Reviewing the practicality and utility of electroluminescence and thermography images

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Extract of TASK13 report
"Review on Failures of Photovoltaic Modules"
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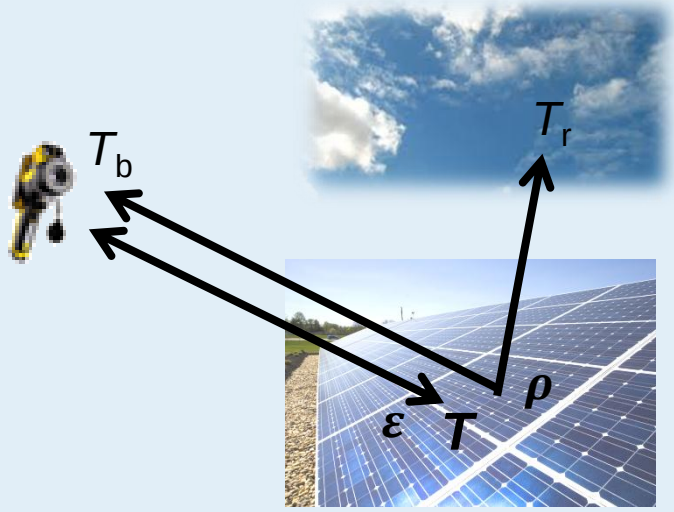
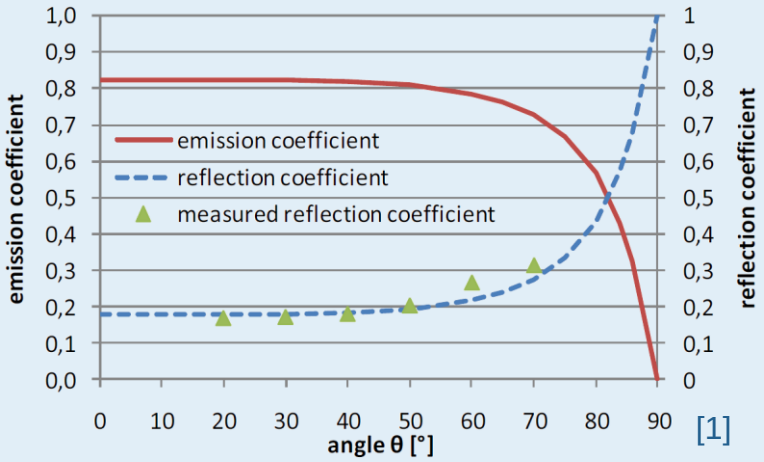
Outline

- Introduction for TG and EL, steady state and lock in techniques
- What physical quantity do we see ?
- Interpretation of the images EL/TG
- How much do the images allow to assess the reliability ?
- Application example for EL: PV module Installation

Steady state thermography (TG)



- Wavelength 8 µm - 14 µm
- Min. 700 W/m² irradiation at the module array
- Measure T in: $\varepsilon(T^4 - T_b^4) + \rho(T_r^4 - T_b^4) = 0$
- Typical emissivity values are[1]
  0.85 for the glass
  0.95 for the polymer back sheet
- Angle of view relative to surface normal
  0° to 40° glass
  0° to 45° polymer back sheet
- Out of angle module appear too cold



[1]

[1] C. Buerhop, H. Scheuerpflug, R. Weißmann: The Role of Infrared Emissivity Of Glass on IR-Imaging of PV-Plants, Proc. 26th EUPVSEC (WIP, Hamburg, Germany, 2011), pp. 3413 – 3416
[2] C. Buerhop, D. Schlegel, C. Vodermayer, M. Nieß: Quality control of PV-modules in the field using infrared-thermography, 26th EUPVSEC (WIP, Hamburg, Germany, 2011), pp. 3894 – 3897

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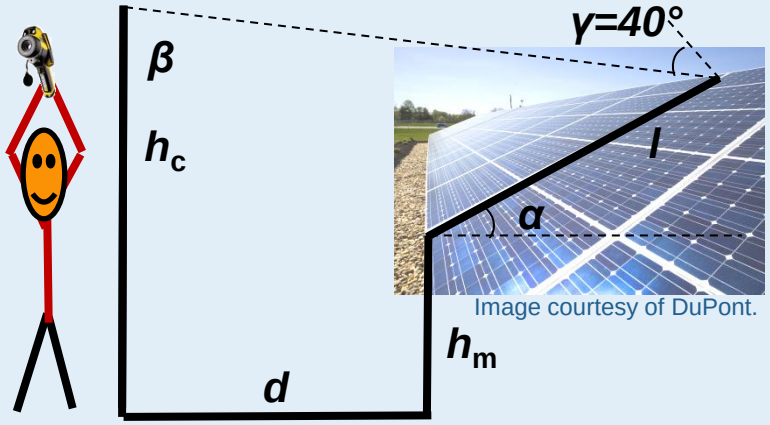
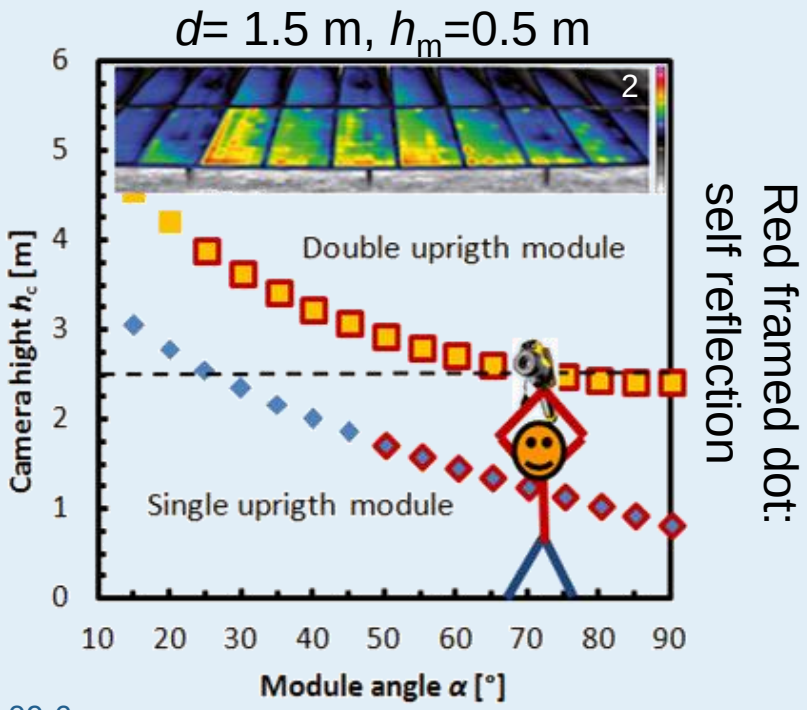
Camera position

- Chose camera height h_c so that view angle $\gamma < 40^\circ$ to normal of glass surface
- A too high position cause self reflection
- Be aware of other reflections: clouds, houses, trees
- Often high position necessary

