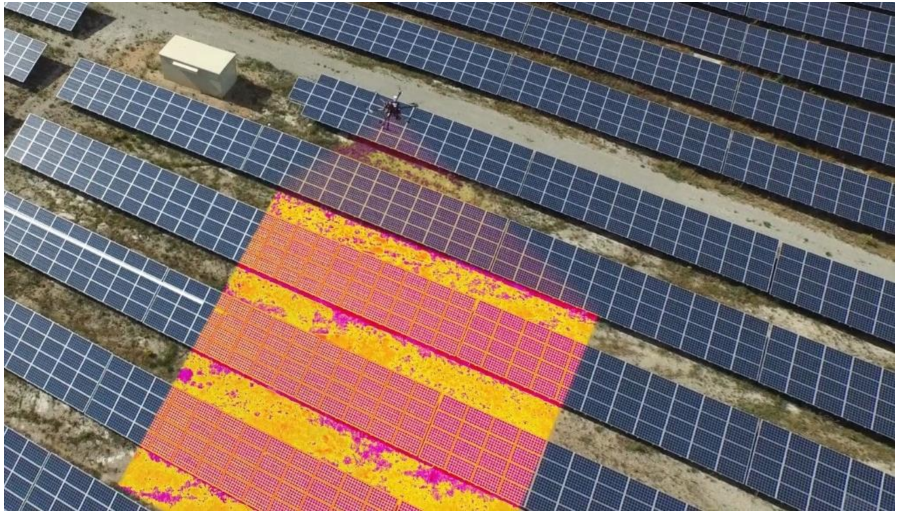
IEA PVPS Task 13

Focus Workshop on Operation & Maintenance

Fraunhofer ISE, Freiburg im Breisgau (Germany), September 30th 2021



Aerial Inspections and Diagnostics of PV Power Plants

Ioannis Tsanakas | R&D Project Manager CEA – INES

Rationale: A *cost* perspective

- PV O&M : major share of PV plants' OPEX; benchmark value as high as **8-15k €/MW per year**, for utility-scale PV [1,2]. Mostly: non optimized corrective and "per-schedule".

- A **cost reduction by 10-15%** (by e.g. limiting unnecessary O&M tasks, underperformance, failures/downtime,…) → annual **savings of ~2-3 million€ per year** (average portfolios of large PV plant developers).

1. Technical Report NREL/TP-5C00-74840, June 2020
2. Technical Report IEA-PVPS T13-08:2017, May 2017

Rationale: A *market* perspective

Focus expands: from development to **operations**

→ Need to *differentiate* through:

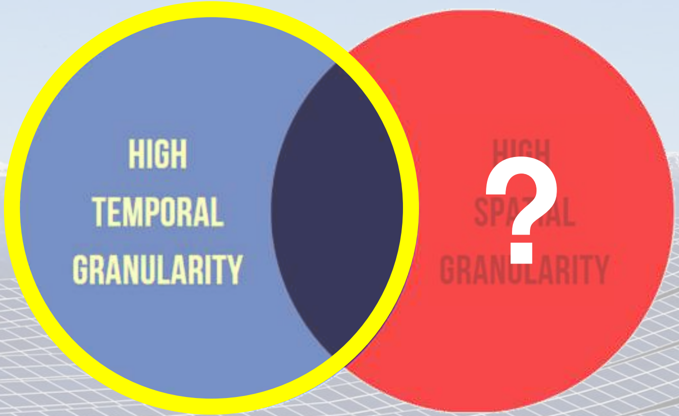
- operational performance of PV assets
- competitive costs of operations

} lean data-driven diagnostics

The <u>cornerstone:</u>

Advanced SCADA/monitoring software solutions, coupled with data analytics and diagnostics.

