Advances in Multi-Junction Solar Cell Characterization by Automation and AI Based Image Analysis

K. Ramspeck[1], M. Meixner[1] and M. Maier[2]

[1]halm elektronik gmbh

[2]neonsee GmbH

Who we are

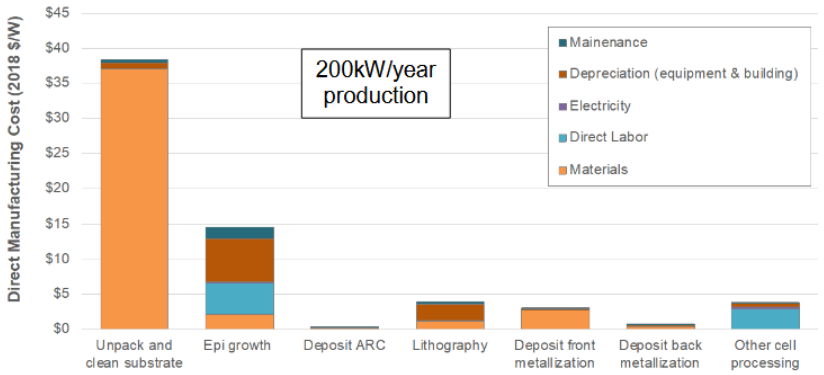
halm introduction

- halm is technology leader in photovoltaic characterization equipment
- from our base in Frankfurt, Germany we design, build and ship solar simulators and measurement technology for the PV industry worldwide
- we installed more than 450 GW production cell testers worldwide
- halm acquired the solar simulator business from Neonsee in 2025

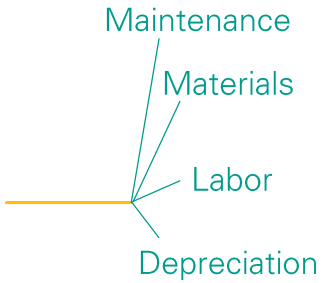
Motivation

- Compared to terestrial PV, space components are extremely pricy especially when accounting for the total cost until operation at the designated position begins
- In Contrast – characterization, automation and device optimization somewhat lacks behind
- We aim to bring automation and AI deployment from terestric together with requirements for space solar cells and multi-junction III-V

Space solar cell



Si-solar cell



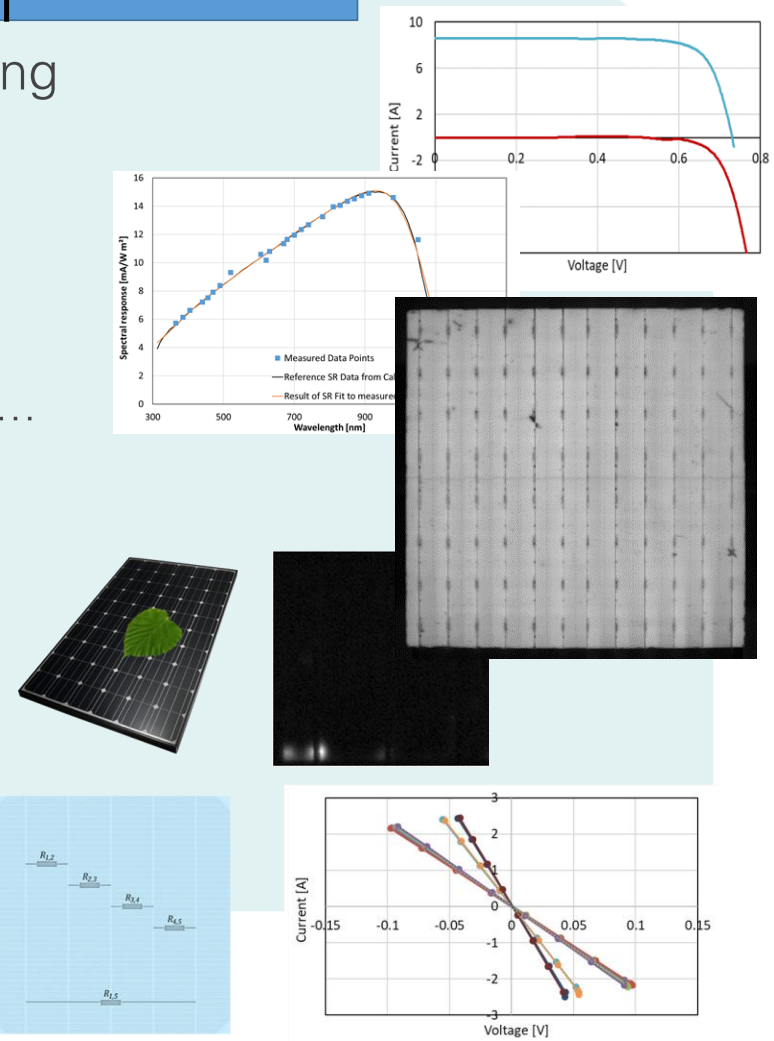
Cost breakdown of space solar cell* compared to terrestrial Si-solar cell

*Horowitz, Kelsey A. W., Timothy Remo, Brittany Smith, and Aaron Ptak. 2018. Techno-Economic Analysis and Cost Reduction Roadmap for III-V Solar Cells. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-72103. https://www.nrel.gov/docs/fy19osti/72103.pdf

What is commonly done in PV manufacturing?

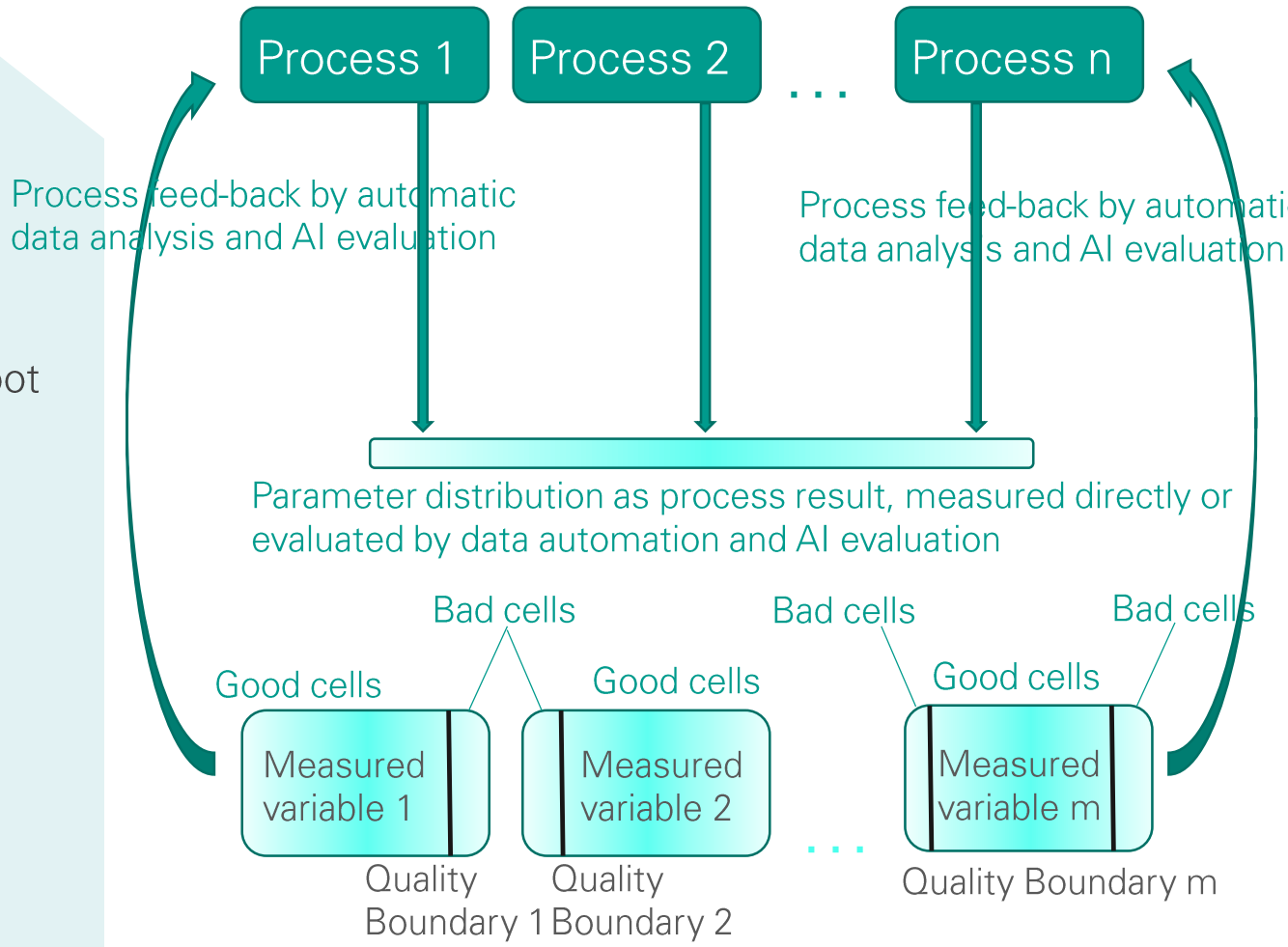
Light *IV* 40 ms	Dark *IV* 35 ms	Shadowless Electroluminescence 30 ms	Reverse *IV* and Thermography - 70 ms	Spectral response – 75 ms	Metallization resistance – 50 ms

