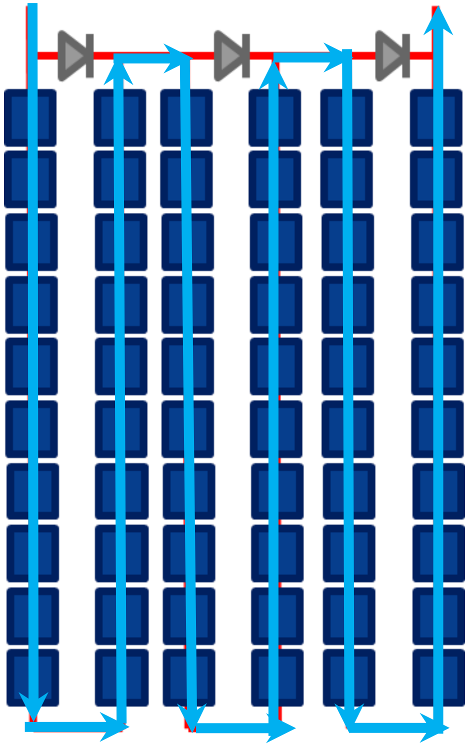
Conventional commercial c-Si module layout

- 60 (or 72) cells are connected in series
- Three bypass diodes (BPD)

One substring of series connected cells with parallel bypass diode

Luminescence imaging for field inspection

UNSW's approach for contactless switching of the operating point

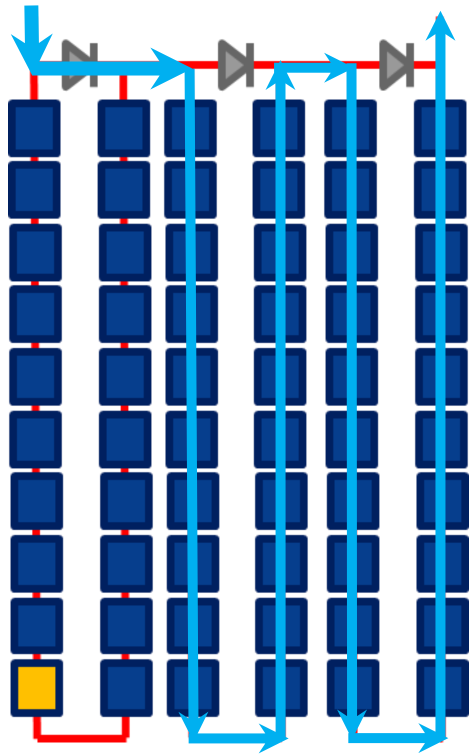


- In normal system operation the maximum power point current I_{MPP} flows through all cells

- All cells are near their respective MPP **(emit close to zero PL signal)**

Luminescence imaging for field inspection

UNSW's approach for contactless switching of the operating point

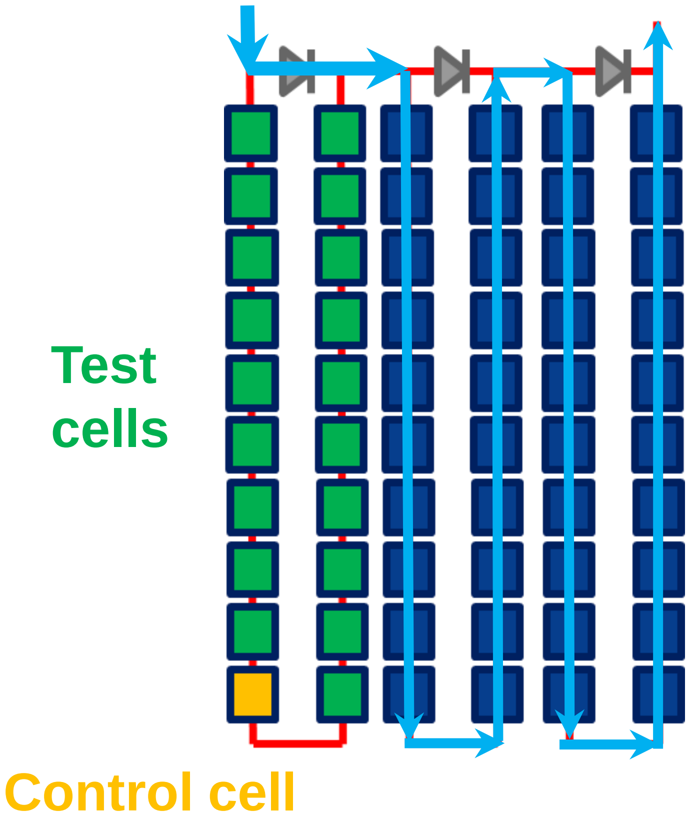


Shaded cell

- **Complete shading of one cell**
- Bypass diode turns on, I_{MPP} flows through the bypass diode