Monitoring-based Diagnostics

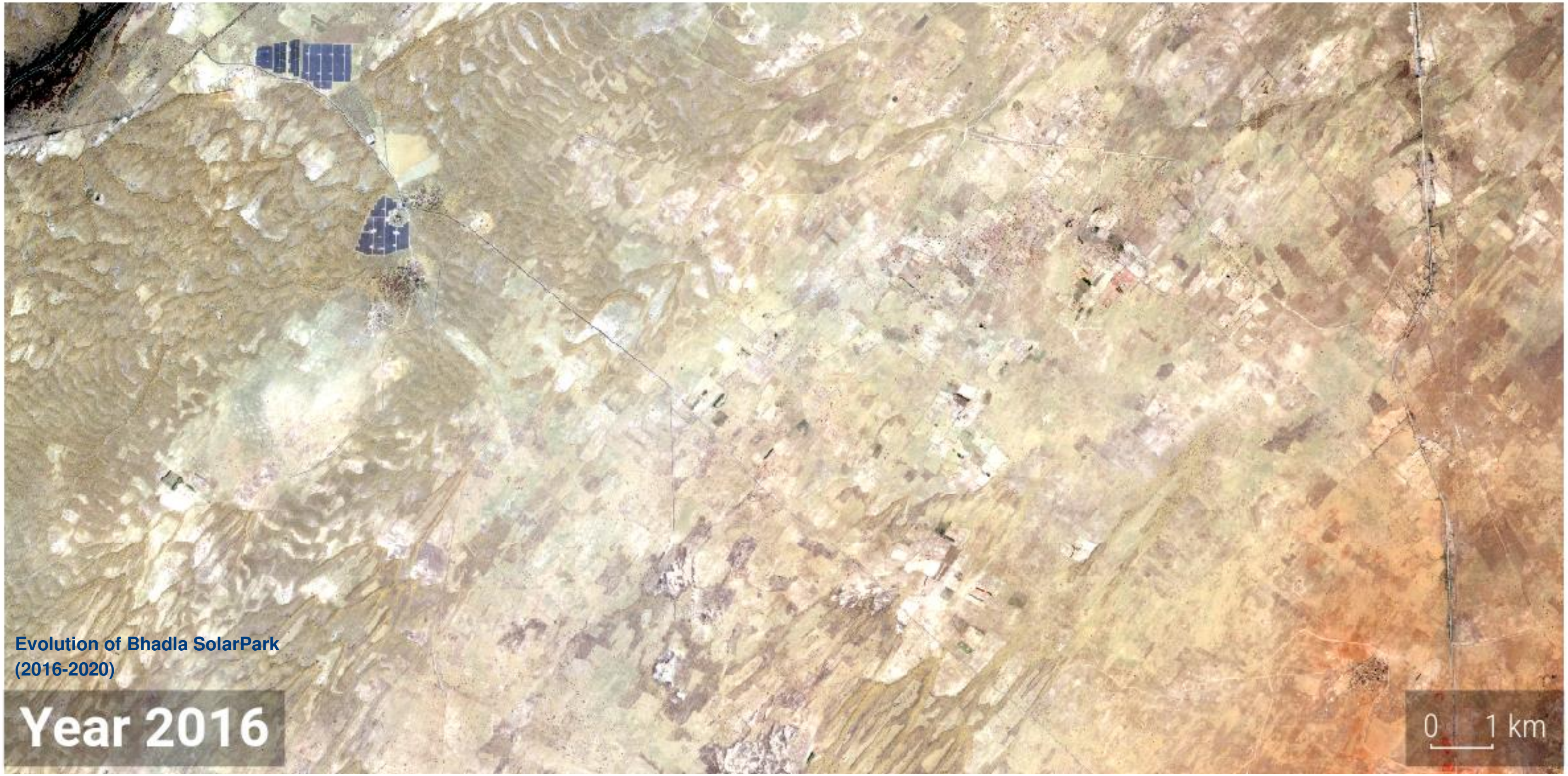


- *How?* Semi-automatic top-down approach, monitoring at real-time [1].
- *What? Where?* Drill-down from substations, inverters to strings and junction boxes [1].