- Characterization made possible by automation for a product containing only one junction, worth less then 5$c per Watt!!!
  - Light-, Dark-, Reverse- and Bifacial light-IV, electroluminescence imaging with AI based defect recognition, thermography, grid-resistance and inline SR
  - AOI: printing defects, misalignements, color changes, chippings, edge breakage…
  - Reflection, PL
  - MES systems gather all the data
  - Single wafer tracking to combine machine parameters and positions with output and defects
  - Additional measurements upstream and downstream in production
  - Production throughput of 5000 wafers/h (single line in solar cell sorter)

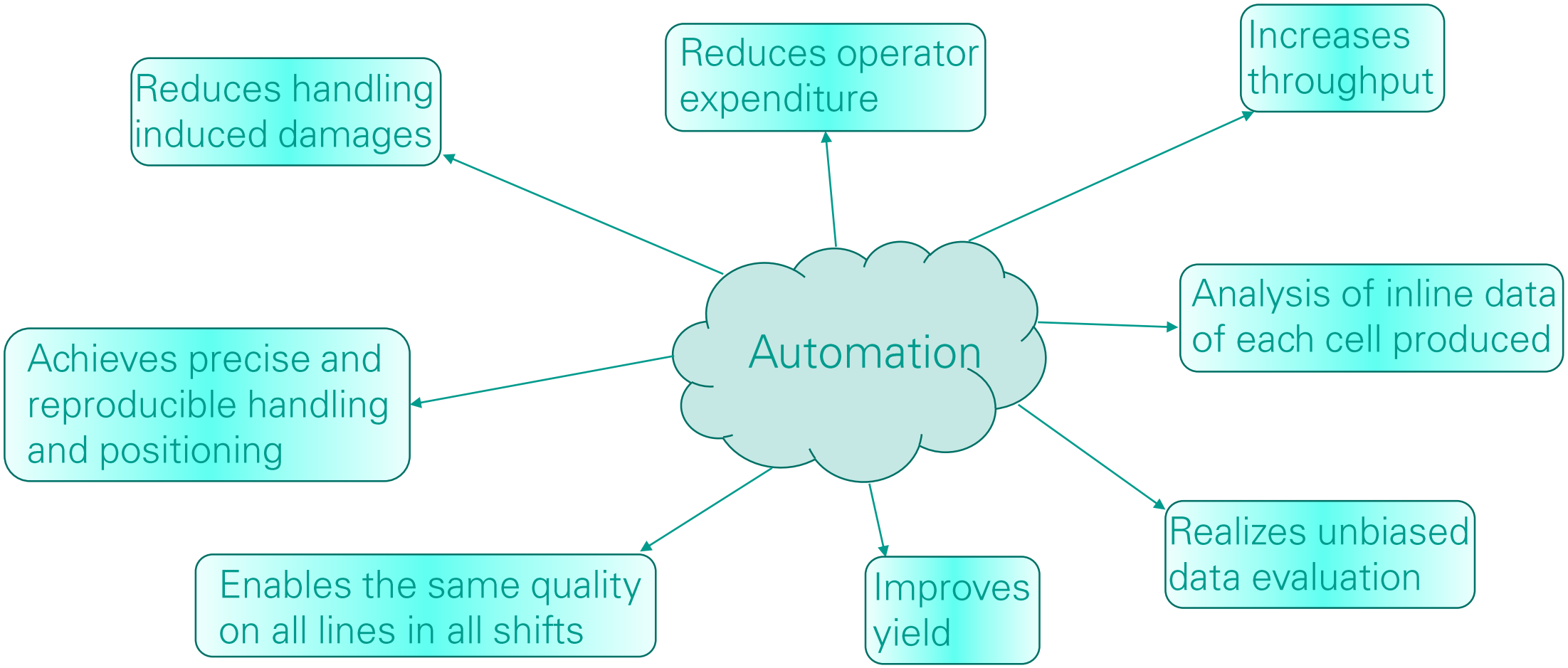


End-of production line characterization

- Two main goals to follow
  - Sort out any defective parts especially such ones which might be prone to early faults - quality control
  - Minimize the number of defective parts by root cause analysis and process optimization
- Collect as much data as possible → concept of digital twin
- Minimize costs by throughput, yield optimization and full exploitation of available data



