Task 13 - Workshop on the Characterisation of PV Systems
ISFH, Hamelin (Germany), October 23rd 2025

Advances needed in PV plants inspections
(to reduce O&M costs)

speaker:
Ioannis (John) Tsanakas

Photo credits :
© **AePVI GmbH**

CACTUS SUPERNOVA

Why PV inspections matter (and will matter more)

- PV capacity is scaling fast and diversifying
- Diverse new applications (bifacial, xyz-PV, trackers) = diverse failure modes & conditions
- Monitoring data alone can’t “see” component-level fault
- Small cell/module faults can cascade to string losses — Early detection = Prevention
- Inspections provide spatial and physical context
- Labour-driven O&M costs dominate many portfolios; reducing truck-rolls and improving triage gives direct ROI.

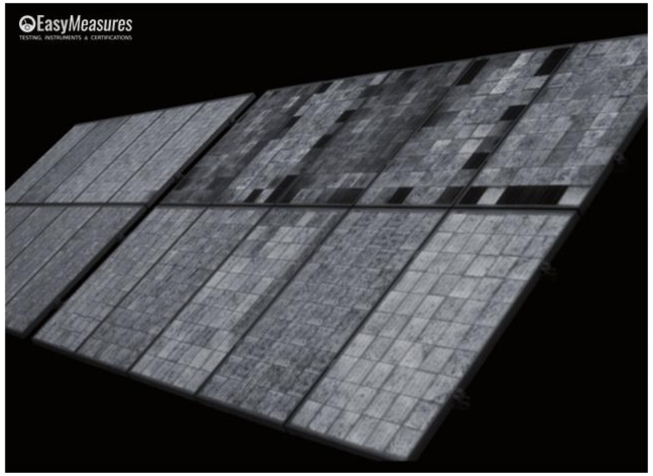
Combining SOTA monitoring + targeted inspections gives the **lowest-cost O&M strategy**: data tells you *when* & *where (?)* to look, inspections tell you ***what’s wrong*** and ***where***.

Taxonomy (in a nutshell)

Drone thermal (IR)

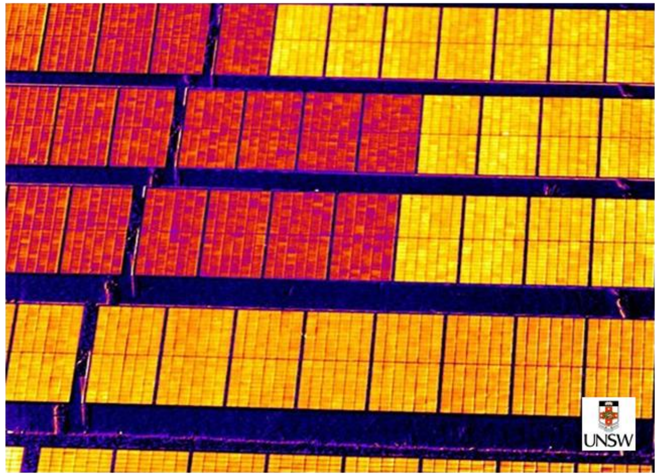
- Rapid fleet-level thermal mapping.
- Finds hotspots, connection/DC faults, PID.

Electroluminescence (EL)



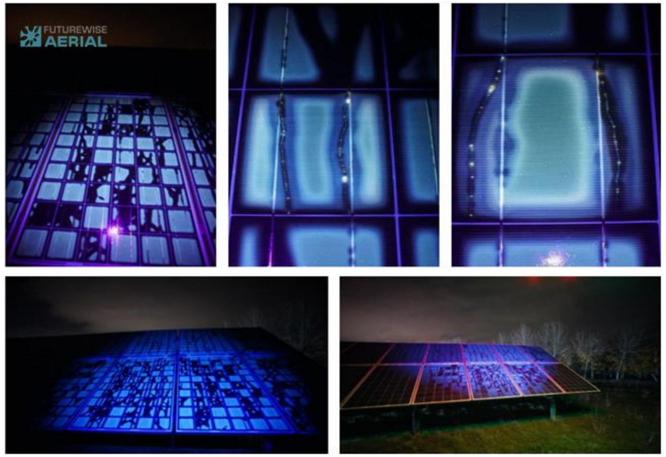
- Cell-level defects: microcracks, solder issues.
- Traditionally night/back-powered.