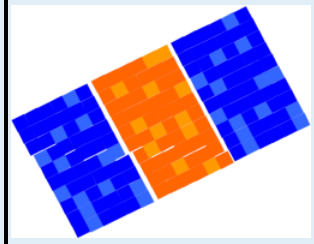
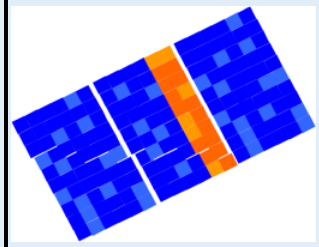
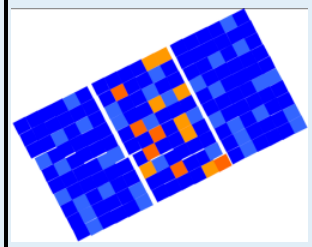
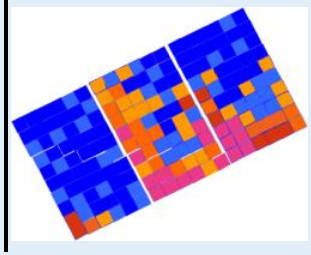
➔ Long stick
➔ Lifting ramp/ladder
➔ Octocopter





[2] B. Weinreich, *Feldstudie zur Modul- und Generatorqualität auf Basis thermografischer Messungen über 100 MW*, Proc. 28th Symposium Photovoltaische Solarenergie (OTTI, Bad Staffelstein, Germany, 2013), ISBN 978-3-943891-09-6

Steady state thermography and their interpretation

Pattern	Description	Possible failure reason	Electrical measurements	Remarks, Chapter
	One module warmer than others	Module is open circuited - not connected to the system	Module normally fully functional	Check wiring
	One row (sub-string) is warmer than other rows in the module	Short circuited (SC) sub-string - Bypass diode SC, or - Internal SC	Sub-strings power lost, reduction of V_{oc}	Probably burned spot at the module 6.2.7 One diode shunted
	Single cells are warmer, not any pattern (patchwork pattern) is recognized	Whole module is short circuited - All bypass diodes SC or - Wrong connection	Module power drastically reduced, (almost zero) strong reduction of V_{oc}	Check wiring 6.2.7 all diodes shunted
	Single cells are warmer, lower parts and close to frame hotter than upper and middle parts.	Massive shunts caused by potential induced degradation (PID) and/or polarization	Module power and *FF* reduced. Low light performance more affected than at STC	- Change array grounding conditions - recovery by reverse voltage 6.2.5 (PID)

TG outdoor

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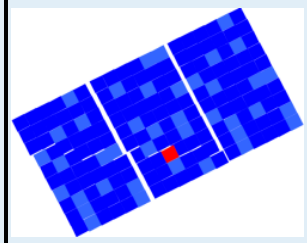
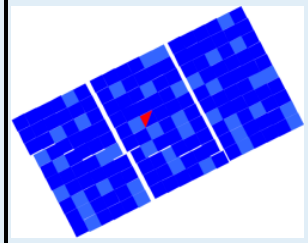
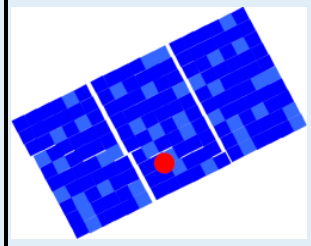
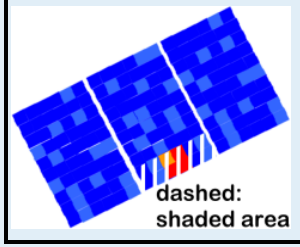
Steady state thermography and their interpretation

Pattern	Description	Possible failure reason	Electrical measurements	Remarks, Chapter
	One cell clearly warmer than the others	- Shadowing effects - Defect cell - Delaminated cell	Power decrease not necessarily permanent, e.g. shadowing leaf or lichen	Visual inspection needed, cleaning (cell mismatch) or shunted cell 6.1.1 (delam.)
	Part of a cell is warmer	- Broken cell - Disconnected cell interconnect ribbon	Drastic power reduction, *FF* reduction	6.2.2 (cell cracks) 6.2.4 (burn marks) 6.2.6 (interconnects)
	Pointed heating	- Artifact - Partly shadowed, e.g. bird dropping, lightning protection rod	Power reduction, dependent on form and size of the cracked part	Crack detection after detailed visual inspection of the cell possible 6.2.2 (cell cracks)
	Sub-string part remarkably hotter than others when equally shaded	Sub-string with missing or open circuit bypass diode	Massive Isc and power reduction when part of this sub-string is shaded	May cause severe fire hazard when hot spot is in this sub-string

TG outdoor

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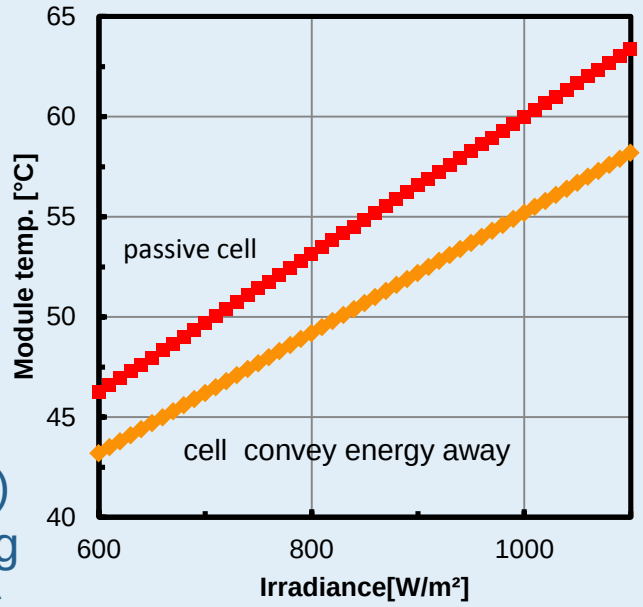
Steady state thermography (TG)

- 2.5 to 10 K temperature increase for:
  shunted by pass diode
  open circuit PV-module
  PID-cells
- Temperature difference increase with irradiation and module efficiency
- Local defects lead to great range of temperatures
- no rejection criterion defined yet (85ºC - 150ºC?)
- Steady state thermography is good for identifying relevant defects, done under working conditions



- Measurement conditions are limiting the technique
- Cheap imaging technique
- High view position necessary (increase costs)