Benefits of automation

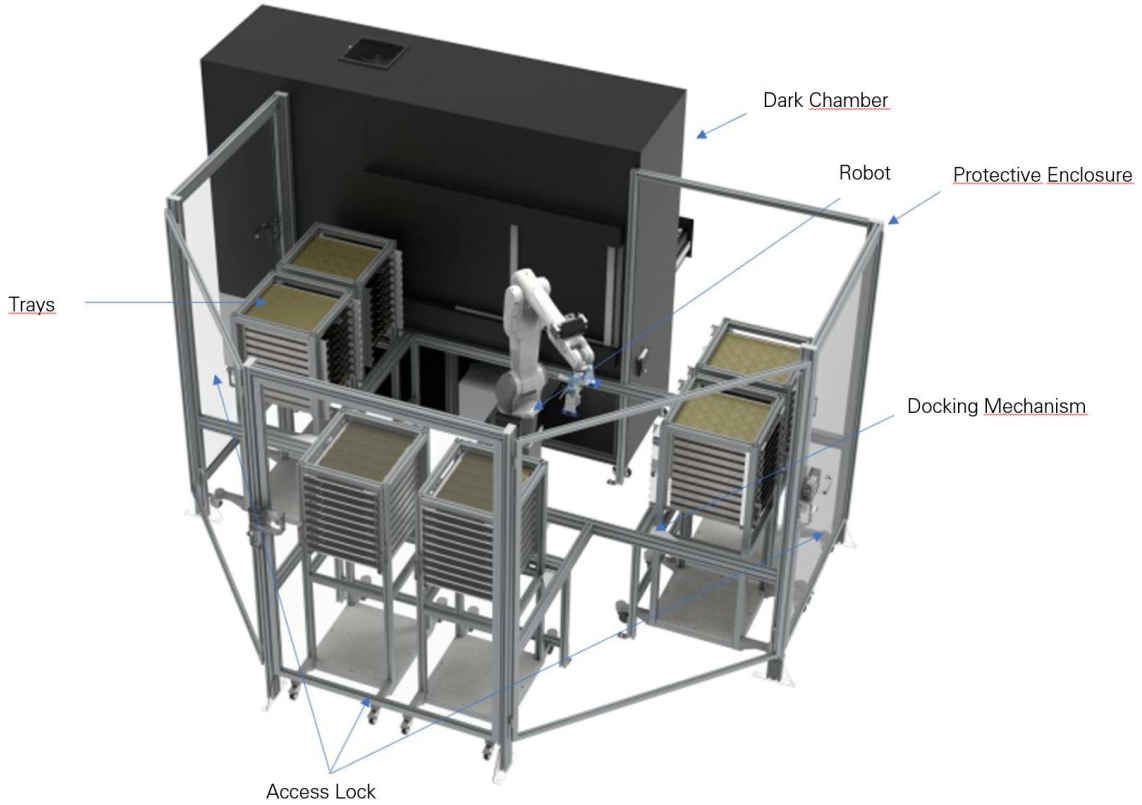


Cell Tester and Sorter for bare cells and SCAs

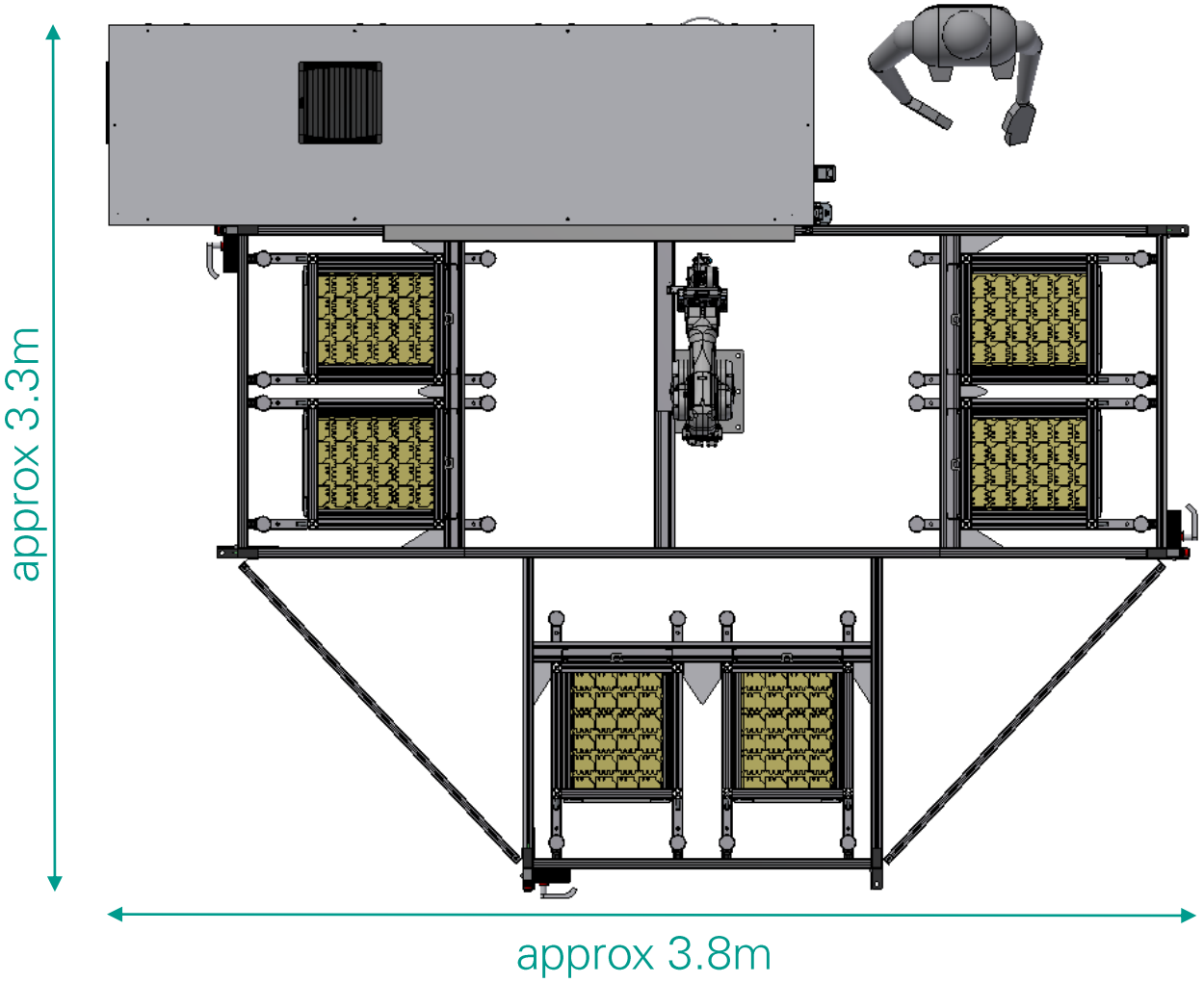
An integrated, end-to end system for testing and sorting high-value solar cells and SCAs

Three main requirements for solar cell measurements:

1. **Excellent measurement precision**
2. **High-throughput automation with gentle and fast handling.**
3. **Process security and stability**



CTS – System layout and footprint

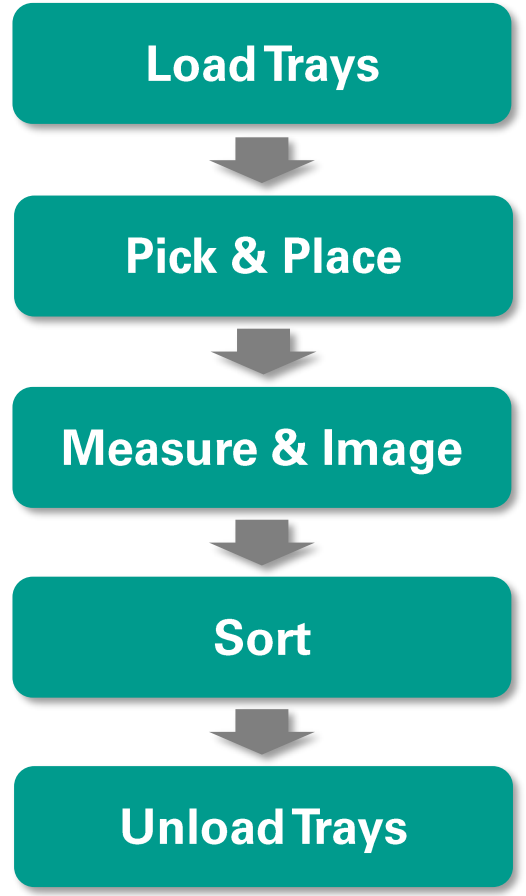


Compact but powerful system

Cycle time of about 15 sek per cell → about 1.5 Mio cells/year in continuous operation

CTS – Automated workflow: from tray to data

1. **Load:** Operator loads up to 6 tray magazines for continuous operation.
2. **Pick:** Dual-gripper robot picks the next cell while the current one is being measured.
3. **Place:** Vision-guided placement ensures sub-millimeter accuracy on the measurement chuck.
4. **Measure:** IV-curve measurement and optional EL/PL imaging are performed in a controlled environment.
5. **Sort:** Cell is sorted into a classified outgoing tray based on performance.



cetisPV-TrueSun

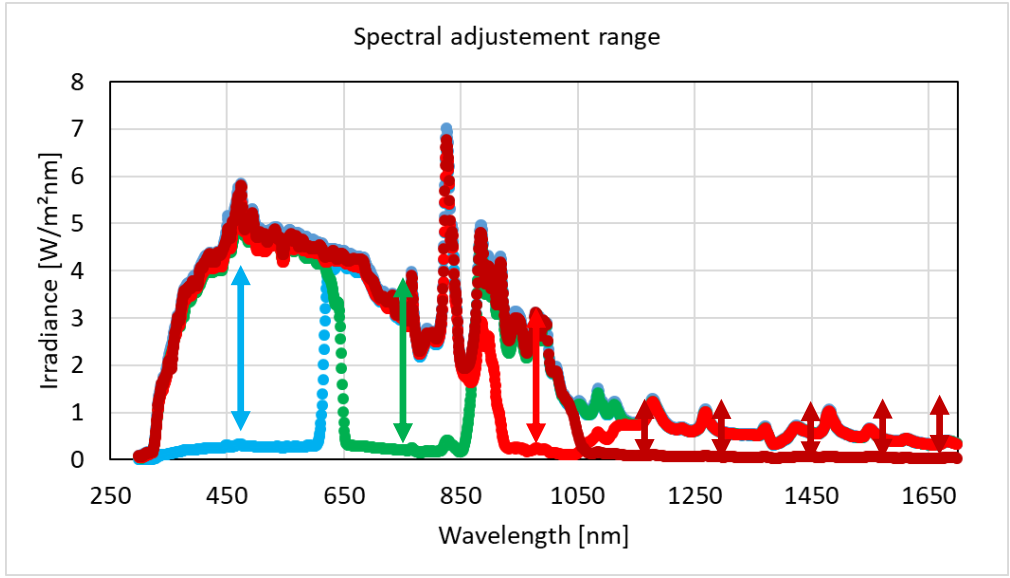
- Continous Xenon light source
- High collimation
- Adjustable spectrum
- Suitable for terestrial and space applications