Luminescence imaging for field inspection

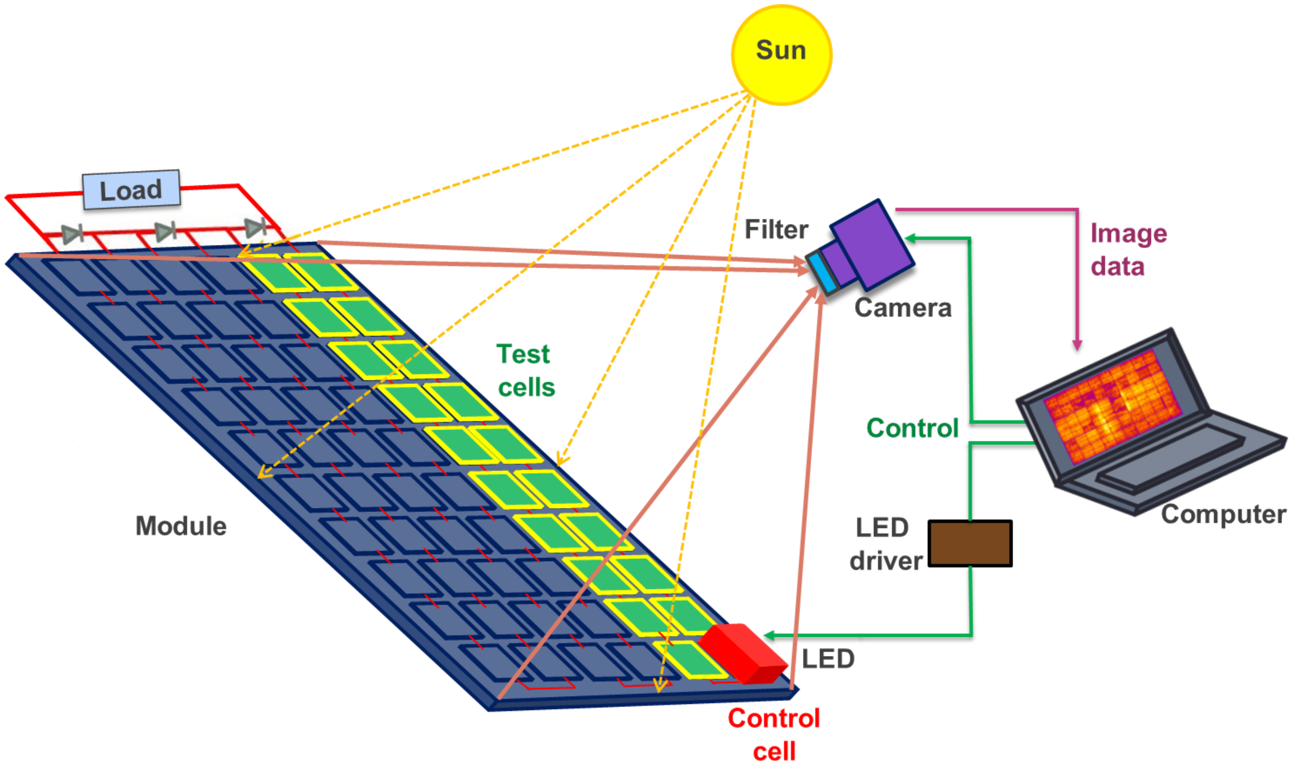
UNSW's approach for contactless switching of the operating point



- All other cells (**test cells**) in the same substring change from MPP to near Voc **(maximum PL signal)**
- Shading / unshading one cell (**control cell**) toggles all other cells between Voc **(maximum PL)** and Mpp **(close to zero PL)**

→ *"Contactless switching"*

Luminescence imaging for field inspection

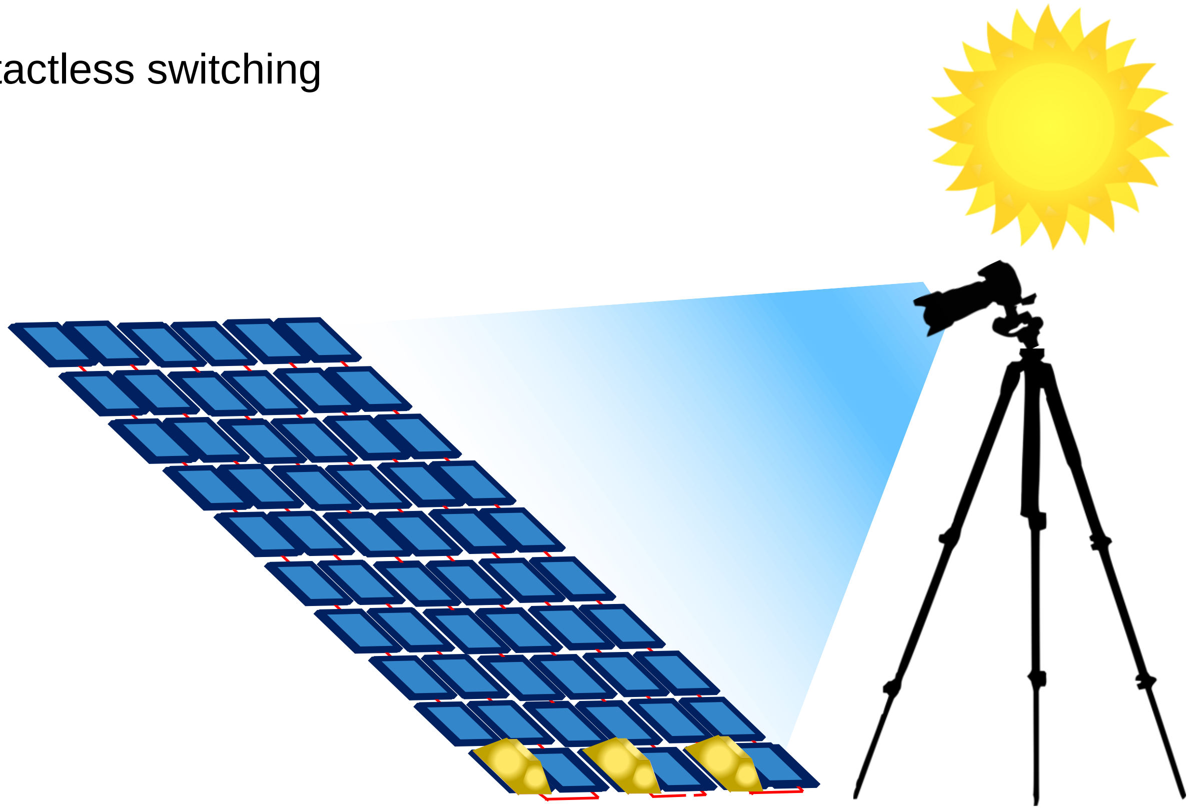


Instead of mechanical shading we can use a high-power LED array:

- LED OFF is equivalent to a shaded control cell
- LED ON is equivalent to normal operating conditions
- LED switching easily syncronised with the Camera acquisition

Luminescence imaging for field inspection

Contactless switching



- **Using three LEDs allows switching the entire module**
- Extra image required to capture the luminescence from the Control cells