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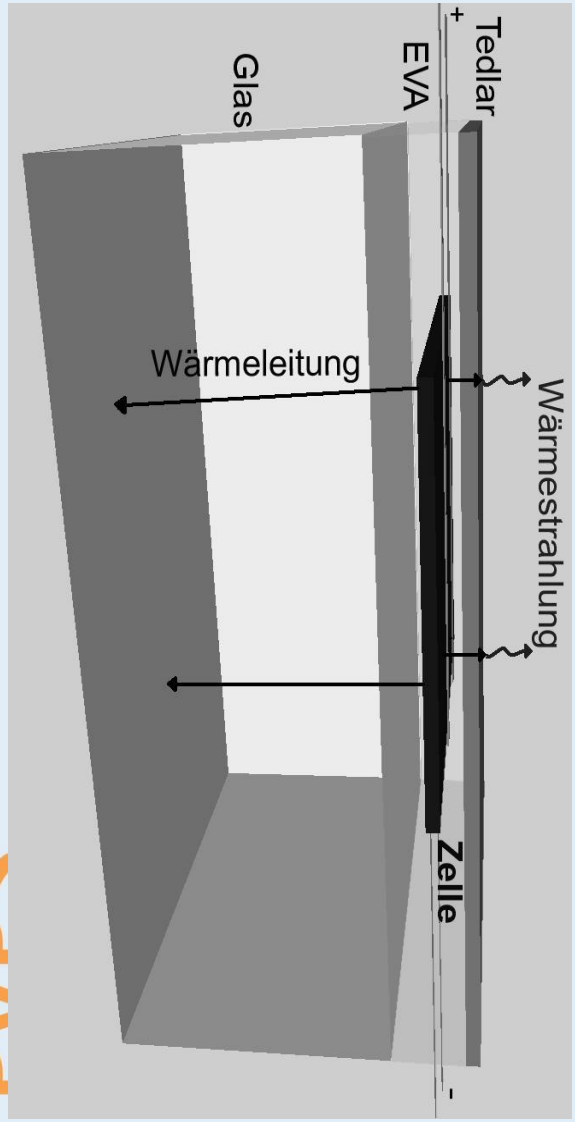
Log-in thermography (LIT)



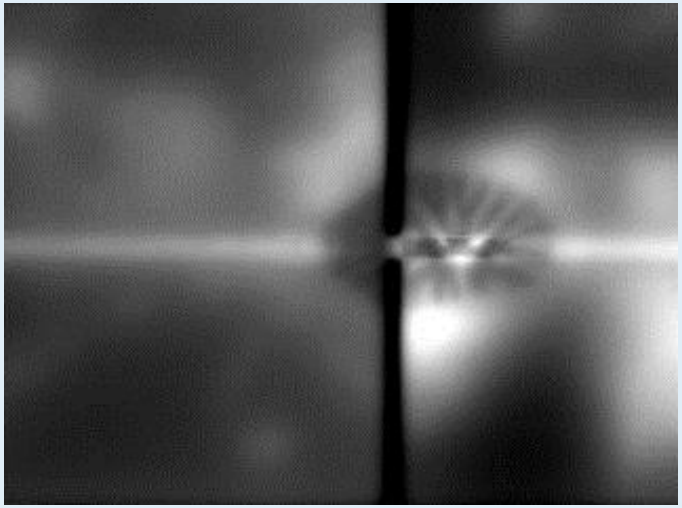
- Wavelength 8 µm up to 14 µm
- AC source to stimulate radiation
- On/off subtraction
- @ Isc ➔ overview
  @ 10% Isc ➔ test for linear shunting
- Visualize power dissipation
- Log-in frequency must be adapted to thermal diffusion length of laminate

$$f_{Lock-In} = \frac{\lambda}{2\pi \cdot \Lambda^2 \rho \, c_P}$$

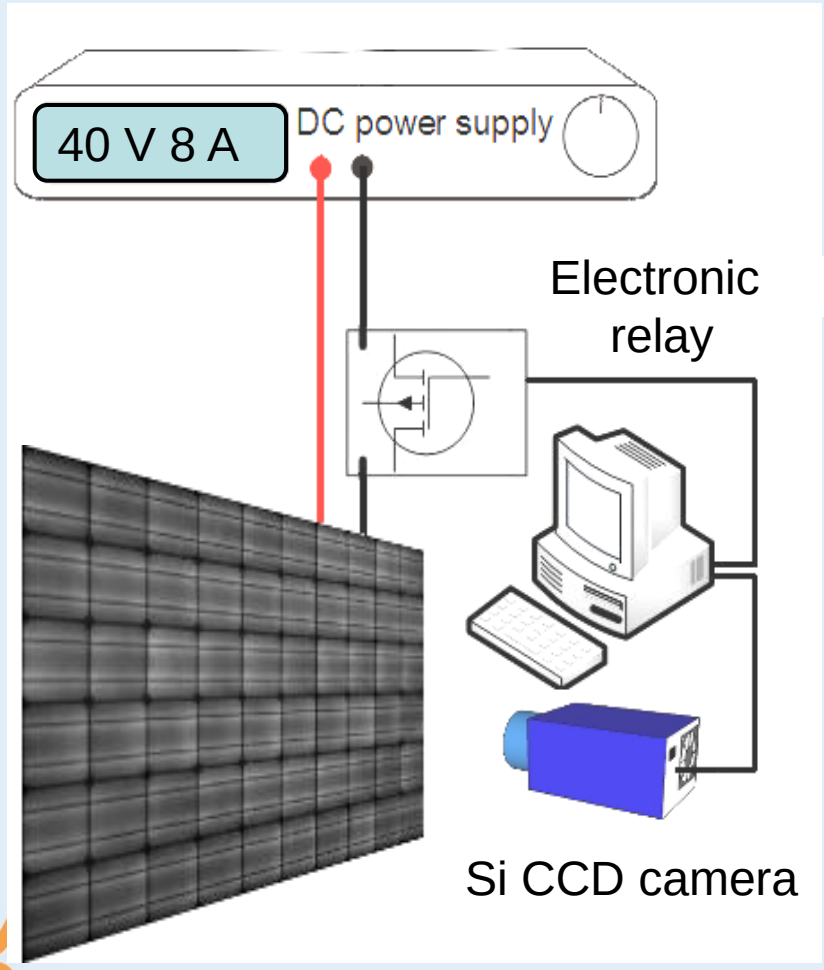
- Lock in frequency for view from backsheet: 0.1 Hz, glass: 0.01 Hz
- Reflections are unimportand

Log in thermography (LIT)

- Medium resolution
- Expensive IR camera
- Slower than EL
- Only lab tool, yet
- Can detect most failures being detectable with EL
- Good for detecting power generating defects (shunts) and invisible laminate defects



Log-in elektroluminescence (EL)

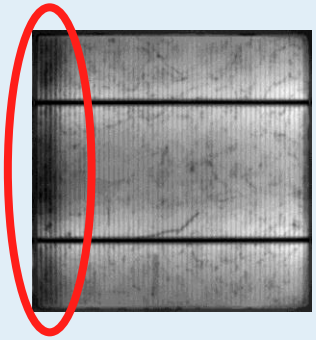


- Wavelength 1150 nm
- Current source to stimulate electroluminescence
- Optional on/off subtraction and 850 nm long pass filter to eliminate extraneous light
- @ Isc ➔ overview
  @ 10% Isc ➔ inactive cell parts, PID
- EL intensity is proportional to logarithmic voltage difference