Photoluminescence (PL)



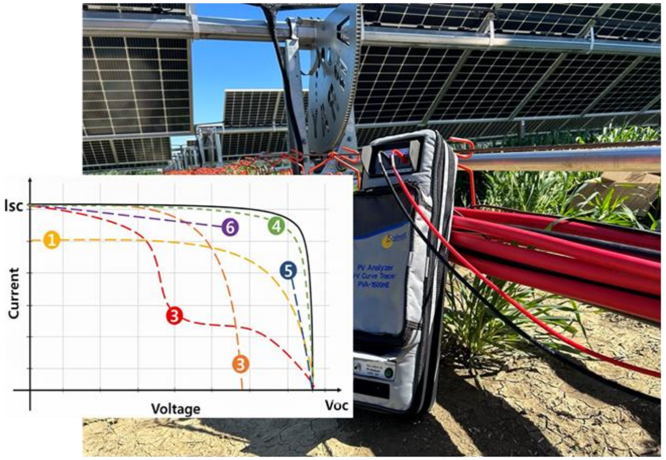
- Cell-level defects.
- Similar to EL but fieldable daytime methods emerging.

UV Fluorescence (UVFL)



- Degraded encapsulants, moisture ingress.
- BOM inconsistencies

IV tracing



- PV output losses at string/module level.
- Ground-truthing → IV patterns

High-res. RGB / Visual

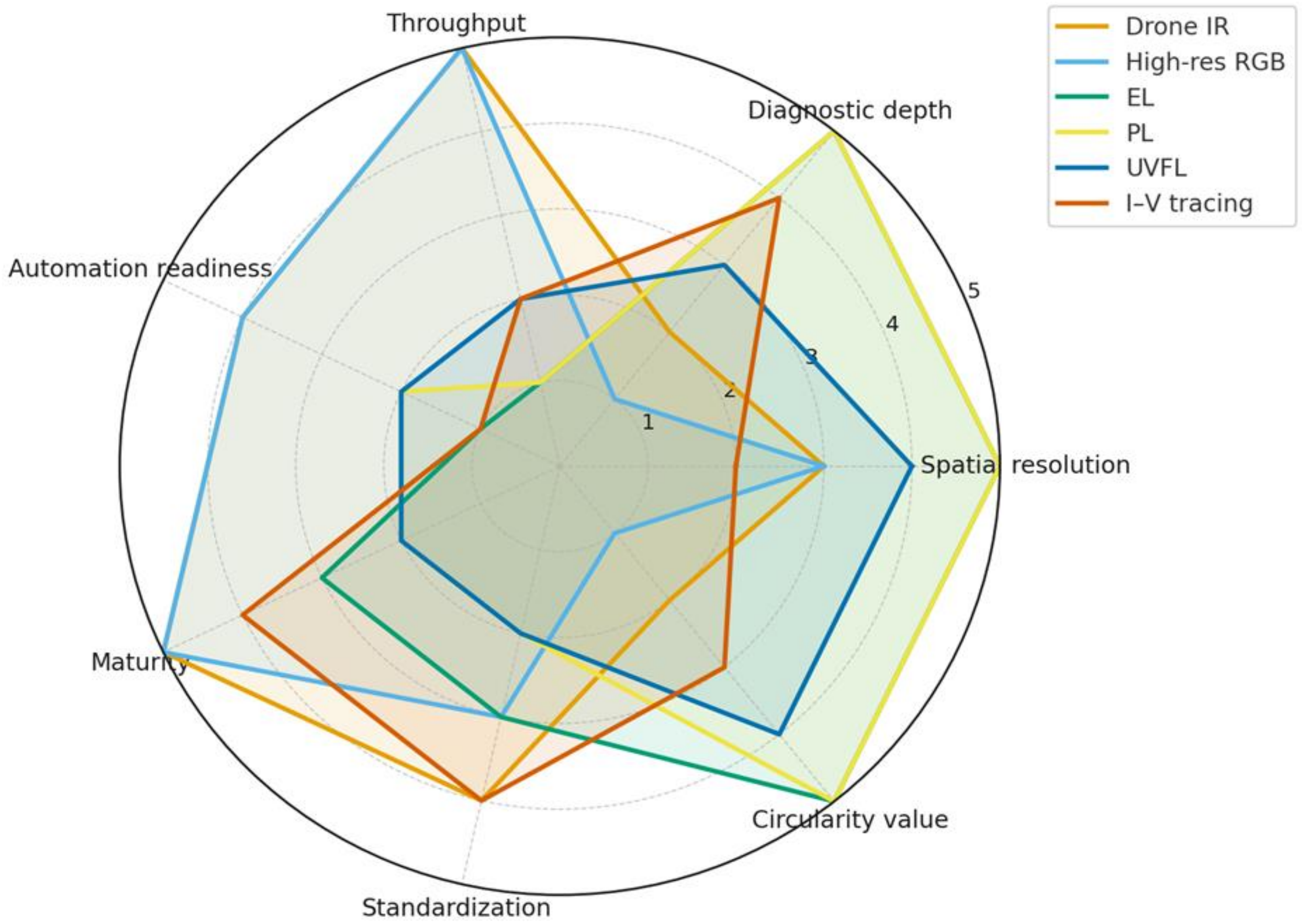
- Ground-truthing of (visible) faults, incl. mechanical/physical damage.
- Tell soiling/shading vs "real" faults.