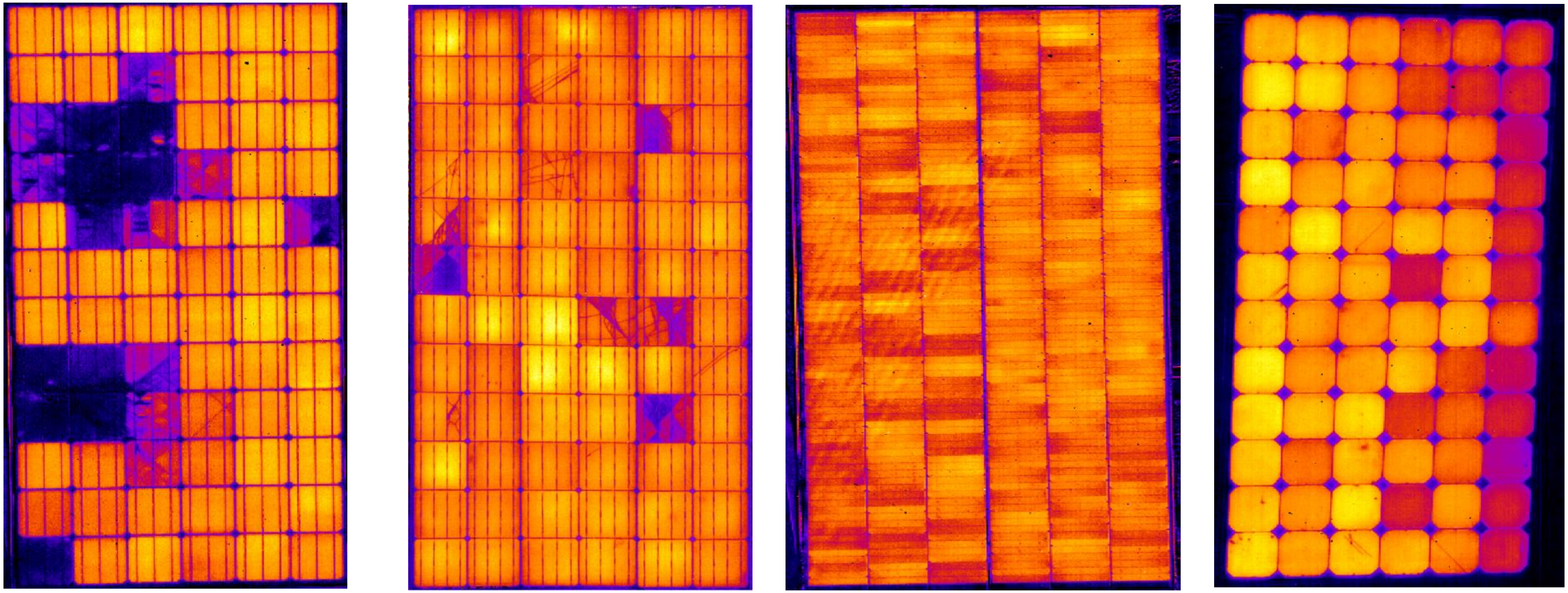
Luminescence imaging for field inspection

- **This method works well!**
- Testing of a commercial prototype is currently underway
- Proof of concept demonstration in full daylight on both conventional and half cell module

R. Bhoopathy, O. Kunz, M. Juhl, T. Trupke, and Z. Hameiri, "*Outdoor photoluminescence imaging of photovoltaic modules with sunlight excitation*," Prog. Photovoltaics Res. Appl., vol. 26, no. 1, pp. 69–73, Jan. 2018.

Luminescence imaging for field inspection

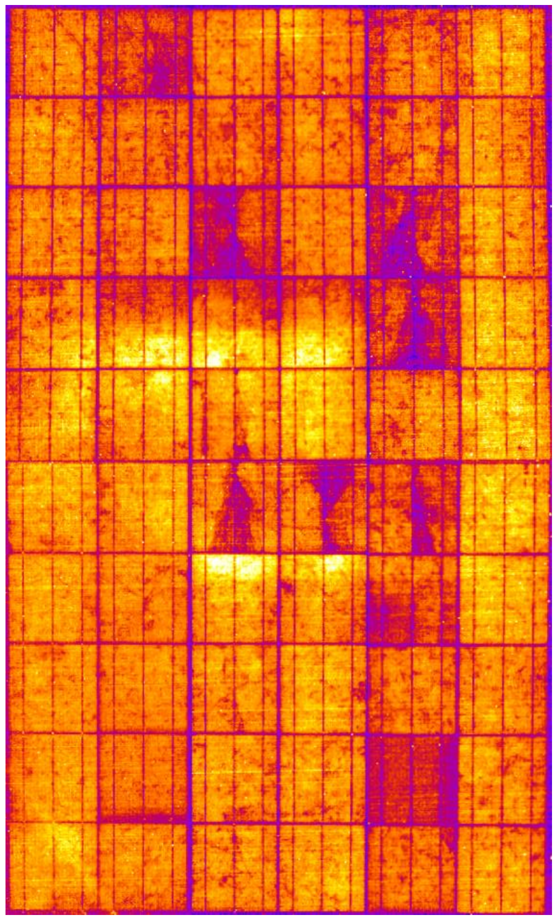
Outdoor PL images - examples

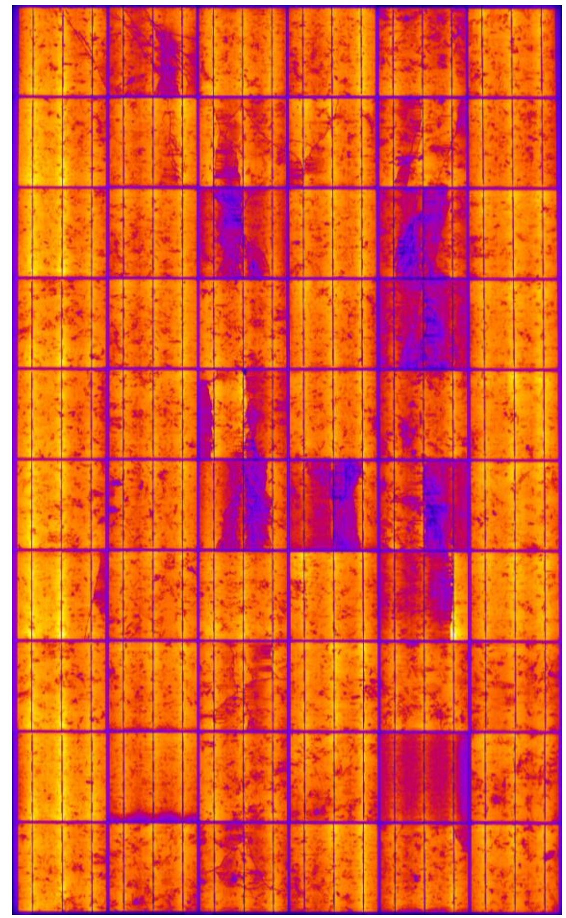


- Successful demonstration for a number of module types

Luminescence imaging for field inspection

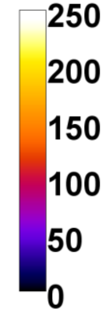
Outdoor: PL image





Lab: EL image

Intensity (a.u)