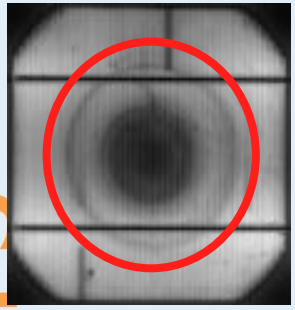
$$\Delta V = V_T \cdot \ln\left(\frac{\Phi_1}{\Phi_2}\right)$$

Features from the wafer

Crystall defects from multicrystallin wafer (multi)
Cell efficiency is higher with smaler defect area



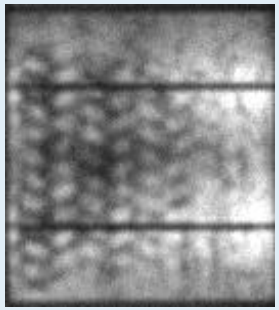
Edge Wafer (multi)
Slightly reduced cell efficiency



Striation rings (mono)
Slightly reduced cell efficiency

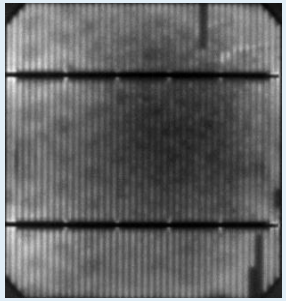
No follow up failure

Metal paste



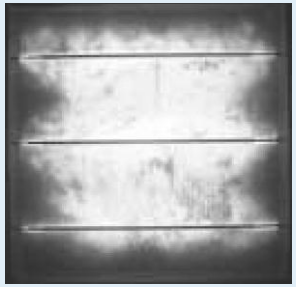
Contact formation – feature A

Temperature distribution during firing of metal paste is inhomogeneous, chain pattern of conveyor belt



Contact formation - feature B

Temperature gradient during firing of metal past from middle to edge



Humidity corrosion

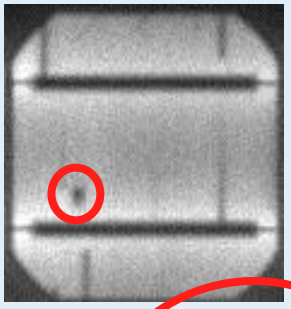
Corrosion of front finger contacts, probably due to acidic acid of laminate, rapidly reduce *FF*

(only reported in DH test, yet)

EL

LIT

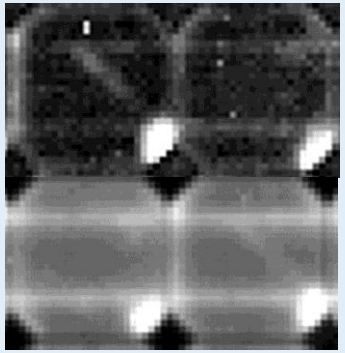
Further failure

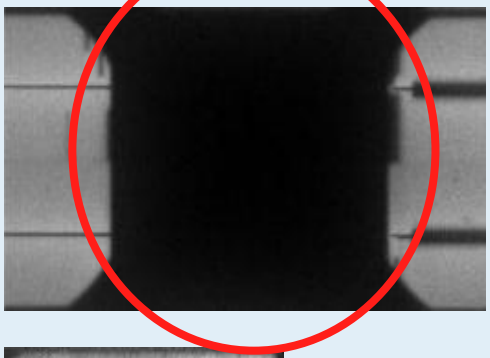


Local shunt on solar cell (validate with TG)

- Edge isolation fault
- Emitter localy defect

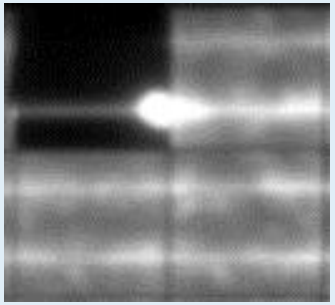
Sligthly reduce V_{oc} and *FF*, possilby hot spot

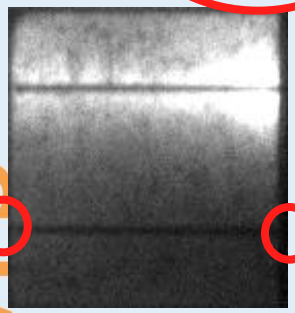




Shunt by cell interconnect ribbon

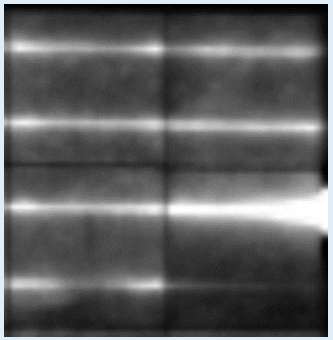
Reduction of V_{oc}





Broken cell interconnect ribbon

Smal reduction of *FF* und I_{mpp},
may generate arcing,
1/3 power loss when last ribbon breaks



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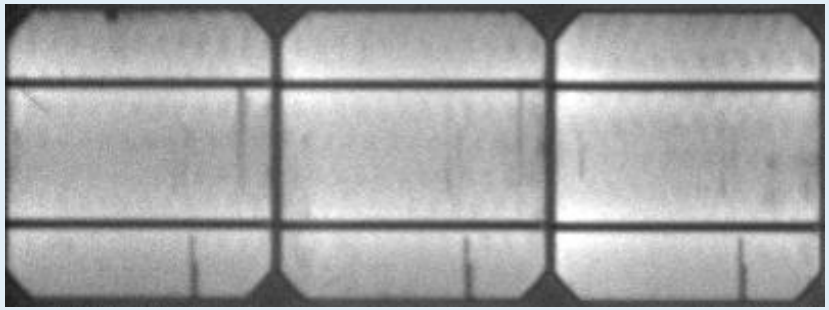
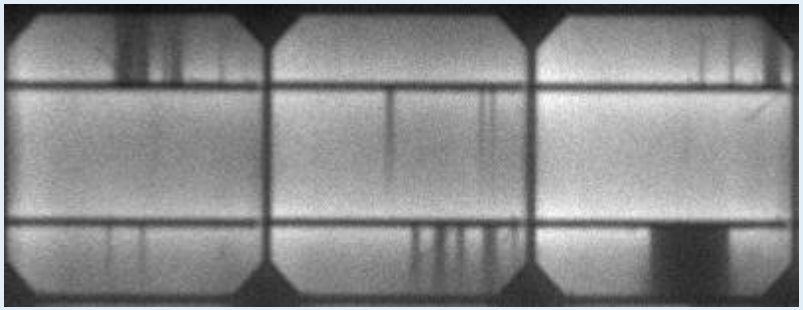
Three classes of finger failure