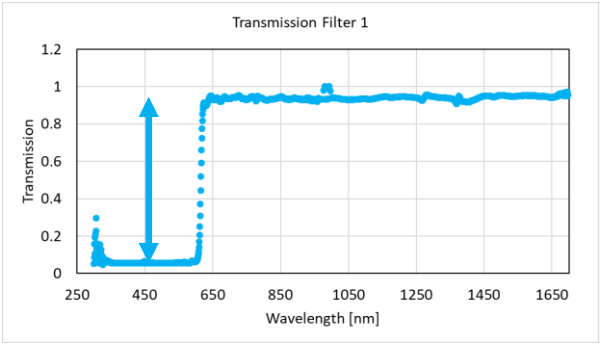
Standalone Lightsource

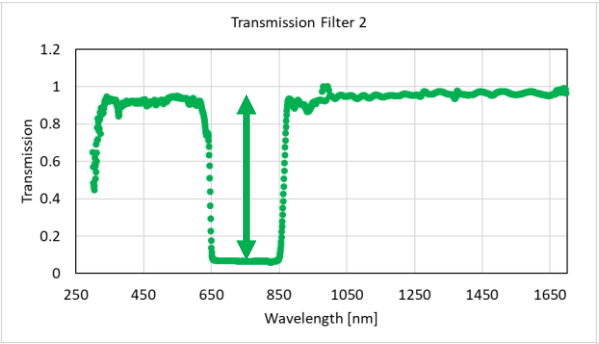
Integrated IV System

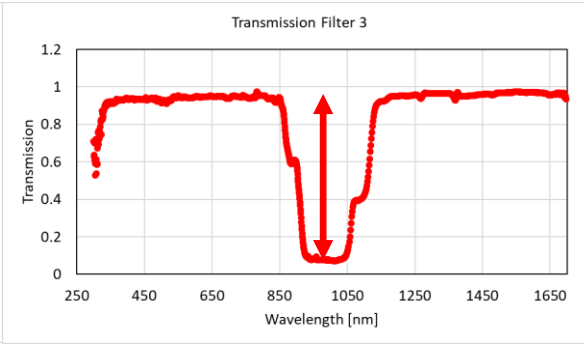
Spectral adjustement

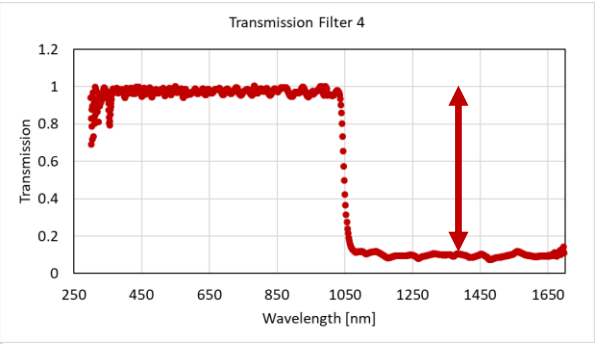
- Example with 4 filters – up to 10 filters possible
- Adjust each spectral band individually
- Perfect match of up to 4 junctions with their AM0 short circuit current is achieved



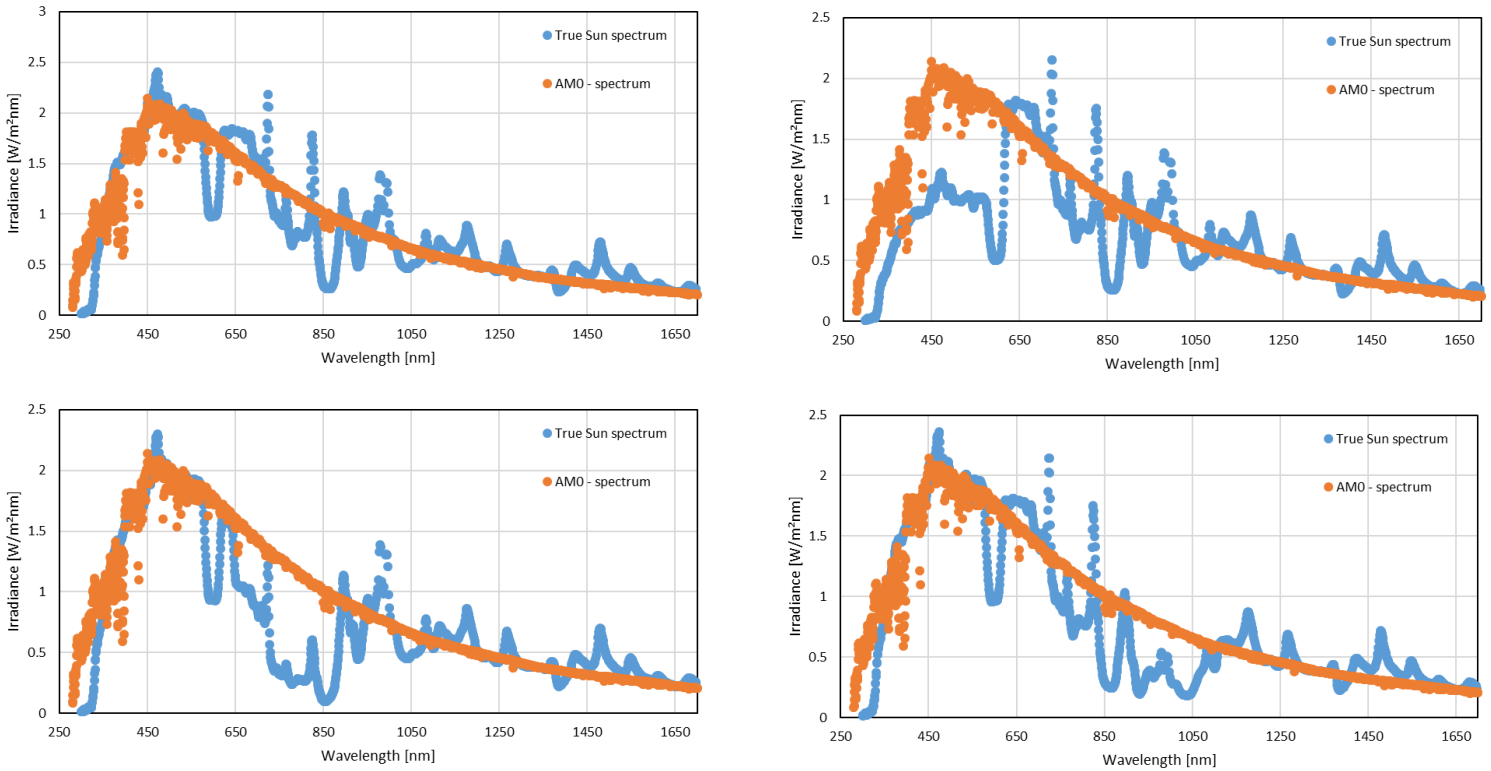




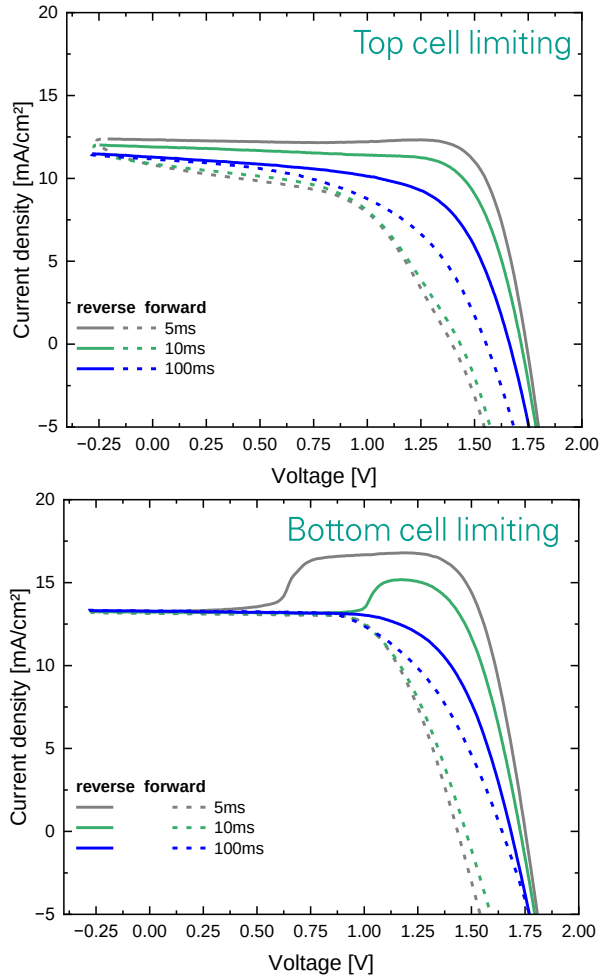




Spectral tuning – versatile tool to assess individual junction properties of multi-junction solar cells



Different spectra usable to limit different junctions of a multi-junction solar cell