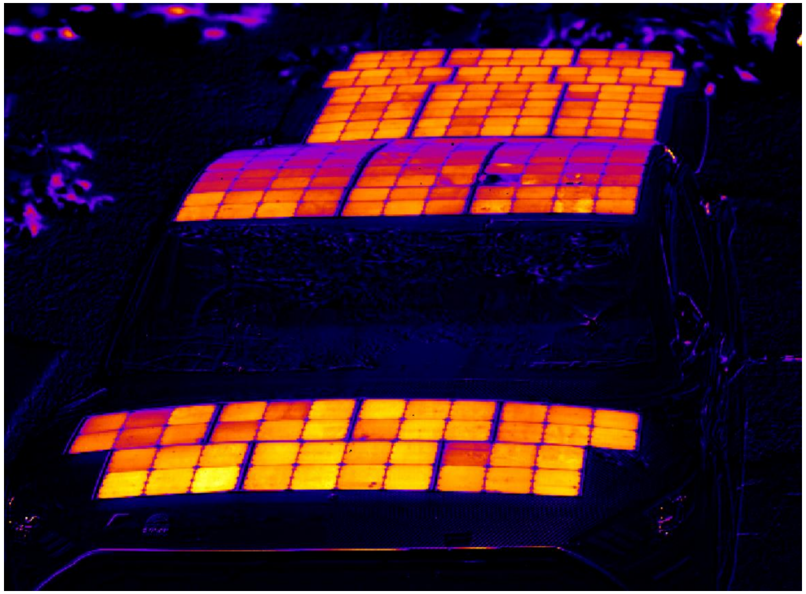


Luminescence imaging for field inspection

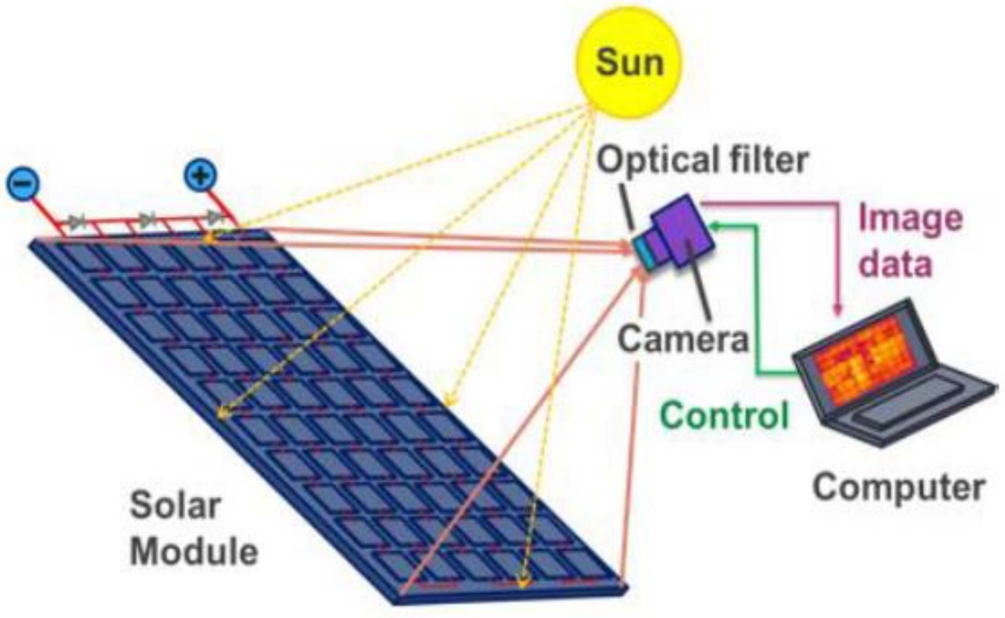
Outdoor PL imaging demonstration on the UNSW solar car

Luminescence imaging for field inspection

- Outdoor PL imaging requires switching the electrical operating point of the modules
- Acquisition of PL images at constant operating point?



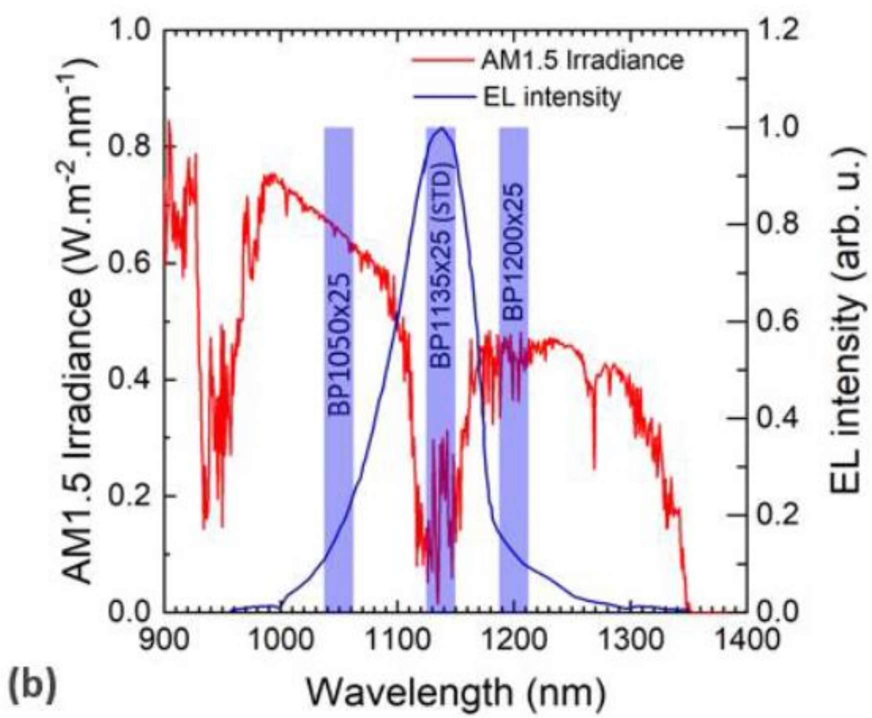
PL imaging at constant operating point
- Two filter method



- Method also relies on an image difference
- Switching optical filters in front of the camera instead of switching the operating point of the module
- No manual operation at or near the module required

O. Kunz, G. Rey, R. Boopathi, S. Hameiri, T. Trupke, *Outdoor PL imaging of crystalline silicon modules at constant operating point*, IEEE 47th PVSC virtual meeting, June - August 2020.