How inspection resources add up

Inspection method	Typical cost (€ / MW inspected)	Time effort (h / MW)	Instrumentation / Main equipment CAPEX (typical)	Typical deliverable
Drone IR imaging	**€450 – 650**	0.4 – 0.8	Radiometric thermal camera + drone €6k – 17k	Thermal orthomosaic, hotspot classification, string-level fault map Preliminary reuse triage
Drone high-res RGB (visual) imaging	**€250 – 400**	0.3 – 0.6	Drone with high-res RGB camera €3k – 12k	Visual orthophoto, soiling/shading, vegetation/mounting anomalies
Field EL / PL imaging	**€1 500 – 2 500**	2 – 4	Fieldable EL/PL setup (camera, excitation) €25k – 40k	Cell-level defects (slow, higher cost) Advanced reuse triage
UVFL imaging	**€700 – 1 200**	> 4 *	UV source + camera(s) €4k – 13k	Component-level aging and inconsistencies, moisture paths
Field I–V tracing / sampling	**€900 – 1 400**	> 4 *	IV tracer + load bank €3k – 15k	Quantitative power loss per module/string
Manual / visual (truck-roll)	**€400 – 800 / visit**	> 4 *	Vehicle(s) + labor + tools	On-site validation, visual inspection, fixes (where applicable)

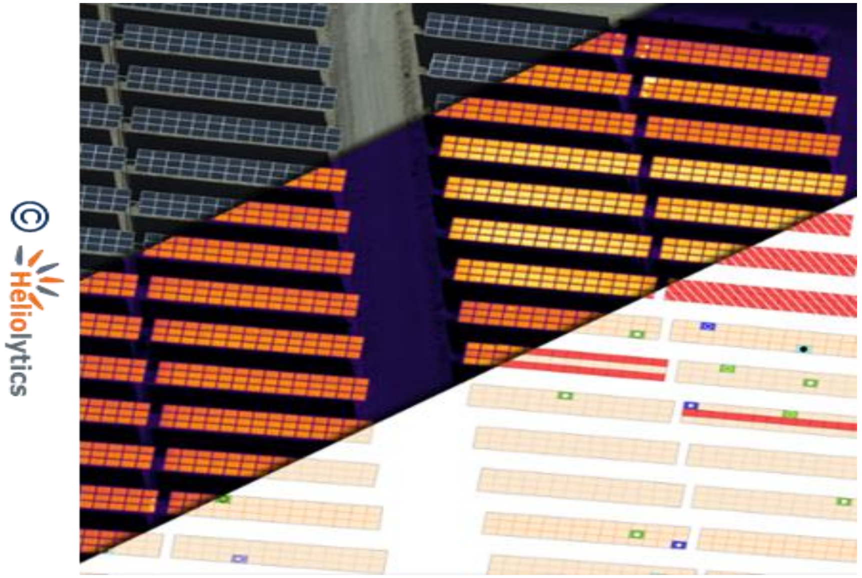
* variable, depending on sample

Comparative landscape

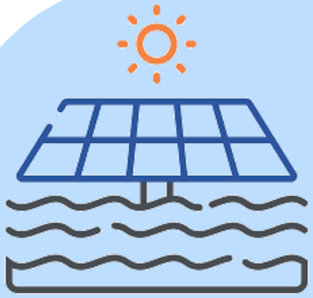


Bottlenecks: Data, AI and workflows

- ML models are limited by small / biased datasets, inconsistent labels and sensor domain shifts.
- Operators need explainable predictions and uncertainty (confidence) not only binary flags.
- Multimodal fusion (IR + RGB + EL + I-V + metadata) is powerful but still immature in production.