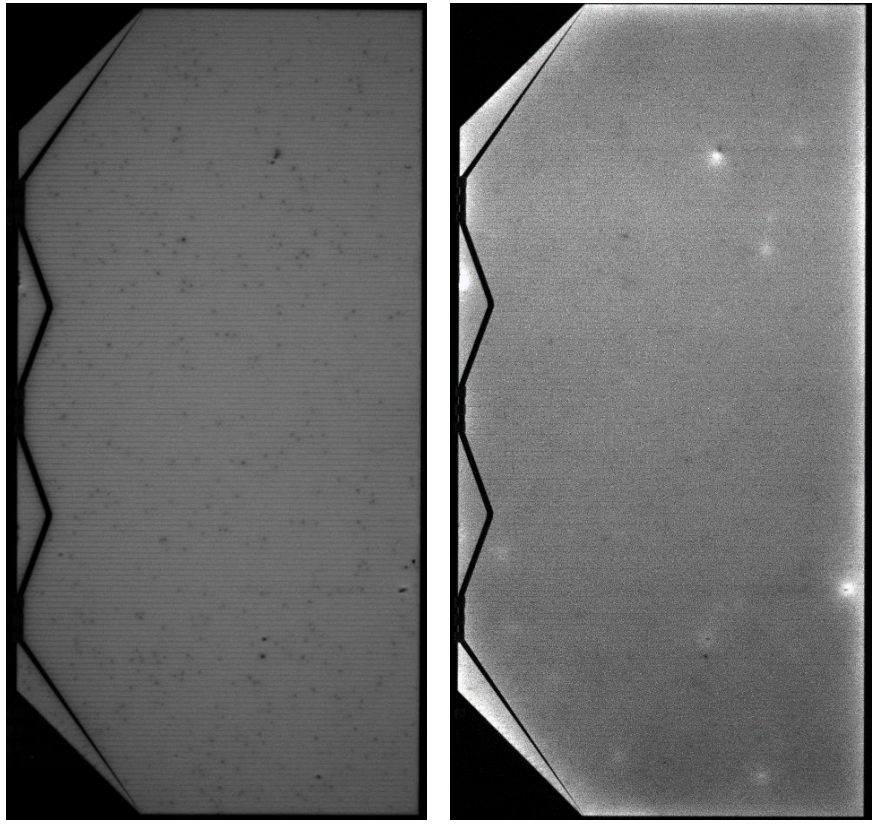


IV-curves of a dual junction cell recorded with different spectral limitation

EL & PL - Advanced quality assurance

Integrated Electroluminescence (EL) & Photoluminescence (PL) imaging

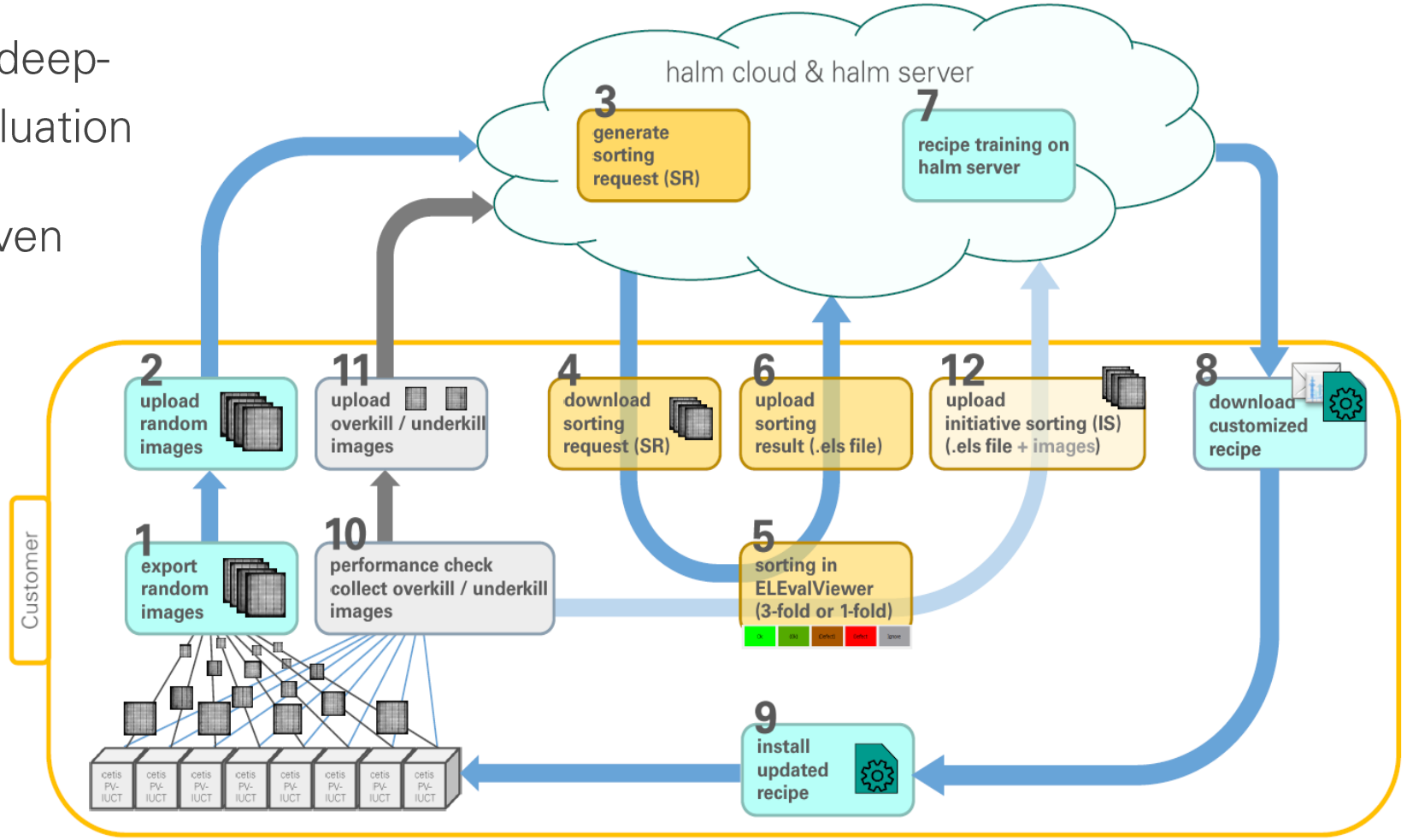
- **See the invisible:** Detect micro-cracks, shunts, material impurities and many other defect types.
- **Prevent field failures:** Screen out defective cells before they are integrated into expensive arrays.
- **Fully traceable:** Link every IV curve to a high-resolution quality image.



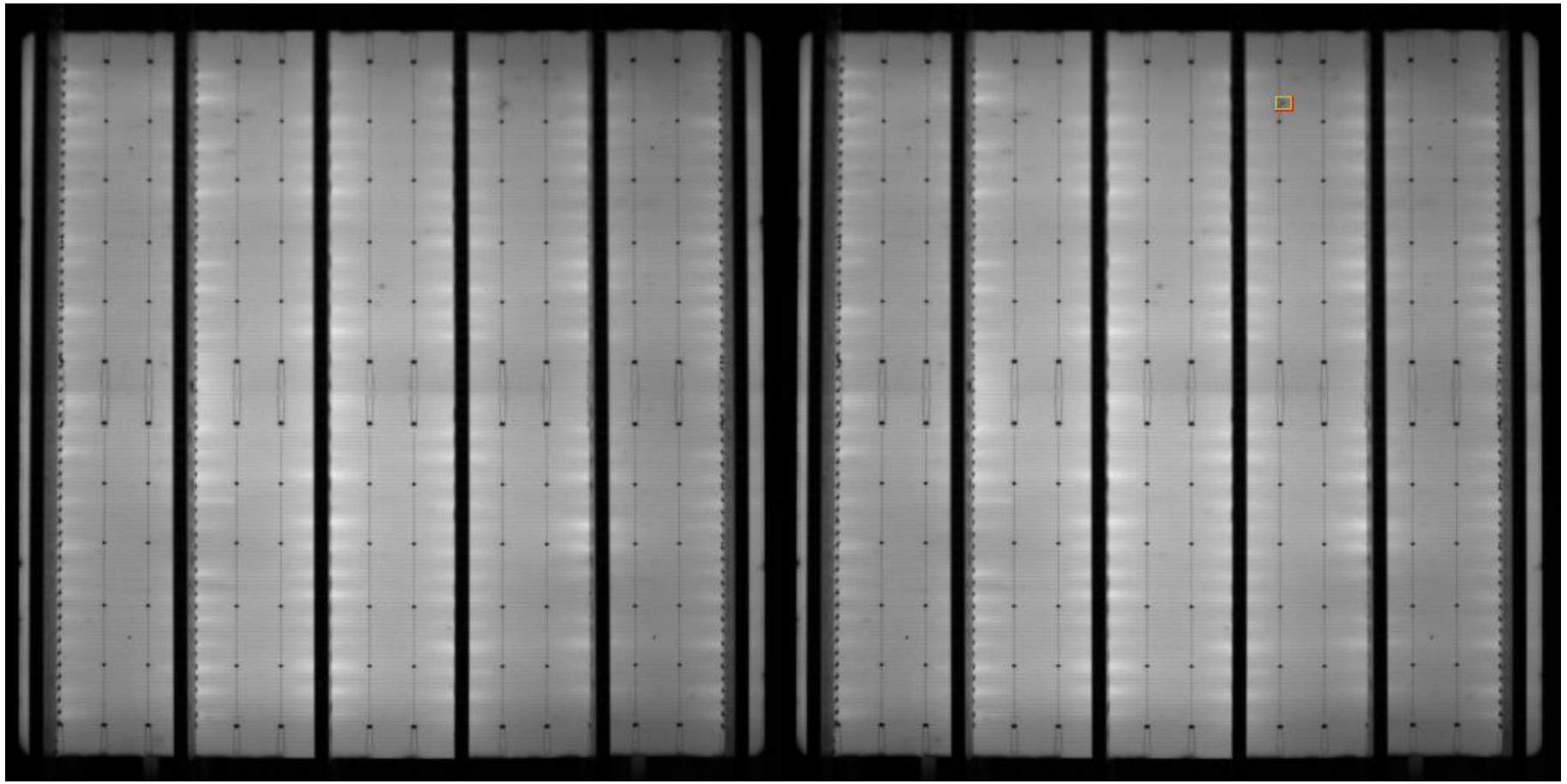
PL EL

Luminescence – Deep learning evaluation

- Fully in-house developed deep-learning based image evaluation
- Automated, customer driven process flow for network generation
- Highest availability and shortest response time due to full automization