PL imaging at constant operating point



Example:

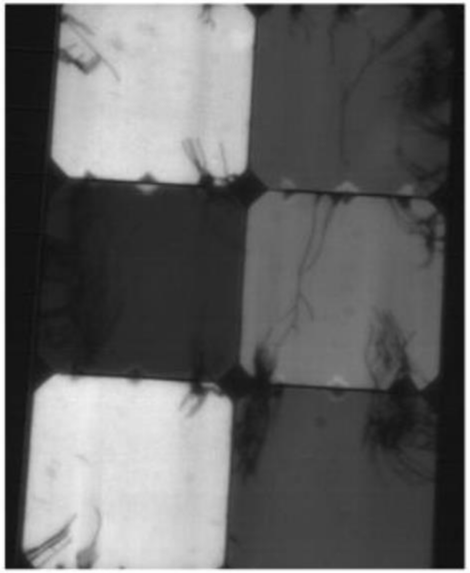
Filter 1, BP 1200: High ambient, low PL
Filter 2, BP 1135: Low ambient, high PL

$$PL = I_{Filter\ 2} - C * I_{Filter\ 1}$$

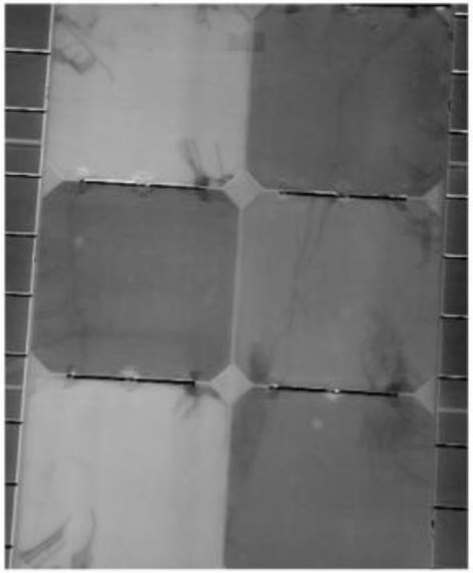
- PL image is calculated as the difference image
- Requires scaling of one image by a calibration constant

O. Kunz, G. Rey, R. Boopathi, S. Hameiri, T. Trupke, *Outdoor PL imaging of crystalline silicon modules at constant operating point*, IEEE 47th PVSC virtual meeting, June - August 2020.

PL imaging at constant operating point



Difference
STD (V_{oc}) – STD (J_{sc})



Difference
STD (V_{oc}) – BP1200

Example:

Filter 1, BP 1200
Filter 2, BP 1135

- Principle of the method works, main defects (cracks) can clearly be identified
- Lower contrast than in the “conventional method”
- **Some image artefacts**
  - Angular dependence of filter transmission
  - Non uniform spectral reflectance across the module

→ **More R&D required!**

O. Kunz, G. Rey, R. Boopathi, S. Hameiri, T. Trupke, *Outdoor PL imaging of crystalline silicon modules at constant operating point*, IEEE 47th PVSC virtual meeting, June - August 2020.

Contactless string modulation

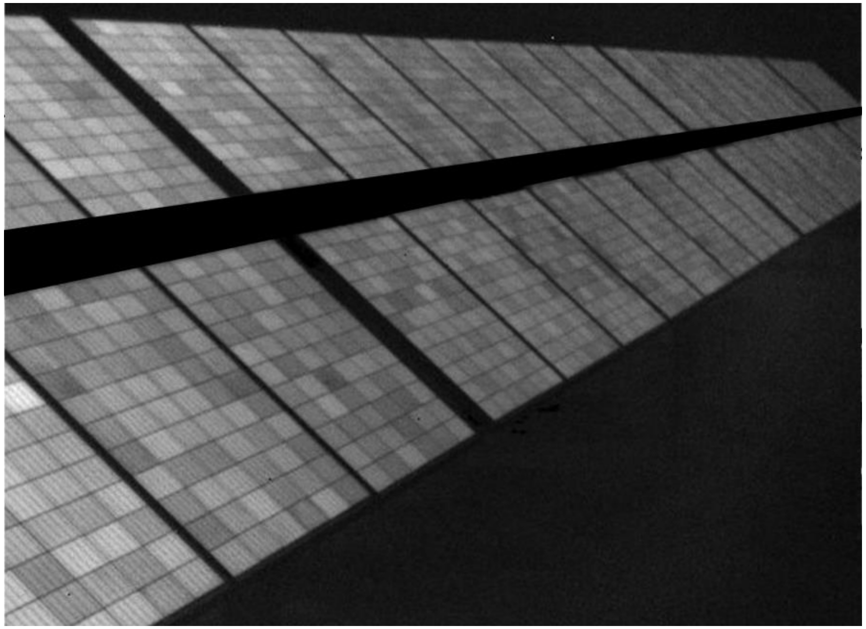
Limitations of the non-contact switching method:

i. Need to acquire two image pairs to capture an image of all cells in a module, since control cells are shaded
ii. Mechanical placement of optical modulator on each module under test limits sample throughput

→ Contactless switching of entire rows of modules…?

- Proof of concept studies of a novel "non contact string modulation" method recently conducted successfully

- **Interested…?** O.Kunz et al., **48th IEEE PVSC Miami, June 2021**, *"High Throughput Outdoor Photoluminescence Imaging via PV String Modulation"*



“Point and shoot” outdoor PL image acquisition?

Methods discussed so far:

1. **Image difference:** Toggle between Voc and MPP
   1. Electrical modulation via the terminals (DaySy)
   2. Non-contact optical modulation (UNSW method)
   3. Non contact modulation of strings of modules (UNSW method)
2. **Image difference:** toggle between two spectral ranges (UNSW two filter method)

The “holy grail” of outdoor inspection

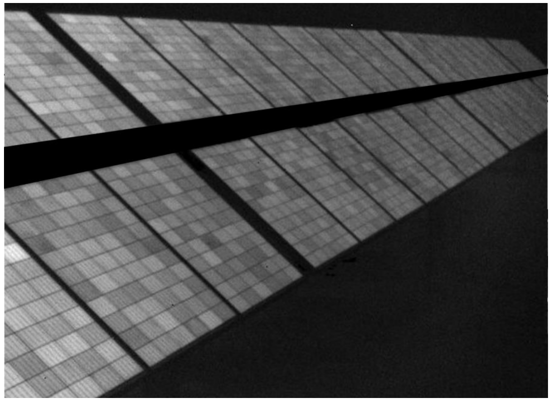
“Point a camera at a module in full daylight, take a single image and obtain a luminescence image, with no need to modulate anything.”