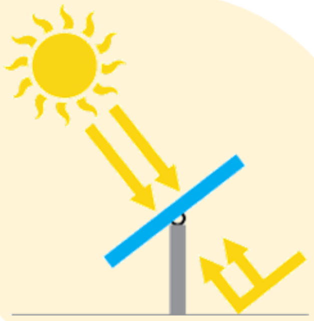


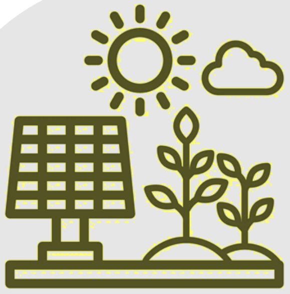
Inspection challenges in new PV applications



- Access & corrosion issues; mooring/floaters : new inspection targets.
- Very high dependence on remote sensing needs and multi-/inter-disciplinary experts.

- Rear-side variability and access
- Dynamic thermal signatures complicate automatic detection.
- Field experience feedback : TS/standardization needs update





- Access & occlusions (plants, rooftop obstacles)
- Safety constraints / dependence on experts.
- New microclimatic stressors = new fault signatures?

Floating PV   Bifacial/tracking PV   AgriPV and BIPV/BAPV

Inspection challenges in new PV applications

Inspections supporting circular economy for PV

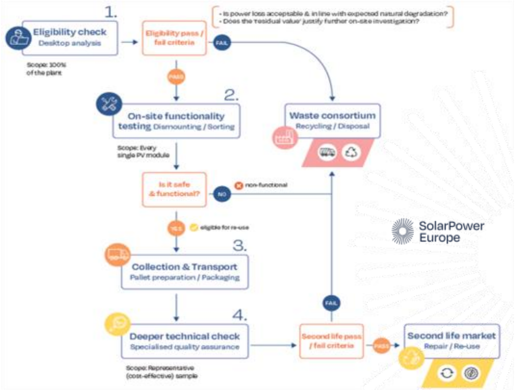
- Diagnostics-enabled triage: IV+automated IR-PL/EL/UVFL classify modules for reuse, repair, or recycling on-site.

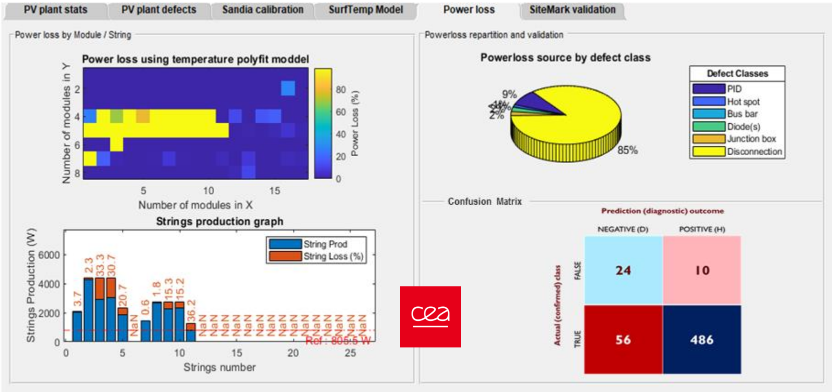
⇨ ***Reuse Readiness*** Score : ← repairability ; residual value; safety
⇨ digital ***Product Passport*** : each module carries its inspection record

trusted 2nd-life certification

- Link with SRIA vision & KPIs (2035):

≥ 50 % of decommissioned modules reused / repaired
≥ 10 years second-life operation
Full traceability via interoperable inspection data standards





AI Agents — Transforming Inspections and O&M

Today:
AI already automates image-based diagnostics (IR, EL, PL), achieving ~80-90 % fault classification accuracy and accelerating inspection analytics.