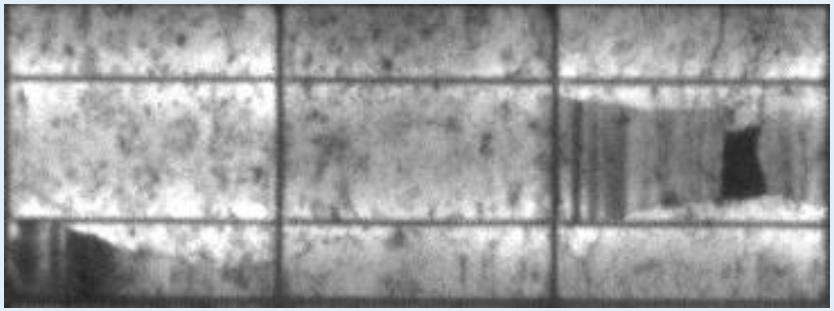
Failure by screen printing
Repeating finger interruption, typically not at cell interconnect ribbon



Failure by stringing
Irregular finger interruption at cell interconnect ribbon



Failure by cell crack
Finger interruption at cell crack, cell part isolation in progress

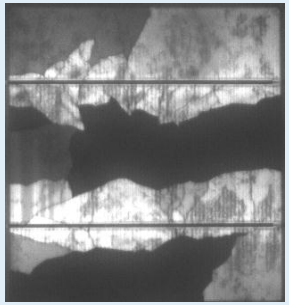


Follow up failure possible

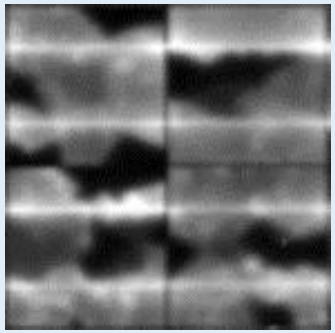
Cracks in solar cells

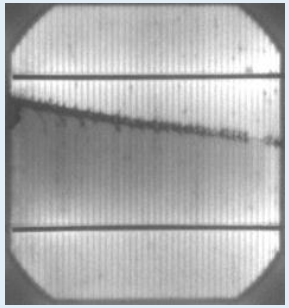
EL

LIT

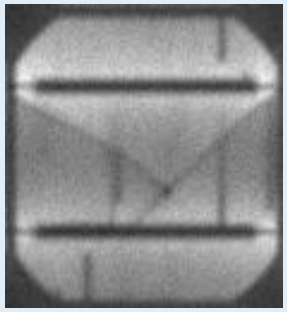


Inactive cell parts
Need to measure image @ 10% I_{sc}
decrease of *FF* and I_{mpp}

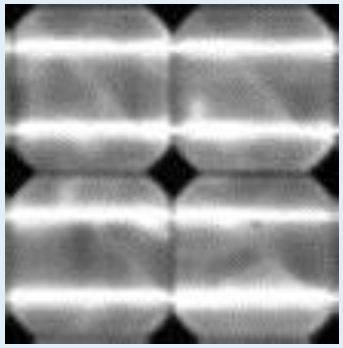




Cross crack line along multiple neighbor cells
E.g. scratching a module corner on back sheet of a PV module
May result in isolation fault, visual inspection needed



Cell cracks in solar cells
How much is the power loss ?



Köntges et al., ep
Photovoltaik aktuell 7/8 2008, S. 36

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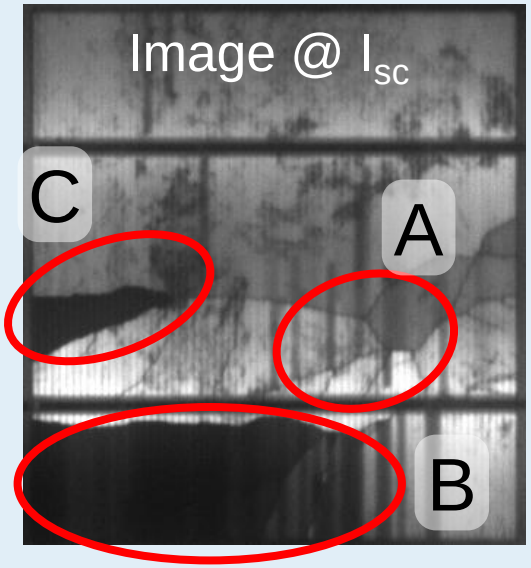
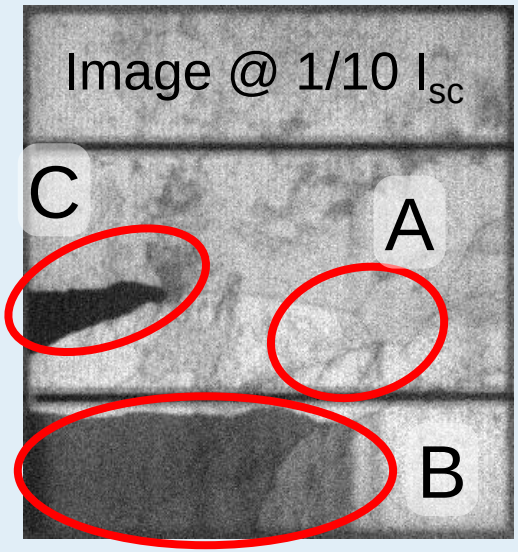
Lock-in electroluminescence (EL)





- With cooled 12 bit CCD camera detectable voltage difference: < 150 mV

$$\Delta V = V_T \cdot \ln\left(\frac{3500}{10}\right) = 150mV$$

- Voltage drop at break resistance is less at lower current
- Therefore low current image is more sensitive to isolated parts

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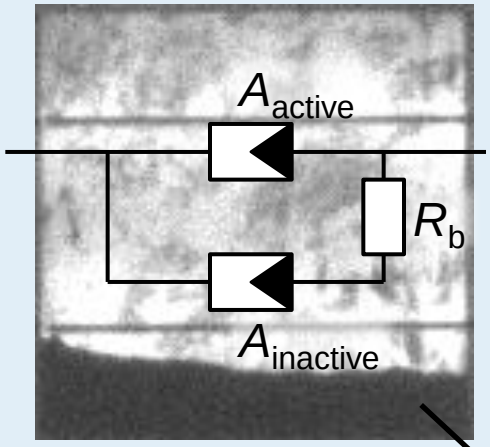
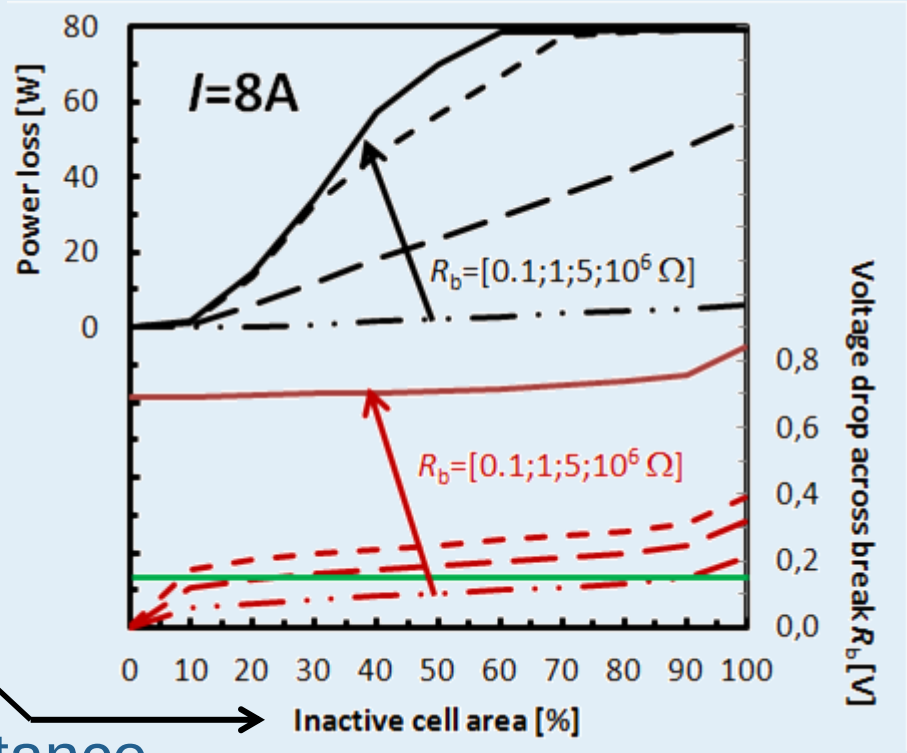
Spice simulation[1] of voltage drop over break resistance R_b