- **Interested…?** G. Rey et al., **48th IEEE PVSC Miami, June 2021**, *“Single Shot Outdoor Photoluminescence Imaging of PV Modules using* **…** *“*

UNSW SYDNEY

Summary

- PV is rapidly becoming the cheapest form of generating electricity, installations are expected to grow dramatically for years to come
- Systematic quality testing of installed modules is required
- Luminescence imaging is a powerful method that enables a wide range of material and device defects to be detected
- PL imaging in full daylight is advantageous but also technically challenging
- PL group at UNSW is very active in this space, several innovative methods are at different stages of development and “commercial readiness”
- UNSW team welcomes opportunities to collaborate or trial our novel methods (subject currently to Covid related travel restrictions)



Acknowledgements

- The excellent Photoluminescence team at UNSW
- The Australian Renewable Energy Agency (ARENA), the Australian Center for Advanced Photovoltaics (ACAP) and the Australian Research Council (ARC)

Questions welcome!

Big Picture – The Present

Loy Yang A power station in the Latrobe Valley: **2.2 GW$_p$**

2021 PV capacity: **~750 GW$_p$**

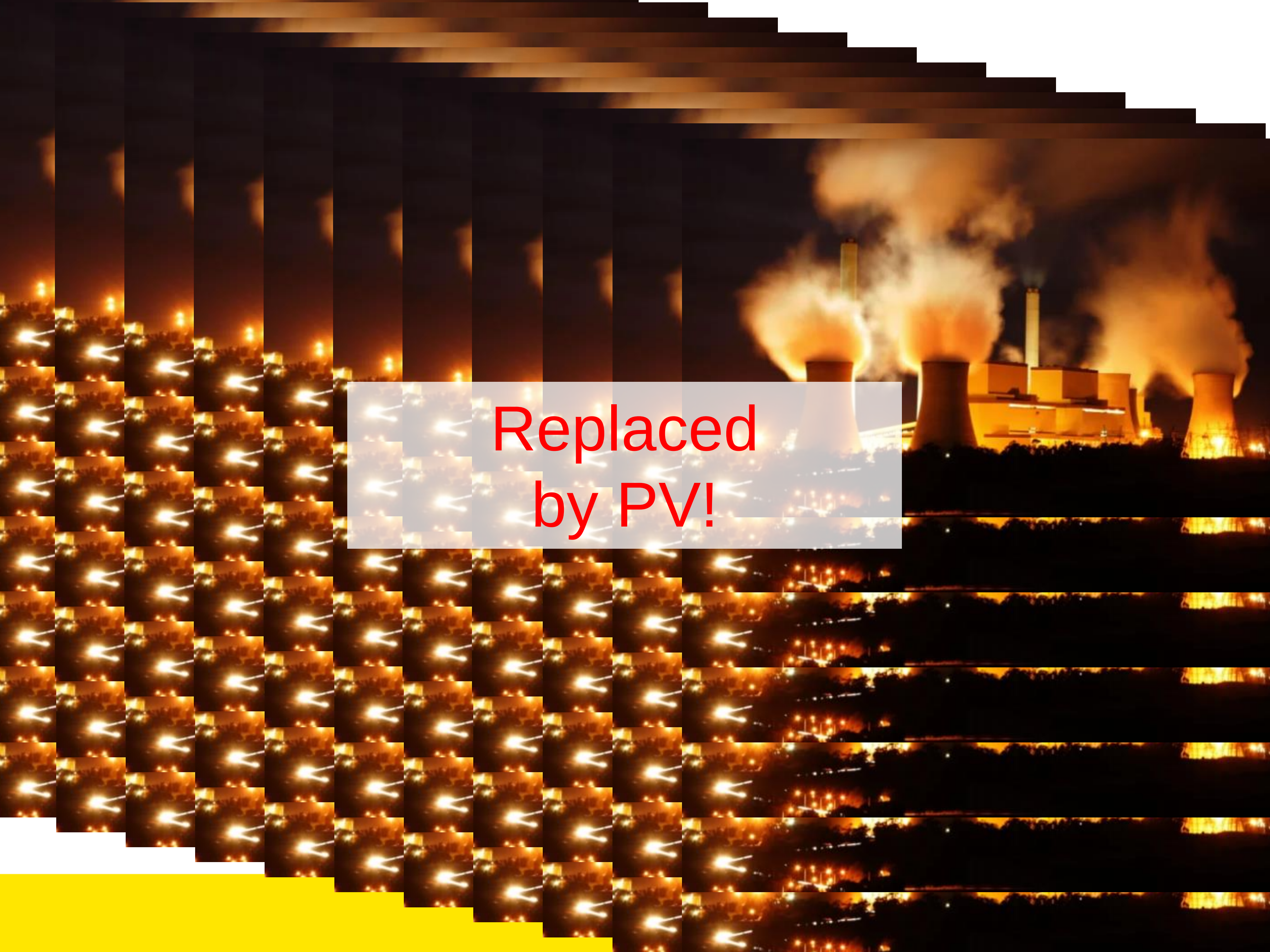
Allow for capacity factors!