Next Step:

- AI agents evolve from classification to autonomous action — linking monitoring, inspection, and maintenance scheduling into a single, adaptive workflow.
- Conversational assistants interpret inspection data ("String 12B shows likely PID — 8 % loss, replace 3 modules") and enable explainable, data-driven O&M.

Vision 2035:
"Self-aware" PV plants where digital twins and AI continuously diagnose, plan, and dispatch maintenance robots — meeting SRIA targets of

- ≥ 95 % automated fault accuracy
- Autonomous inspection throughput ≥ 6 MW · h^{-1}
- CPN (O&M + soft costs) < €10 / kWp·yr

Concrete advances we need

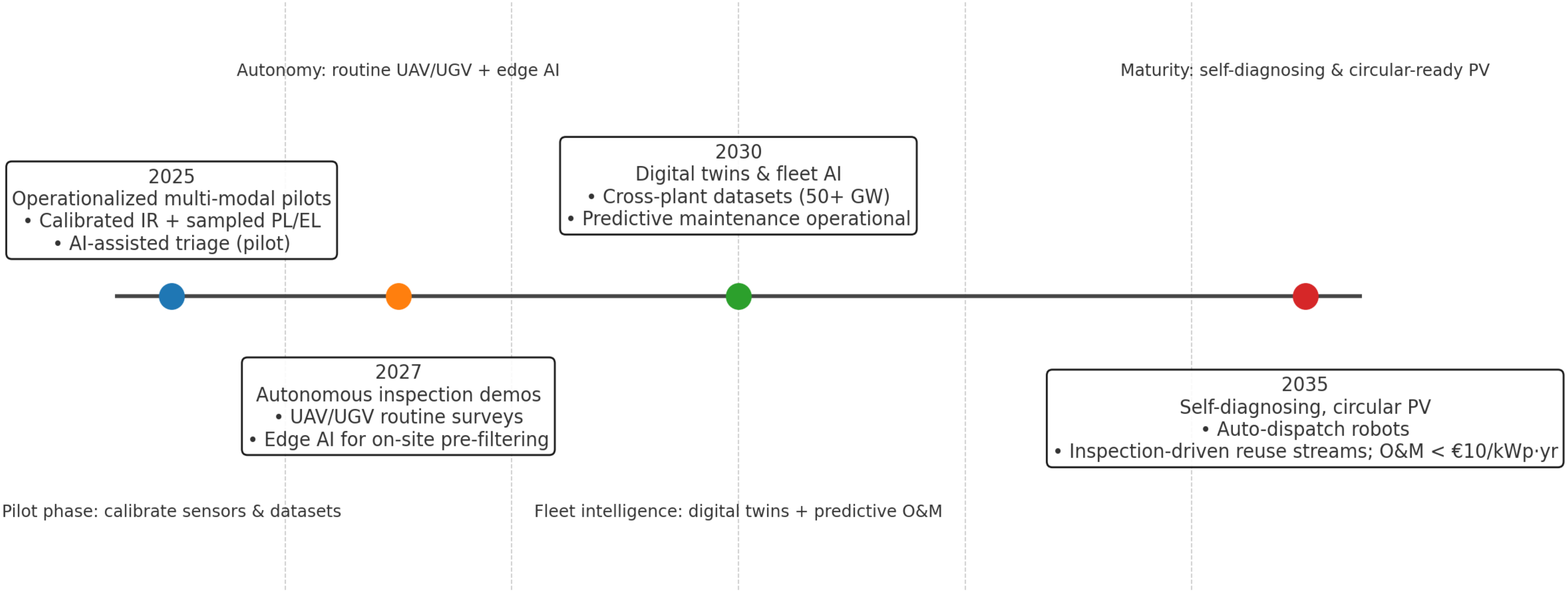
Need

1. Update IR normative (TS) framework
2. Faster, field-ready PL/EL workflows
3. Open, multimodal benchmark datasets
4. Explainable AI with uncertainty scoring
5. Standards for field EL/PL/UV & reuse scoring
6. Autonomous inspection platforms (esp. for FPV, rooftops, harsh sites)

Impact

1. Address faults in emerging PV technologies and applications
2. Cell-level insights without prohibitive cost or downtime.
3. Robust ML models and cross-vendor comparability.
4. Auditable, prioritized maintenance actions.
5. Build market trust and enable second-life trade.
6. Safer, repeatable operations.