Is it enough? **Size matters**

1. Solar Power Europe, O&M Best Practice Guidelines Version 4.0, 2020.

Rationale: A *size* perspective



Evolution of Bhadla SolarPark
(2016-2020)

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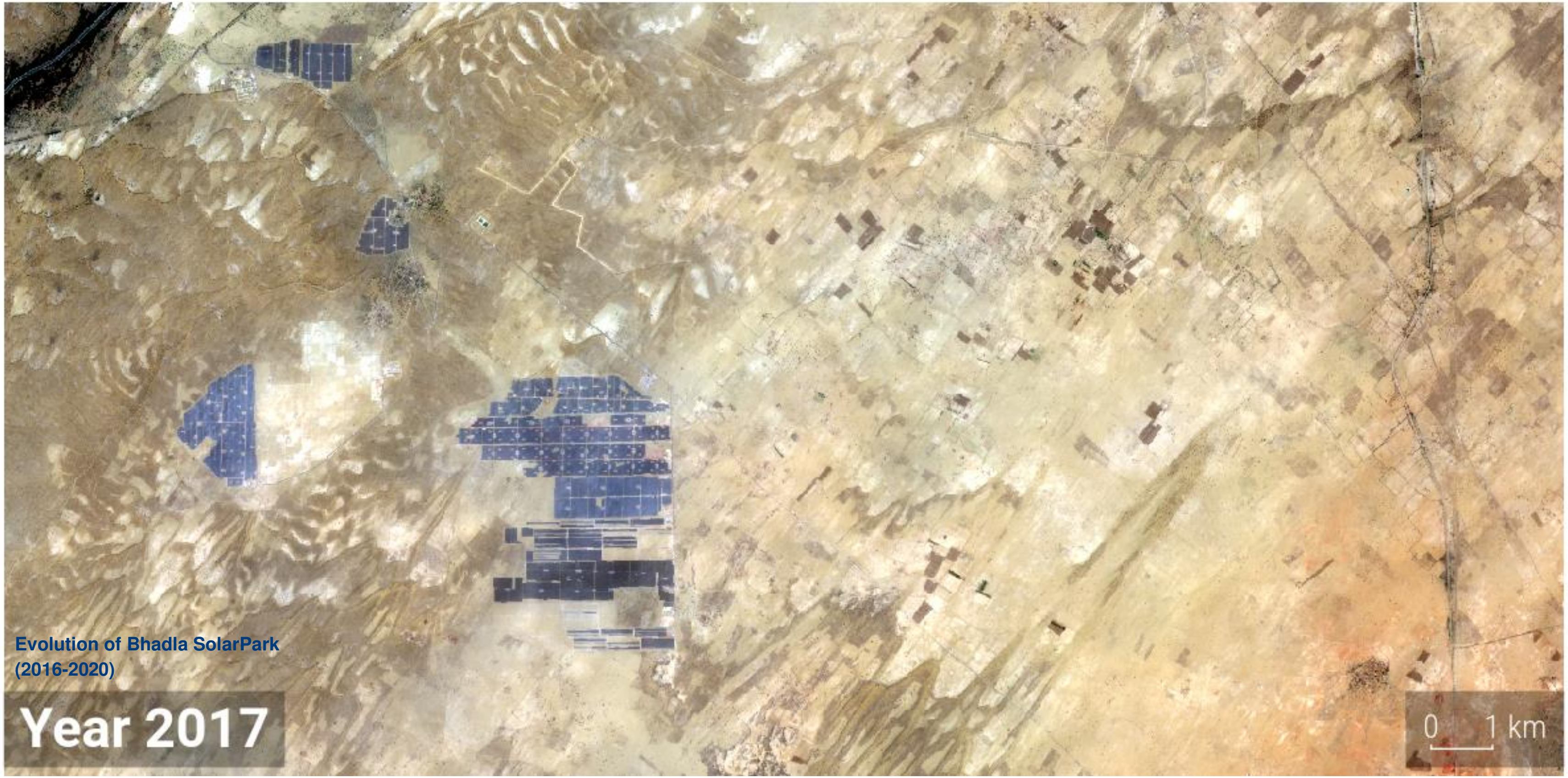
Rationale: A *size* perspective