2021 global PV capacity

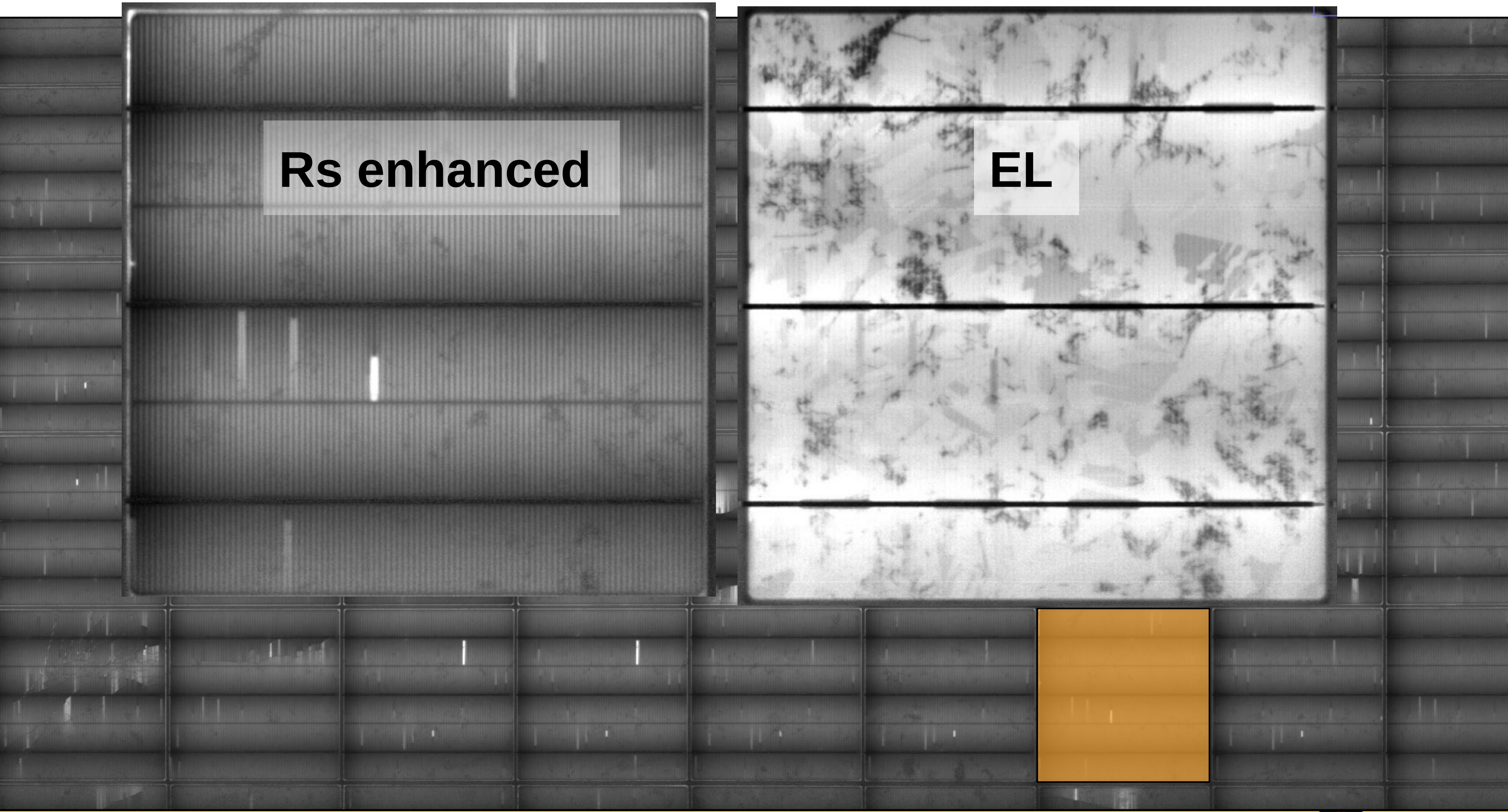
- replaces 100 -150 coal fired power stations
- generates ~ 10 times the electricity used across Australia

*"Loy Yang A has experienced an **outage 29 times since the start of 2018**, including a breakdown of one of its four units, expected to take **seven months to repair"***

https://www.theage.com.au/politics/victoria/victoria-s-coal-fired-power-plants-the-least-reliable-in-the-country-20190614-p51xvb.html

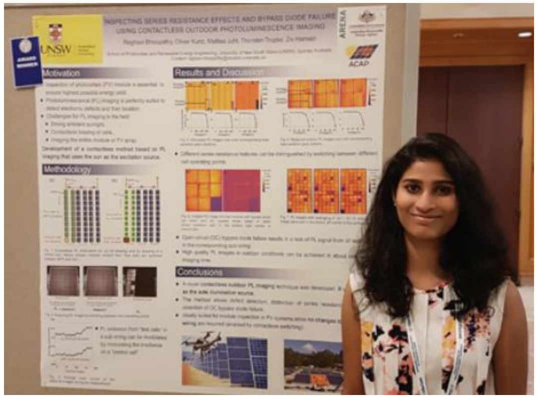

Replaced
by PV!

Line scan PL on modules



Outdoor PL imaging: UNSW Team

- **Raghavi Bhoopathy**, Just finished PhD
- **Matthias Juhl**, Postdoc
- **Rhett Evans**, Postdoc , CTO at 5B
- **Oliver Kunz**, Postdoc
- **Germain Rey**, Postdoc
- **Ziv Hameiri**, Senior researcher and lecturer
- **Thorsten Trupke**, CTO at BT Imaging