Roadmap towards 2035



Example RDI and pilots/demos pipeline

- 0–12 months
  - Evolve and re-engineer models/software prototypes;
  - Build open multimodal datasets (anonymized).

- 1-3 years:
  - Run of 2 pilots to pair IR+RGB+PL with targeted I–V verification;
  - Deploy field multispectral imaging demos and digital twins;
  - Integrate explainable AI into workflows, incl. PV reuse triage.

- 3–5 years:
  - Upscale fieldable “complete” inspection platforms;
  - Mature reuse-scoring standards;
  - Scalable autonomous inspectors.

SUPERNOVA

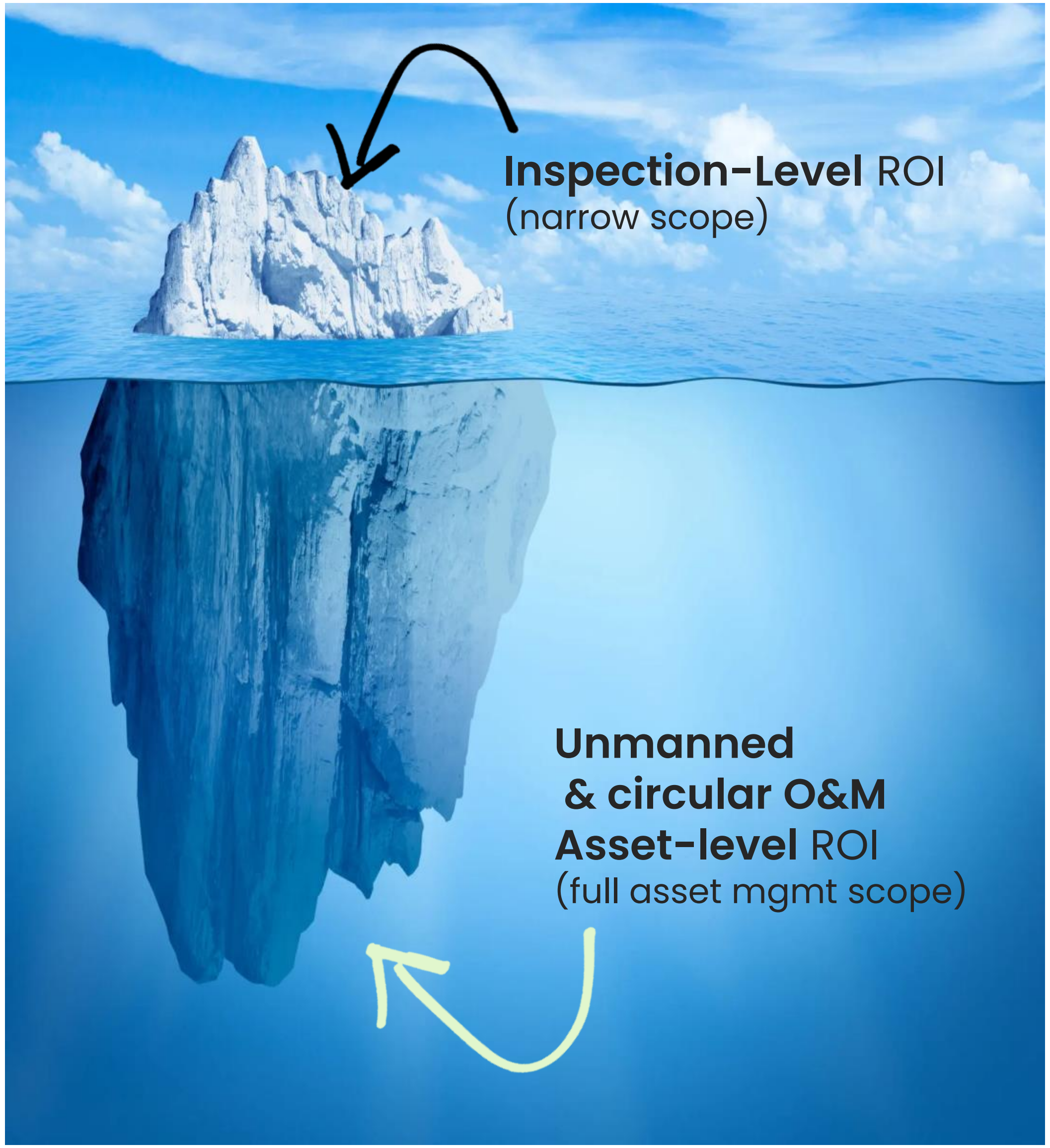
Financial impact of improved inspections: **reality check**