Evolution of Bhadla SolarPark (2016-2020)

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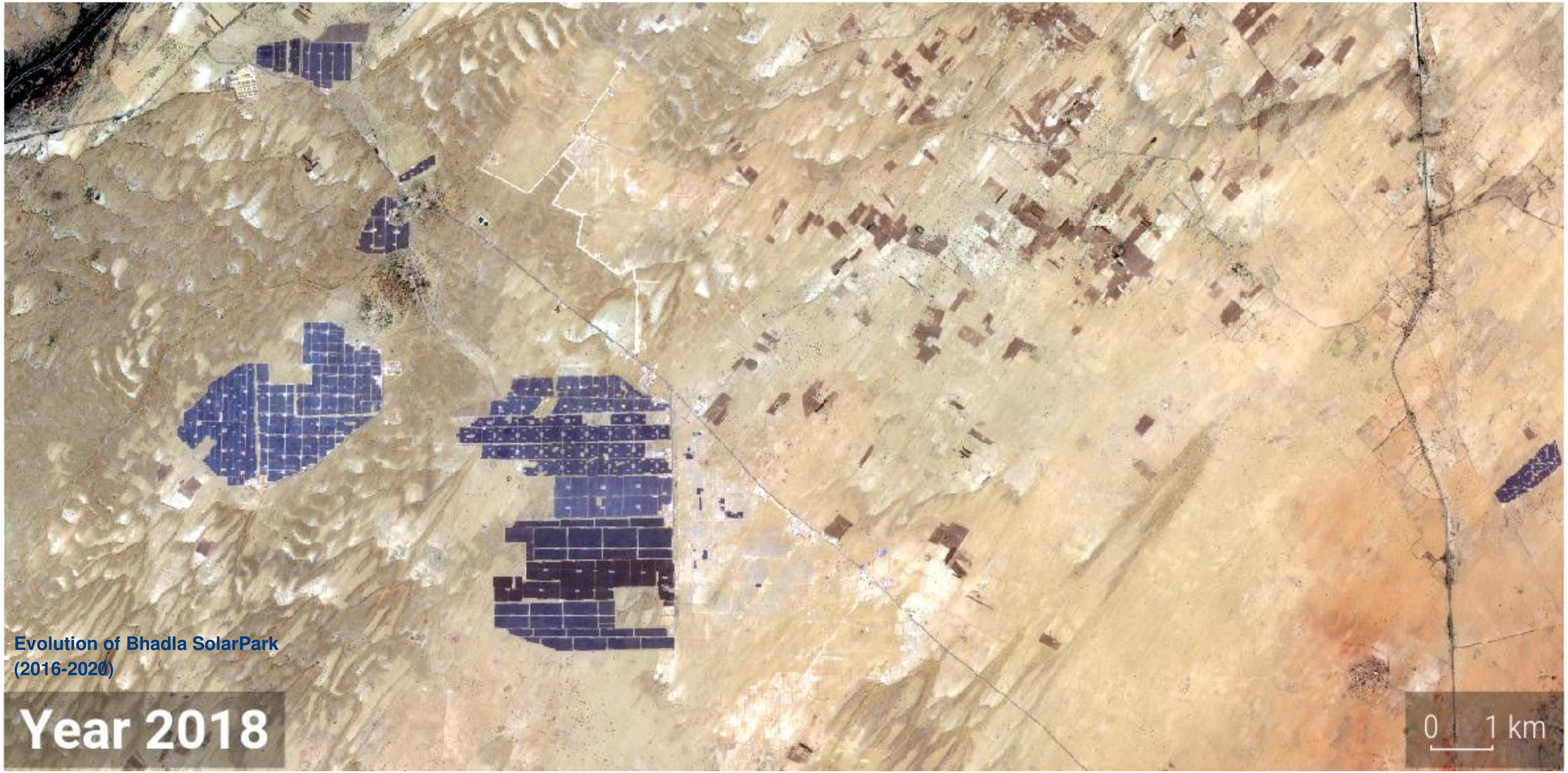
Rationale: A *size* perspective