Raghavi, best poster award, 7th WCPEC, Hawaii, 2018

Mattias

Rhett

Oliver

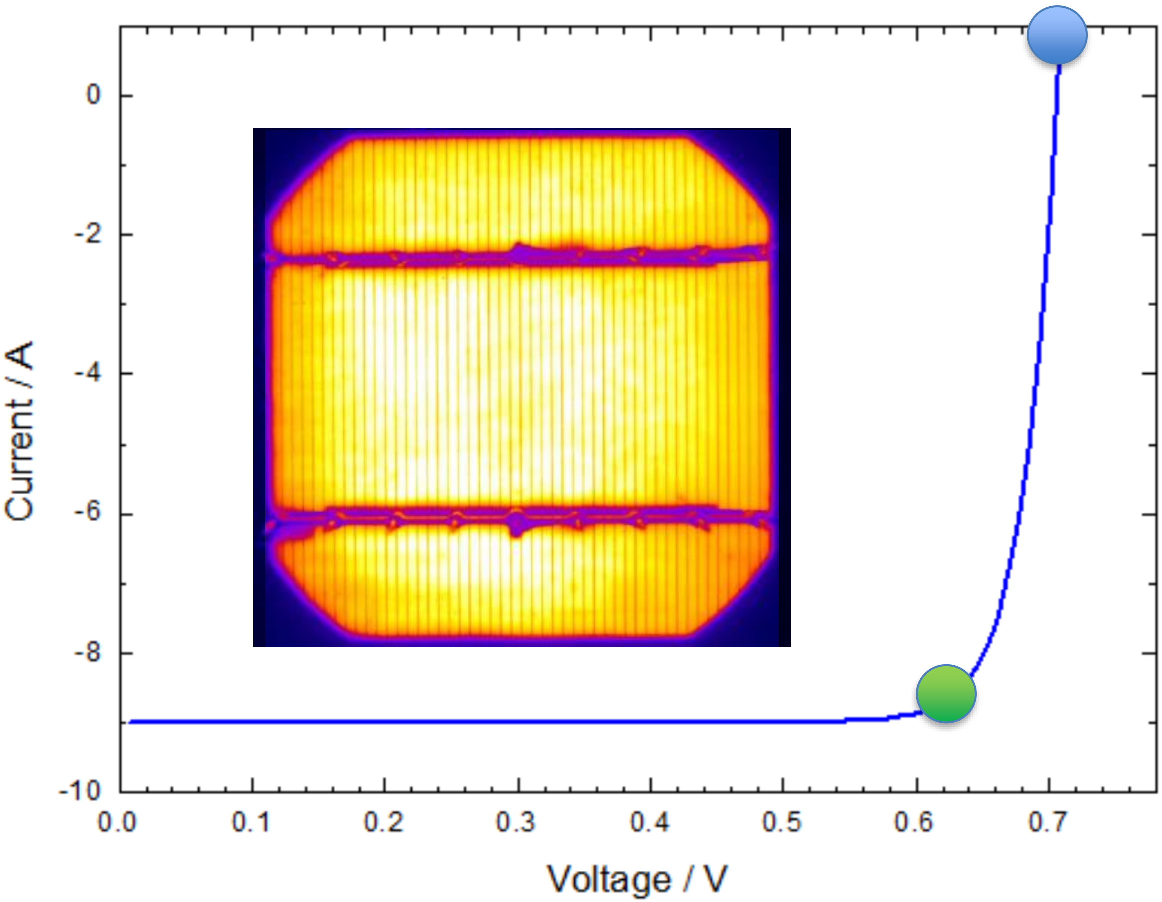
Germain

Ziv

Thorsten

Rs in outdoor PL images

2006: *PL images with uniform illumination and simultaneous current extraction*



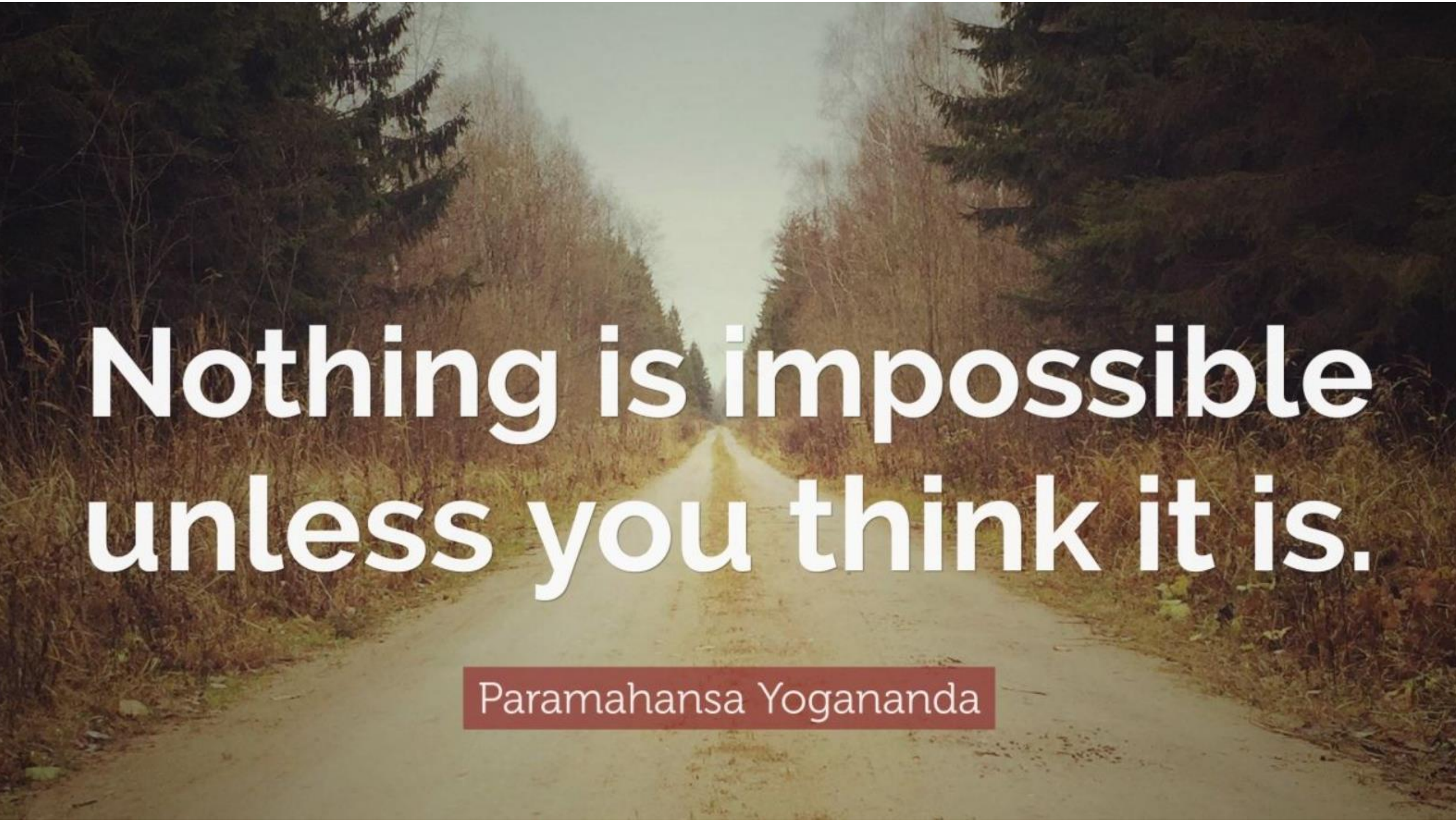
LED ON

- *Control cell generates > Isc*
- *All test cells at MPP*
- *Areas with high Rs have higher PL intensity*

LED OFF

- *Zero Current in Control cell*
- *All test cells at Voc*
- *Rs features not visible*

T. Trupke, E. Pink, R.A. Bardos and M.D. Abbott, *Spatially resolved series resistance of silicon solar cells obtained from luminescence imaging*, Applied Physics Letters **90**, 093506 (2007).


Nothing is impossible unless you think it is.
Paramahansa Yogananda