Parameter	**Symbol / Unit**	**Typical / Example**	**Notes**
PV plant size	P_n	100 MWp	utility-scale
Annual O&M baseline cost	C_0	€ 8 / kWp·yr → € 800 k / yr	Europe-specific
Baseline inspection type	—	Manual + handheld IR	legacy practice
Improved inspection	—	Drone IR + sample PL + AI analytics	advanced pilot
Baseline truck-roll rate	R_0	0.6 / MW·yr	~60 visits / yr total
Avg. truck-roll cost	C_t	€ 700 / visit	labour, travel, admin
Energy loss per undetected fault	L_0	0.3 % / yr	typical undetected degradation
Energy price	P_e	€ 60 / MWh	wholesale average (Europe-specific)
Inspection cost – baseline	C_{i0}	€ 350 / MW	manual + IR
Inspection cost – new	C_{i1}	€ 550 / MW	drone + AI proc.
Fault detection improvement	Δf	+45 %	faster + more precise
Avoided truck-roll rate	ΔR	40 %	via targeted interventions

Metric	**Formula / Definition**	**Example (100 MW)**	**Comment**
Baseline O&M cost	$C_0 \times P_n$	€ 800 000 / yr	reference value
Baseline truck-roll cost	$R_0 \times P_n \times C_t$	€ 42 000 / yr	current reactive maintenance
Baseline energy loss	$L_0 \times (1\,600\ \text{MWh/MW}) \times P_e$	€ 28 800 / yr	undetected yield loss
New inspection cost	$C_{i1} \times P_n$	€ 55 000 / yr	
Avoided truck-roll savings	$\Delta R \times R_0 \times P_n \times C_t$	€ 16 800 / yr	
Recovered energy value	$\Delta f \times L_0 \times \text{yield} \times P_e$	€ 12 960 / yr	
Total annual benefit	—	**€ 29 760 / yr**	
Extra inspection cost	$(C_{i1} - C_{i0}) \times P_n$	**€ 20 000 / yr**	
Net gain (1st year)	benefit - extra cost	**+€ 9 760 / yr**	modest positive ROI (~50 %)
Payback horizon	—	**< 2 years (with scaling)**	automation → -20 % cost/yr

Financial impact of improved inspections: **reality check**

Scope	What's Added Beyond Inspections	Typical Annual Savings (100 MW)	Mechanisms
Inspection Upgrade	Drone multi +AI vs. standard IR	**€ 10 k – € 30 k**	Fewer truck-rolls, faster fault detection
Predictive Maintenance Integration	Analytics + failure models + scheduling	**€ 250 k – € 500 k**	Reduced unplanned maintenance, optimized cleaning
Fully automated O&M Ecosystem	AI agents, digital twin, smart dispatch		+0.5–1.5 % yield, 15–30 % O&M reduction
Full Lifecycle Asset Mgmt.	Circularity, EoL triage, reuse logistics	**› € 500 k**	Improved asset lifetime value, lower replacement capex