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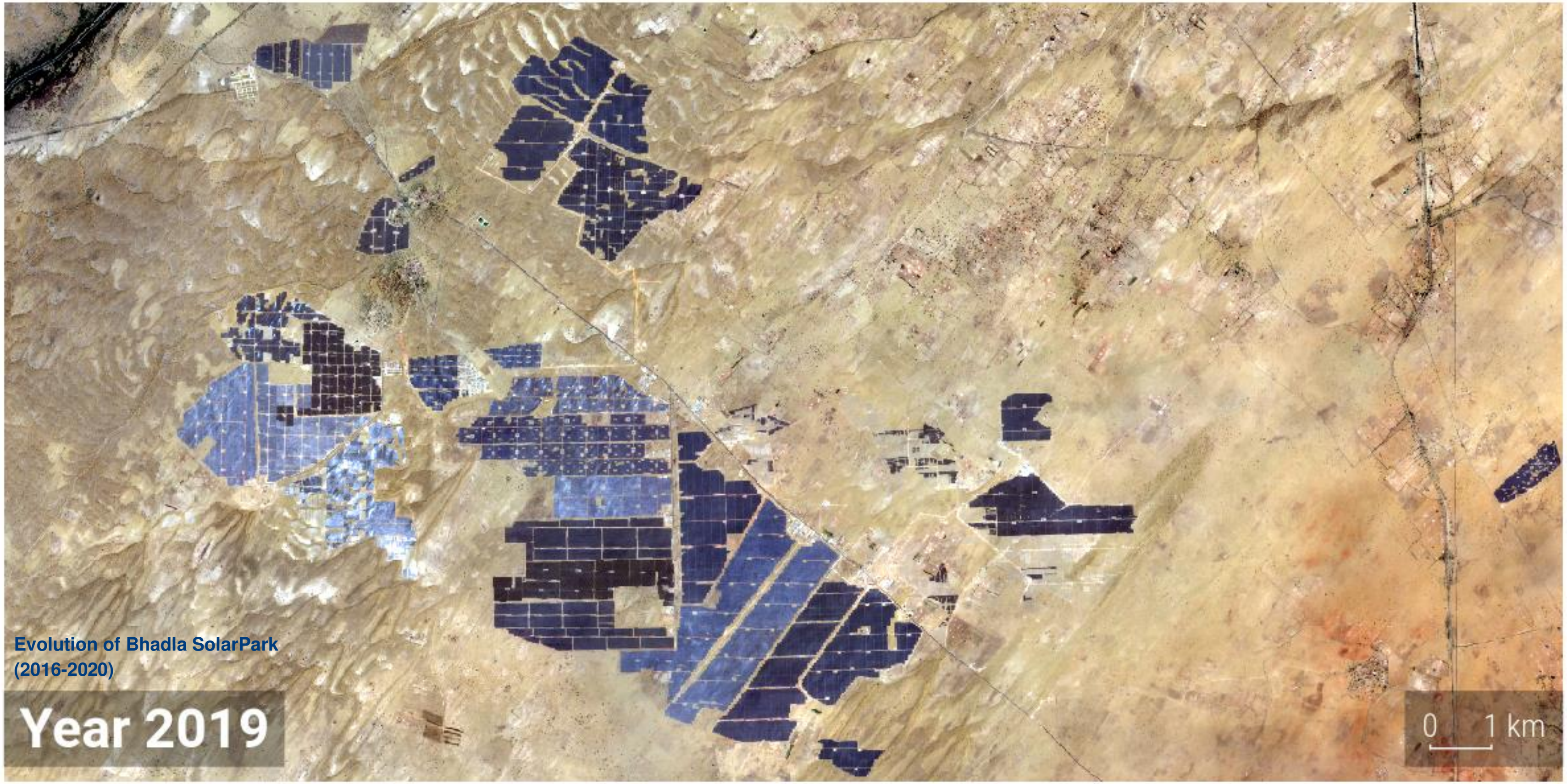