60 cells 228 W PV module



- At *I*=8 A one **can not** detect if the break resistance is high enough to generate power loss

[1] M. Köntges, I. Kunze, S. Kajari-Schröder, X. Breitenmoser, B. Bjørneklett, Solar Energy Materials & Solar Cells **95** (2011), pp. 1131–1137

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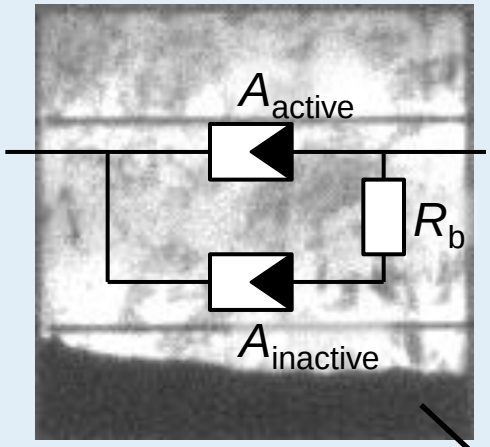
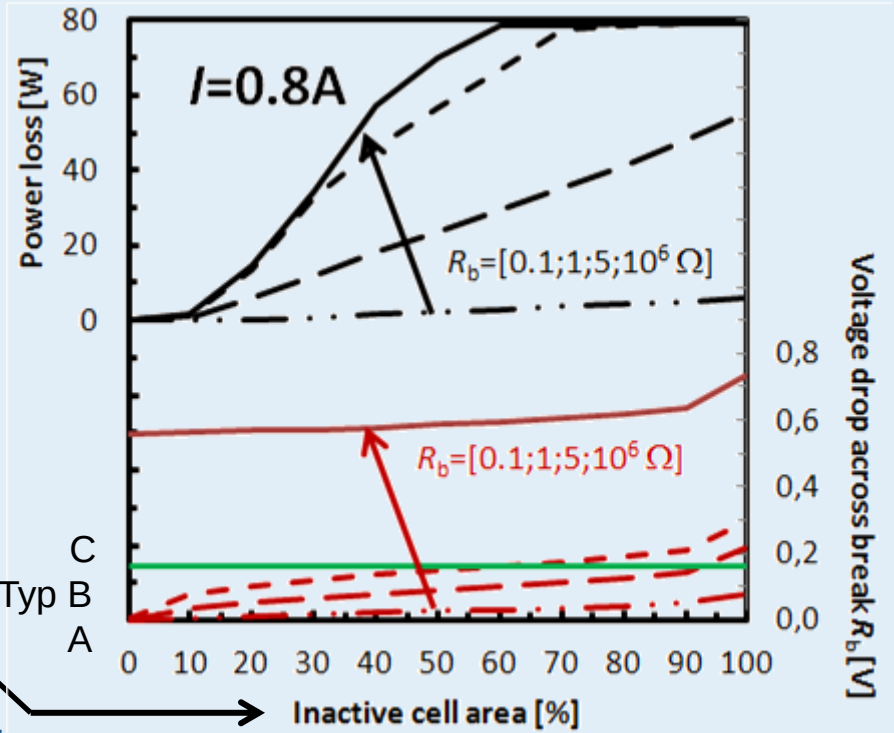
Spice simulation[1] of voltage drop over break resistance R_b



60 cells 228 W PV module



- At I=0.8 A one **can** detect if the break resistance is high enough to generate power loss

[1] M. Köntges, I. Kunze, S. Kajari-Schröder, X. Breitenmoser, B. Bjørneklett, Solar Energy Materials & Solar Cells **95** (2011), pp. 1131–1137

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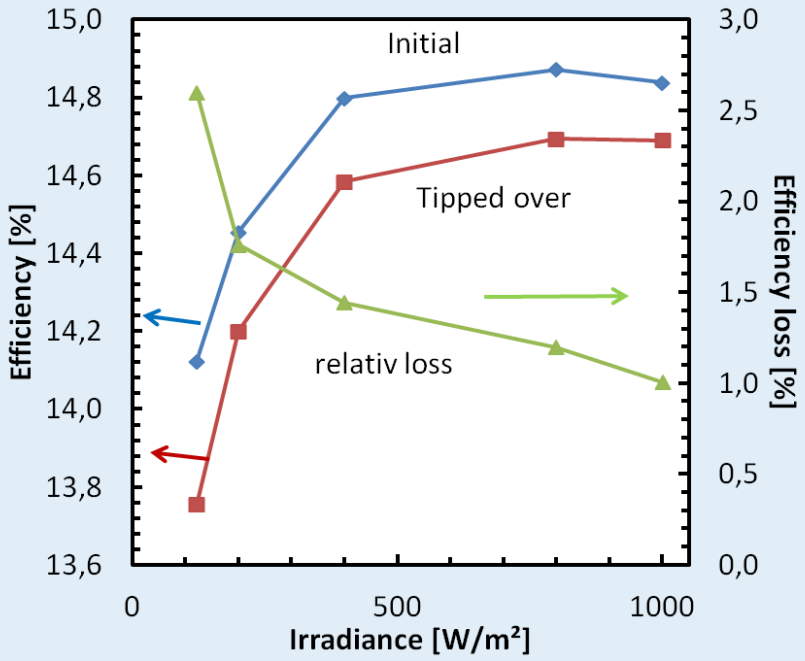
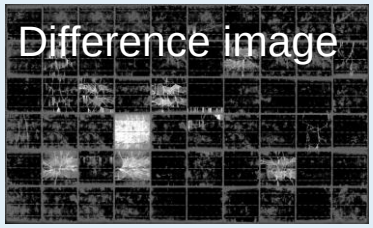
Power loss of PV module with lots of typ A cracked cells at low light conditions