Sources – References

- Seel, Joachim, et al. *U.S. Utility-Scale Solar: 2025 Data Update. Lawrence Berkeley National Laboratory, 2025, emp.lbl.gov/utility-scale-solar
- Abdulla, Hind, et al. "Photovoltaic Systems Operation and Maintenance: A Review and Future Directions." Renewable and Sustainable Energy Reviews, vol. 195, May 2024, p. 114342. https://doi.org/10.1016/j.rser.2024.114342
- M Vuković et al 2024 Prog. Energy 6 032001, DOI 10.1088/2516-1083/ad4250
- Aghaei, M., et al. "Autonomous Intelligent Monitoring of Photovoltaic Systems: An In-Depth Multidisciplinary Review." Progress in Photovoltaics: Research and Applications, vol. 33, no. 3, 2025, pp. 381-409. Wiley Online Library, https://doi.org/10.1002/pip.3789
- Enbar, Nadav, et al. Budgeting for Solar PV Plant Operations & Maintenance: Practices and Pricing. Electric Power Research Institute, 2015.
- Hermann, W., et al. *Qualification of Photovoltaic (PV) Power Plants using Mobile Test Equipment: Report IEA-PVPS T13-24:2021*. International Energy Agency Photovoltaic Power Systems Programme, 2021.
- H2020 SERENDI-PV, serendipv.eu/
- H2020 TRUST-PV, trust-pv.eu/
- © 2025 Raptor Maps. Global Solar Report: 2025 Edition, The State of PV Performance.
- Huawei. Global PV Trends: Report 2020. Huawei, June 2020, www.pv-magazine.com/wp-content/uploads/2020/06/HuaweiSE2020-web-1.pdf
- Koester, L., et al. "Review of Photovoltaic Module Degradation, Field Inspection Techniques and Techno-Economic Assessment." Renewable and Sustainable Energy Reviews, vol. 165, 2022, p. 112616. ScienceDirect, https://doi.org/10.1016/j.rser.2022.112616
- Lindig, Sascha, et al. "Towards the Development of an Optimized Decision Support System for the PV Industry: A Comprehensive Statistical and Economical Assessment of over 35,000 O&M Tickets." Progress in Photovoltaics: Research and Applications, vol. 31, no. 3, 2023, pp. 219-33. Wiley Online Library, https://doi.org/10.1002/pip.3637
- Oviedo Hernandez, G., et al. "Trends and Innovations in Photovoltaic Operations and Maintenance." Progress in Energy, vol. 4, no. 4, Oct. 2022, p. 042002. IOPscience, https://doi.org/10.1088/2516-1083/ac8f2b
- End-of-life Management: Best Practice Guidelines. SolarPower Europe, 2024.
- Operation & Maintenance Best Practice Guidelines. Version 6.0, SolarPower Europe, 2025.
- Tsanakas, I. A., et al. "Toward Reuse-Ready PV: A Perspective on Recent Advances, Practices, and Future Challenges." Advanced Energy and Sustainability Research, 2024, https://doi.org/10.1002/aesr.202400237
- Walker, Andy, et al. Model of Operation-and-Maintenance Costs for Photovoltaic Systems. National Renewable Energy Laboratory, 2020. NREL, www.nrel.gov/docs/fy20osti/74840.pdf
- Bommes, Lukas, et al. "Computer Vision Tool for Detection, Mapping, and Fault Classification of Photovoltaics Modules in Aerial IR Videos." Progress in Photovoltaics: Research and Applications, vol. 29, no. 10, 2021, pp. 1150-1161. Wiley Online Library, https://doi.org/10.1002/pip.3448
- Tsanakas, John A., et al. "Faults and Infrared Thermographic Diagnosis in Operating c-Si Photovoltaic Modules: A Review of Research and Future Challenges." Renewable and Sustainable Energy Reviews, vol. 62, Sept. 2016, pp. 695-709. https://doi.org/10.1016/j.rser.2016.04.079
- Tsanakas, John Ioannis A., and Philippe Marechal. "Decoding Pixels: A Modular Software Prototype for Cognitive Image-Based Diagnostics of PV Plants." EPJ Photovoltaics, vol. 16, 2025, p. 24, https://doi.org/10.1051/epjpv/2025013
- ETIP PV. (2024). Strategic research and innovation agenda 2.0: Towards a climate-neutral Europe by 2050. European Technology and Innovation Platform for Photovoltaics. https://etip-pv.eu/wp-content/uploads/2024/04/ETIP-PV_SRIA-2.0_Final.pdf
- IEC TS 62446-3 (2017)

WE INTERUPT THIS PROGRAM FOR A

COMMERCIAL BREAK

Buckle up – time to refresh your French!

SOPHIA

PV RELIABILITY WORKSHOP

April 23rd – 24th, 2026

INES – National Institute for Solar Energy

Le Bourget-du-Lac, France

More Information Coming Soon!

host: cea

Thank you

▪

Vielen dank

Ioannis Tsanakas
ioannis.tsanakas@cea.fr

CACTUS

This project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement No. 101132182.

SUPERNOVA

This project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement No. 101146883.