Evolution of Bhadla SolarPark (2016-2020)

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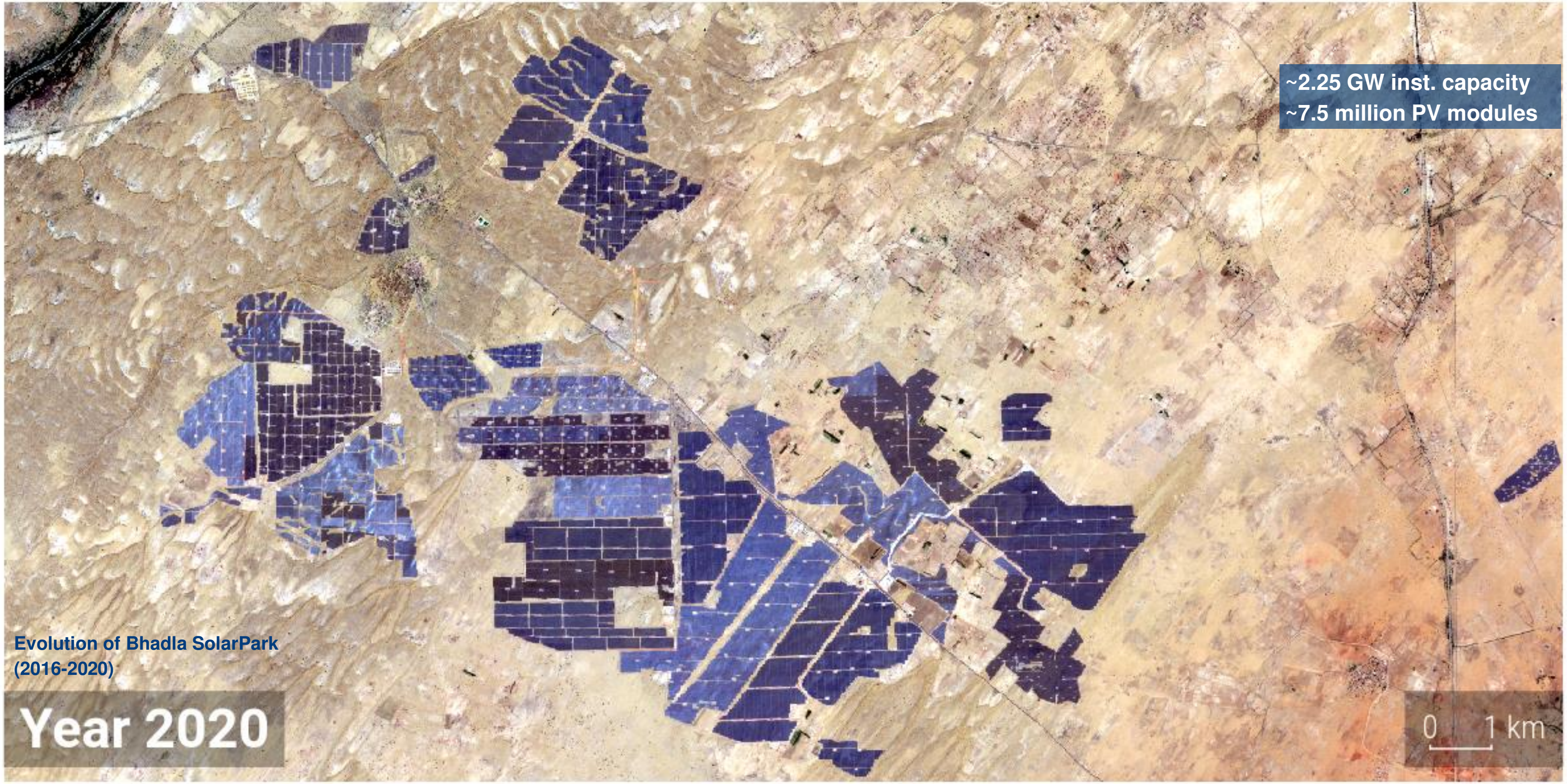
Rationale: A *size* perspective