- Typ A cell cracks behave like shunts
- Low intensity efficiency is more influenced (2.6%) than high intensity efficiency (1.0%)
- Weighted assessment with European efficiency definition for inverters
- $\eta_{Euro} = 0{,}03 \times \eta_{05\%Pn} + 0{,}06 \times \eta_{10\%Pn} + 0{,}13 \times \eta_{20\%Pn} + 0{,}10 \times \eta_{30\%Pn} + 0{,}48 \times \eta_{50\%Pn} + 0{,}20 \times \eta_{100\%Pn}$
- Production for this PV module reduced by approx. 1.7%



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Electroluminescence (EL)

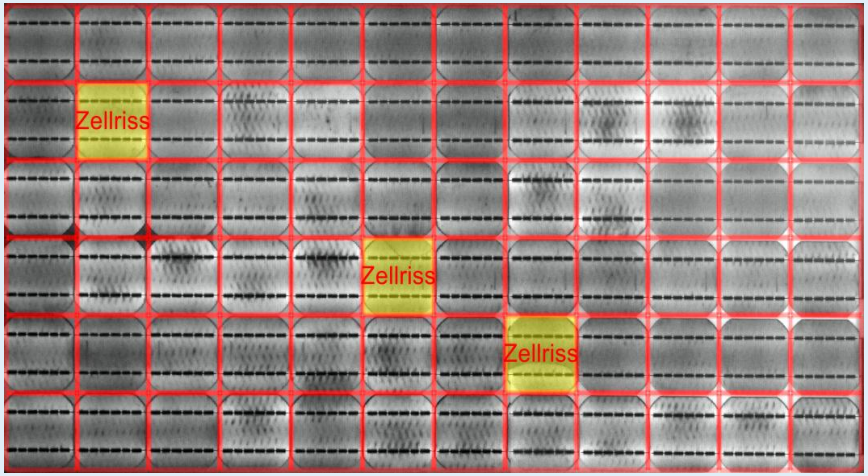
- High resolution
- Cost efficient Si CCD camera for dark environment
- Very expensive camera for daylight imaging
- Fast image recoding
- Often difficult to differentiate between feature and failure
- Automation of failure detection only for production possible
- “Failure cells” are detectable by deviation from mean intensity, but a human has to classify further

- For much more detectable failure and more explanations ➔read TASK13 report

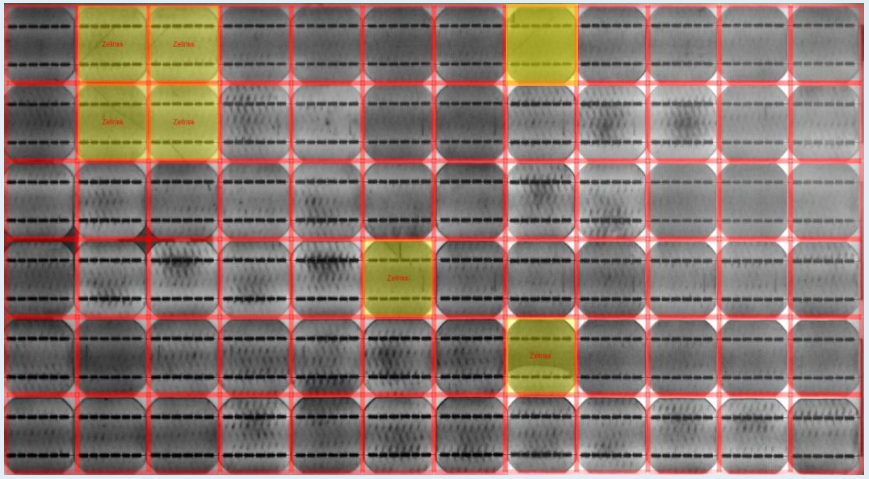
Application example: checking typical handling faults

PV module falls back to stack 20 cm while de-stacking

EL before:



EL after:



Power before:

169,4 Wp

Power after:

169,5 Wp

- 4 cell cracks typ A, no power loss

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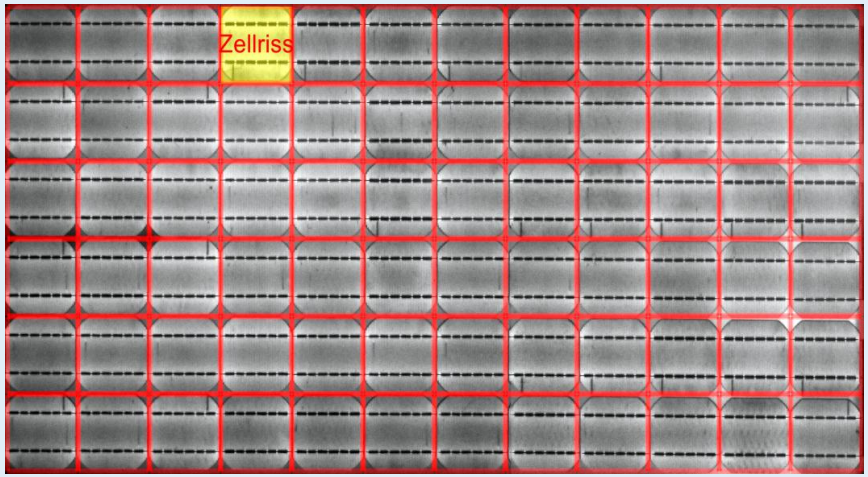
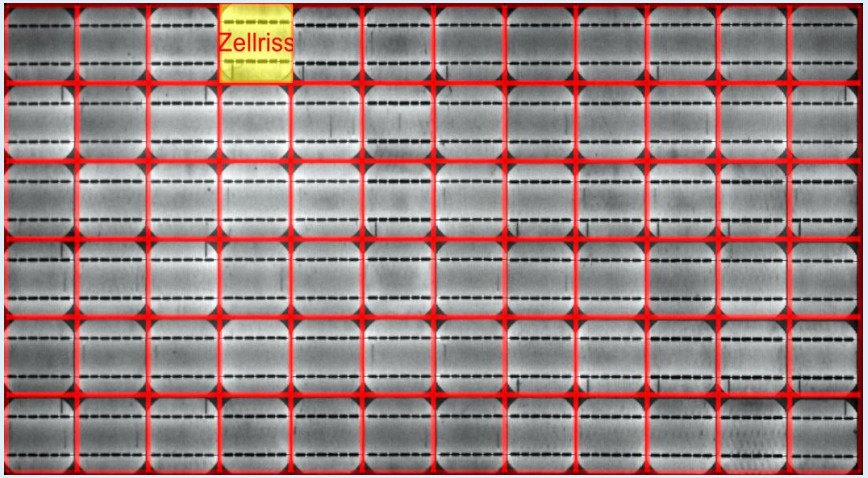
PV module fall down on long side edge 20 cm

EL before:



EL after:



Power before:

171,0 Wp

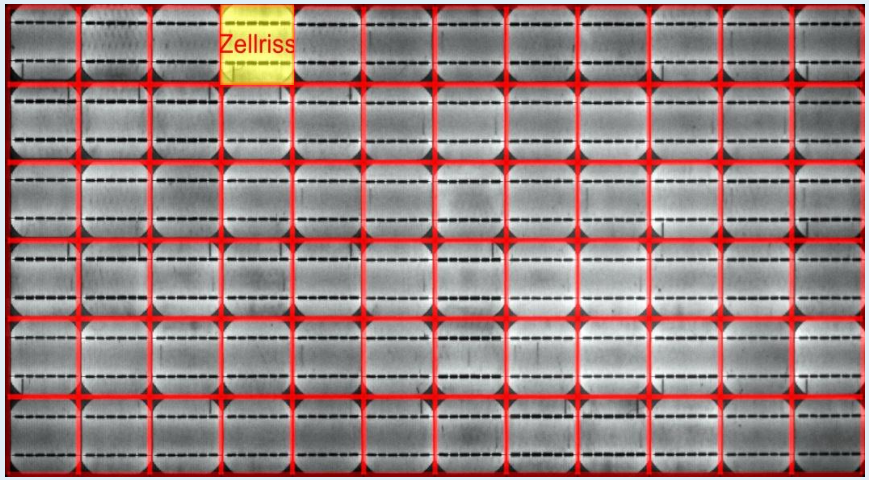
Power after:

171,2 Wp

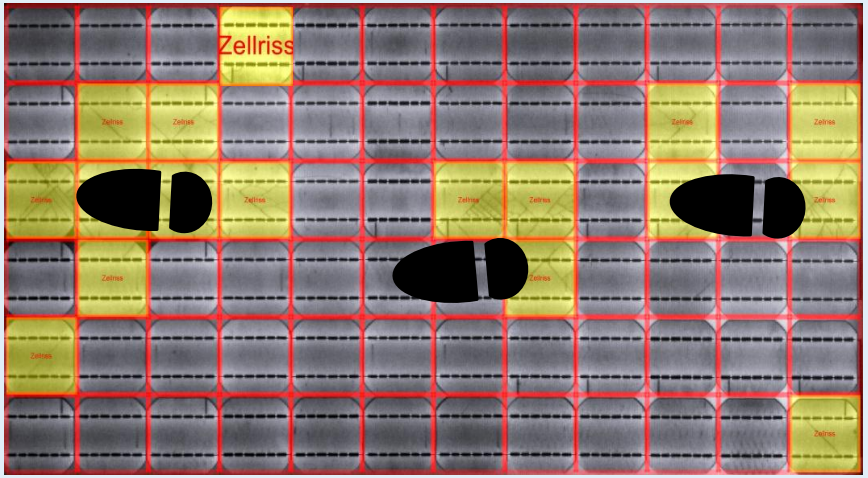
- No cell cracks, no power loss

Walk on sunny side of PV module

EL before:



EL after:



Power before:

171,2 Wp

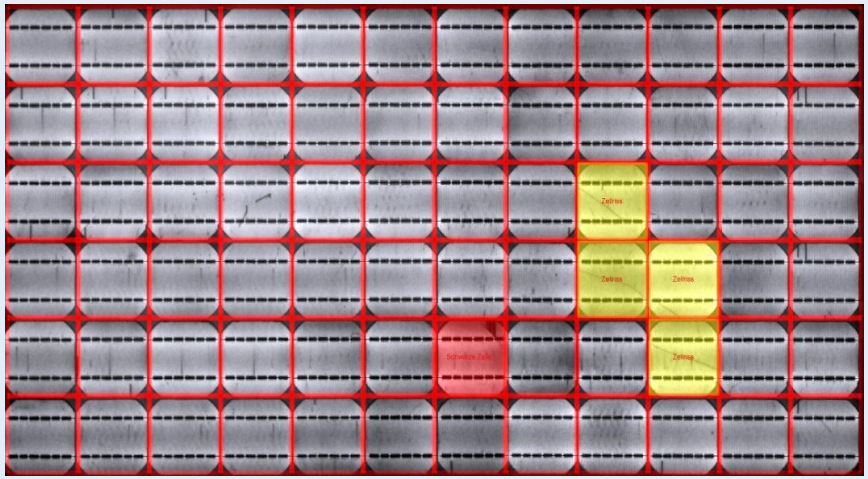
Power after:

170,3 Wp

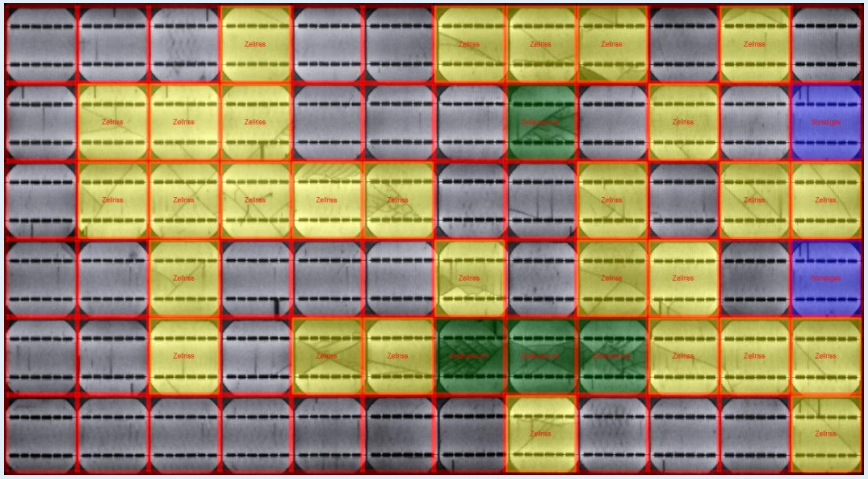
- 16 cell cracks typ A, 1 W power loss

Tiped over module from vertical position on rear side

EL before:



EL after:



Power before:

172,2 Wp

Power after:

170,3 Wp

- 30 cell cracks typ A incl. 4 dendritic cell cracks + 1 typ B, 2 W power loss

Summary:

- Steady state TG is a cheap technique for failure detection in the field, but is strongly restricted by weather conditions
- LIT shows similar defects like EL, but is more expensive and has lower resolution. Strong in stunt detection and hidden laminate bubbles
- EL can detect most defects, often difficult to differentiate between failures and effects, inexpensive technique
- EL for outdoor same advantages like indoor, but quite expensive technique

- TASK13 report “Review on Failures of Photovoltaic Modules” will be available in April 2014

PVPS

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Ongoing standardization:

- Udo Siegfriedt und Eva Schubert, Deutschen Gesellschaft für Sonnenenergie (DGS) e.V. is working on a German standard on “Thermographic tests of PV-modules and plants“
- Bengt Jäckel, Renewable Energies UL International: Suggestion to put together characterization methods for PV modules under one IEC number in two general parts: Non destructive (e.g. VIS, EL, TG, PL, …) and destructive methods (EVA cross linking …)
- Peter Hacke, NREL: preparing IEC initial drafts for EL and TG until June 14
  - goal: support other standards and tests
  - scope: provide some metrics for the interpretation of images

Thank you for your attention