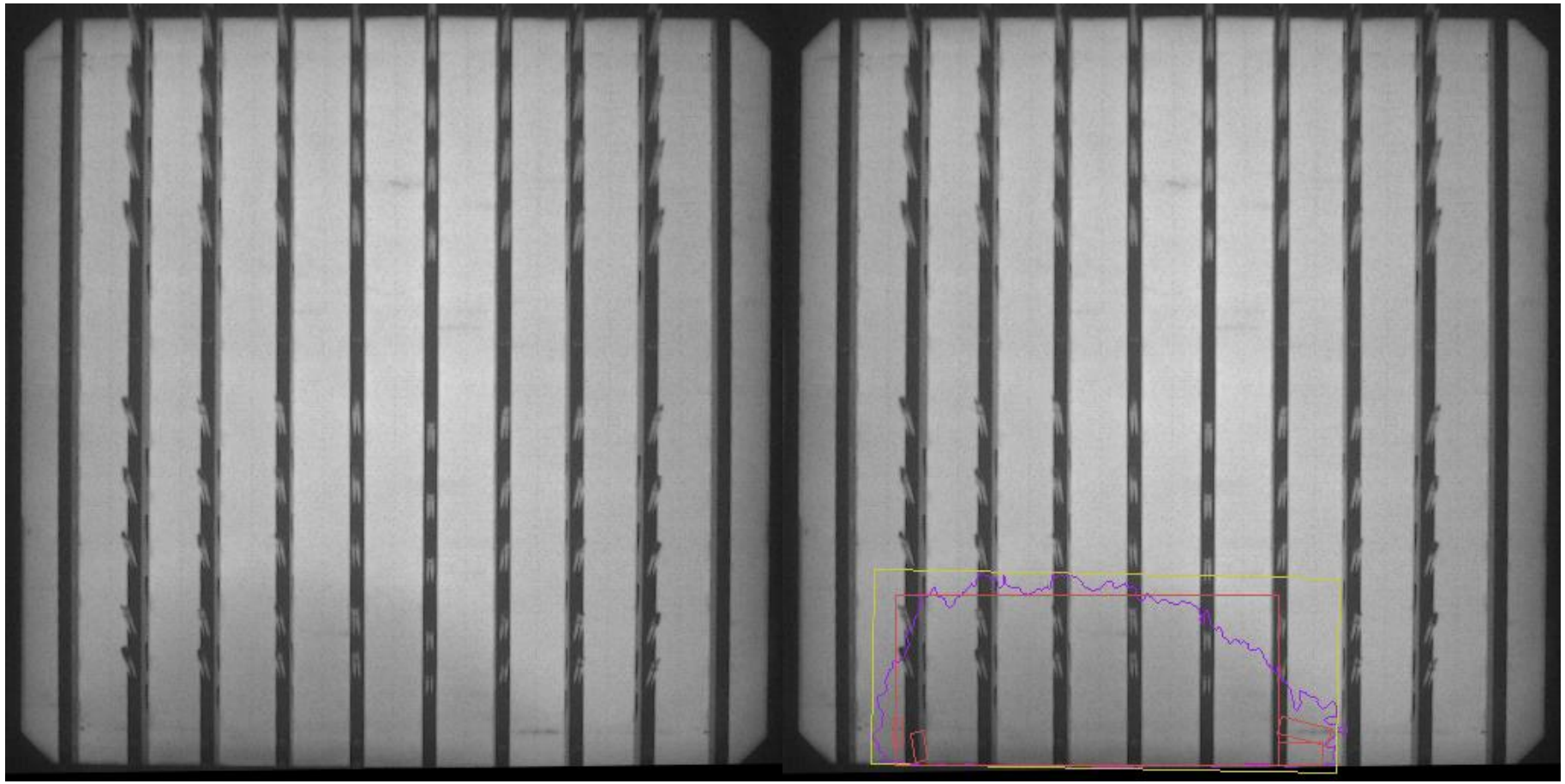


AI Example images



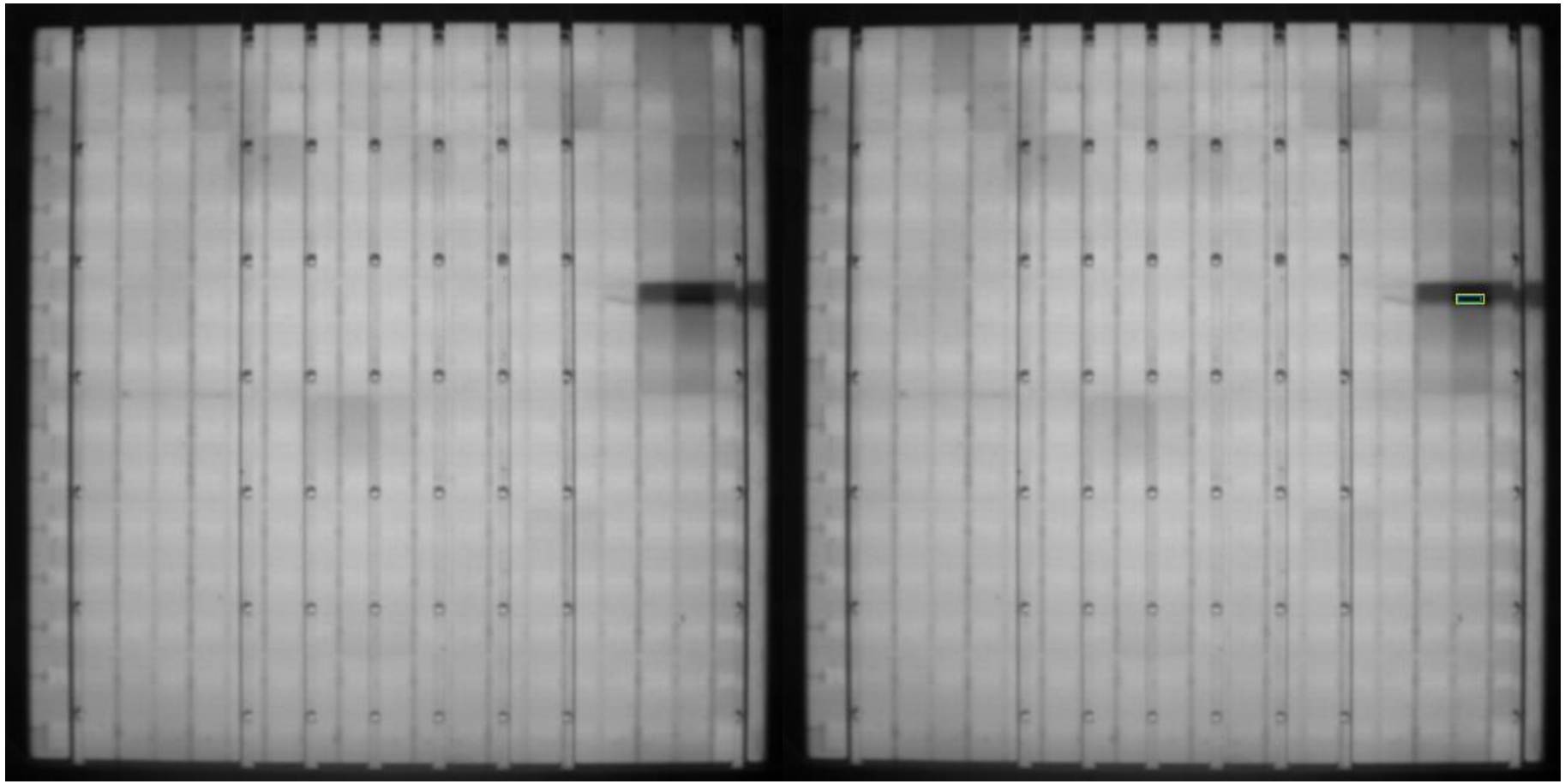
Light Cross Crack

AI Example images



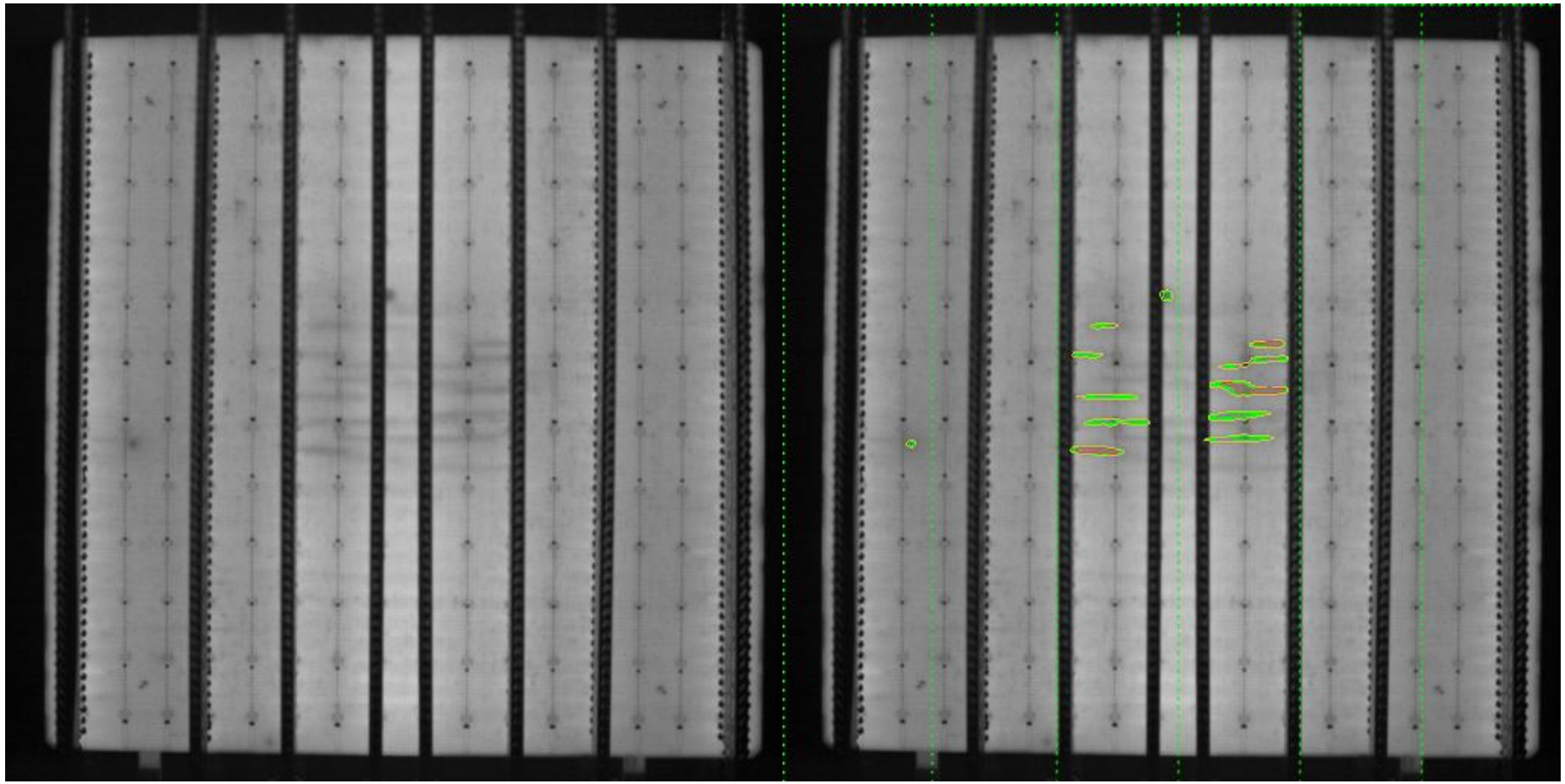
Light Dark area

AI Example images



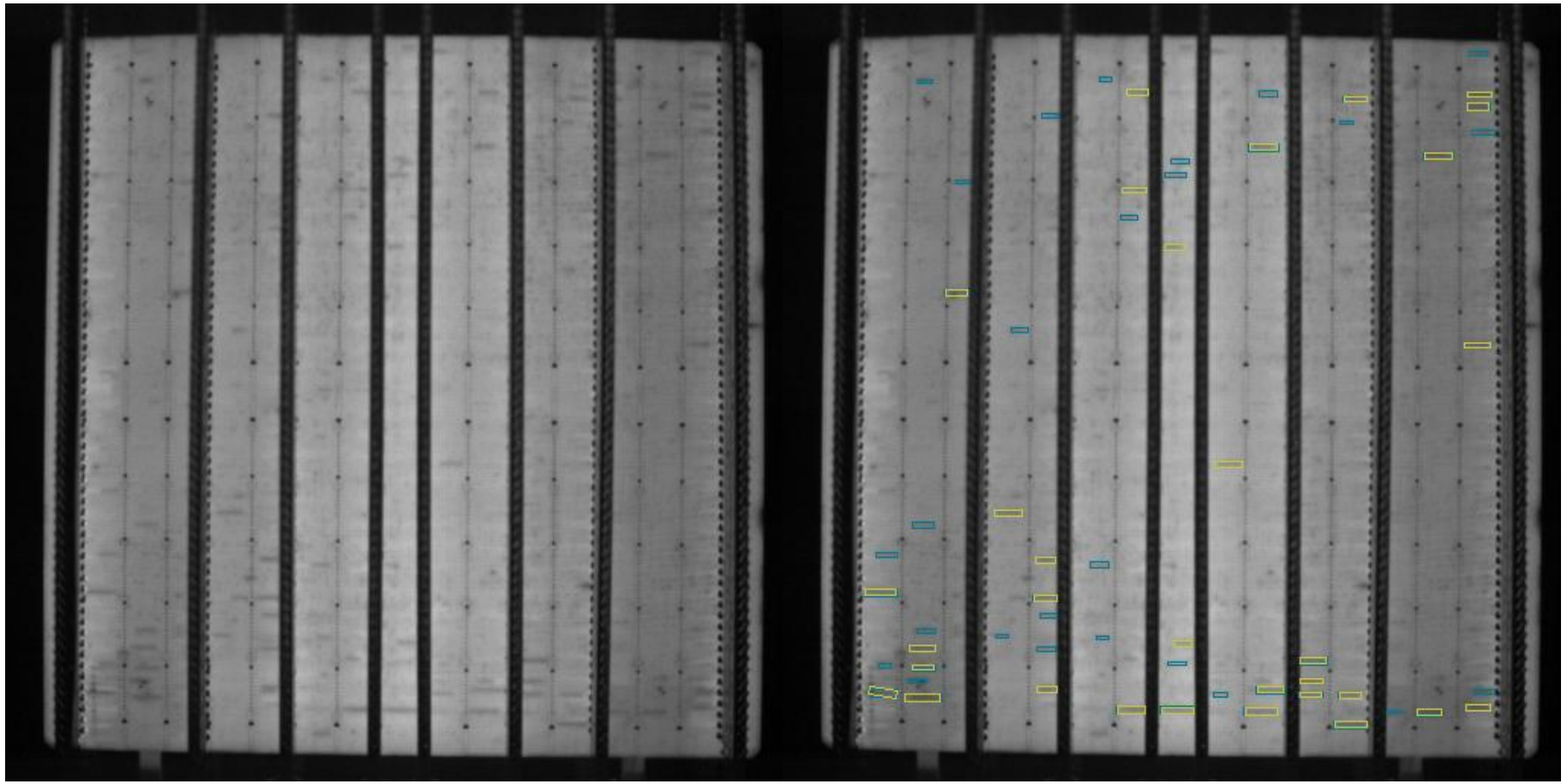
Shunt

AI Example images



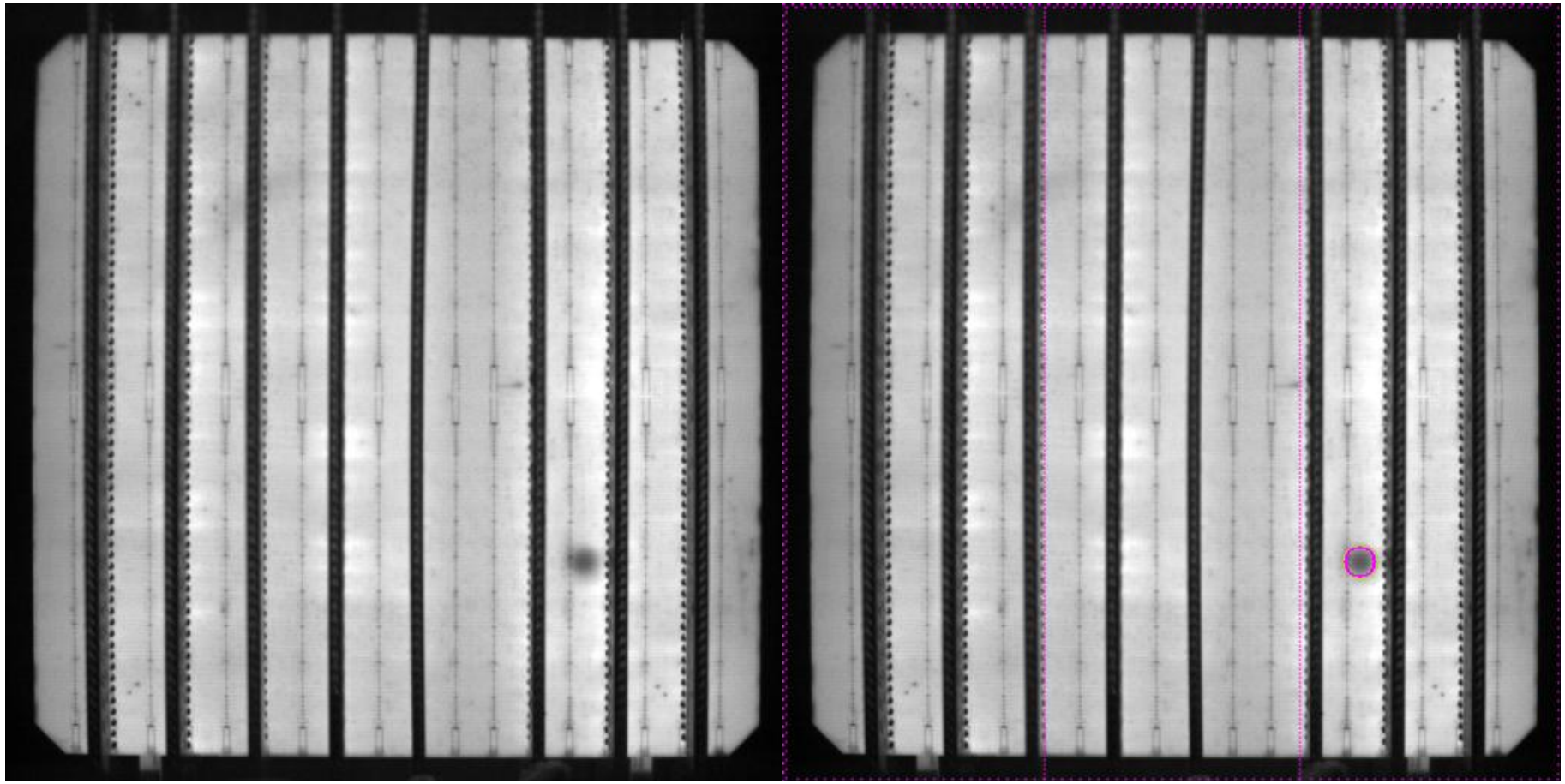
Dark area

AI Example images



Grid finger interruptions

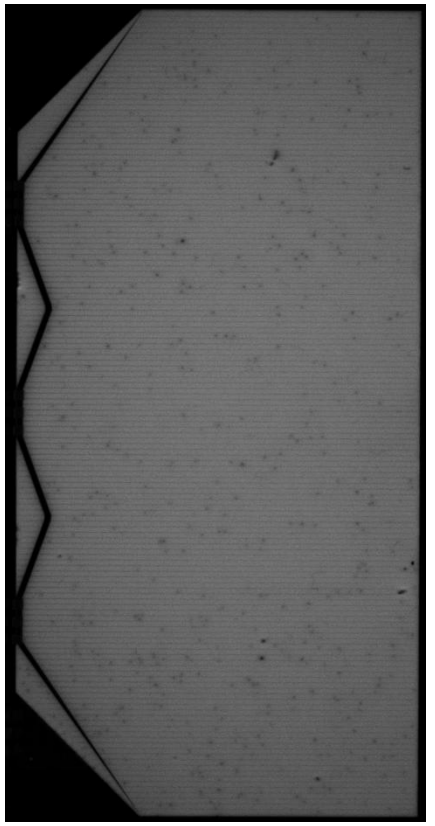
AI Example images



Spot defect

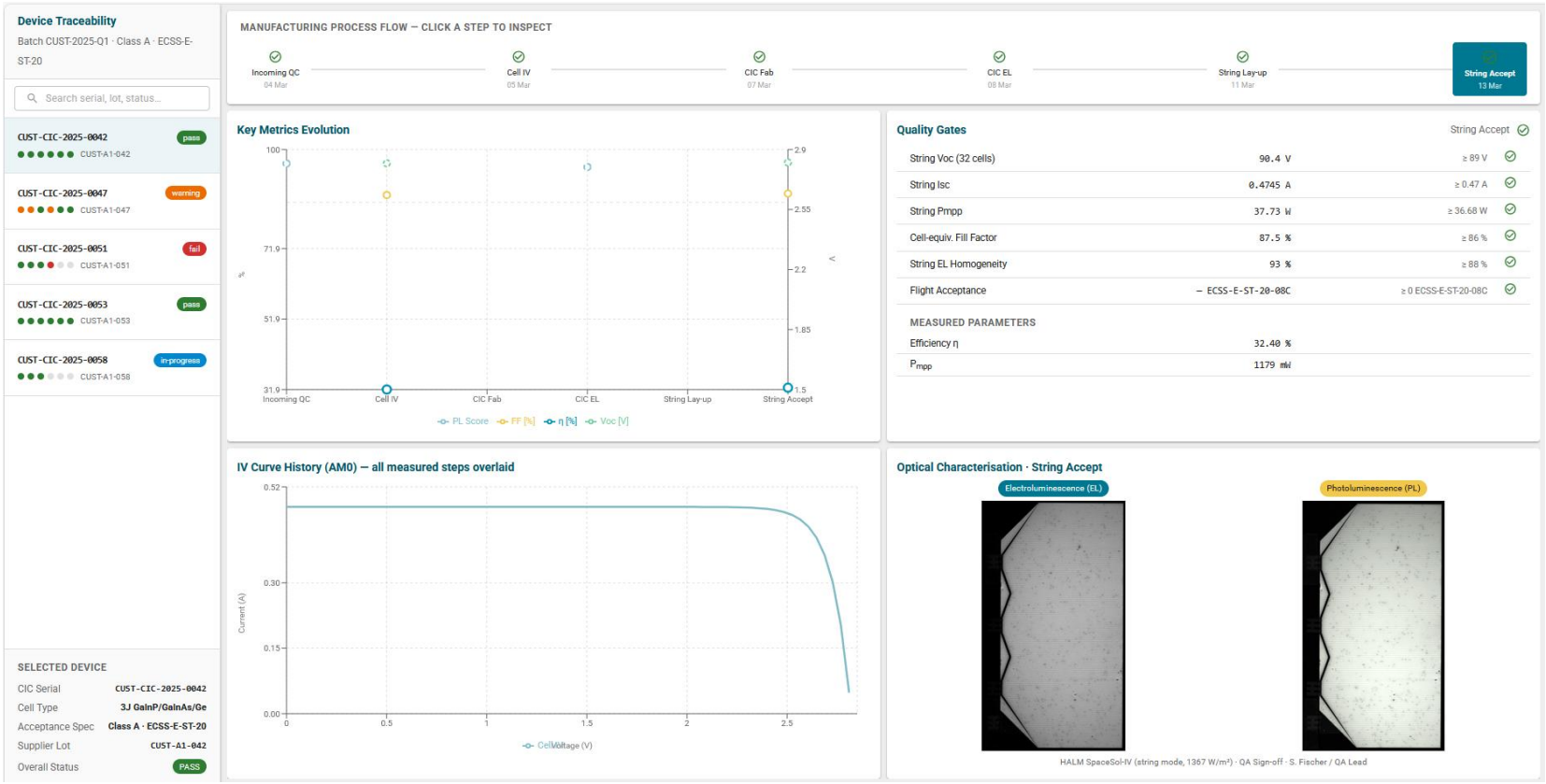
Tracking quality – from cell to wing

- Point defects in EL/PL imaging can be used as fingerprint of cells – AI can easily identify the cells through downstream manufacturing
- Remeasure what is required – after one thorough inspection e.g. at cell level, intermediate steps could be monitored by a rather simple PL or EL imaging system eventually including a dark-IV
  - Check if changes are observable in comparison with cell characterization before
- Module inspection and final inspection „in-wing“ to make sure all cells are fully functional and not prone to degradation



PVExplore – Product Tracking

- Exemplary view on a product tracking software tool
- The tool collects data from different manufacturing steps and displays it
- Different data comparisons are possible and can be customized



Conclusion

- Automation is a key enabler for throughput and a standardized continuous process quality
- Data acquisition and exploitation of data can guarantee product quality and optimize yield and power output
- EL/PL and IV curves recorded under different conditions allow for a deeper device characterization and are recommended to assign defects to junctions and processes