Evolution of Bhadla SolarPark (2016-2020)

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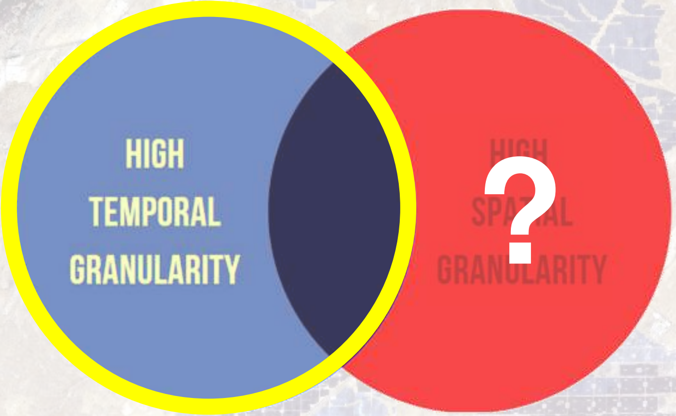
Monitoring/Diagnostic limitations at large-scale



- **Insufficient spatial granularity**
- At **component** / **subsystem** level:
  - Undetected losses or failures
  - Triggered false-negatives
  - Root-cause analysis practically impossible, time- and labor- intensive.

Year 2020

0 1 km

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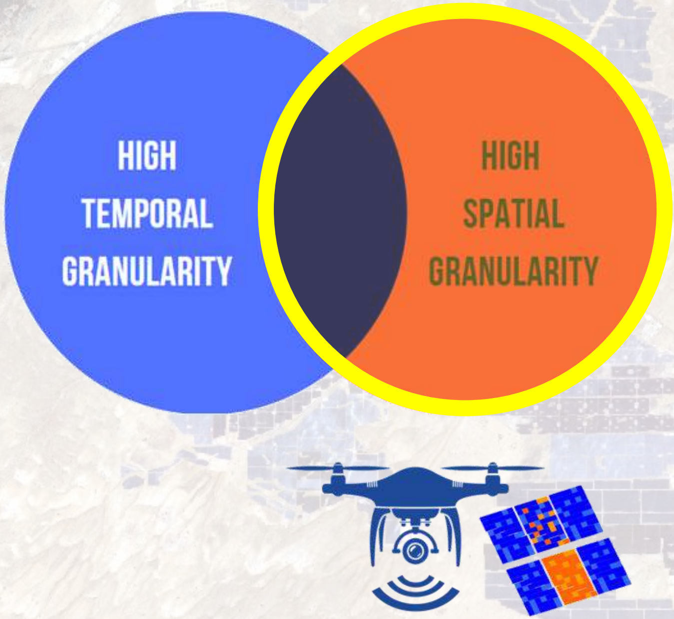
Value of **aerial inspections/imagery**

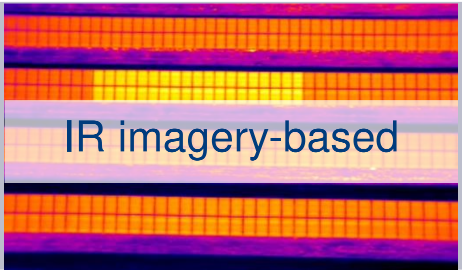


- **Very high spatial granularity**
- From **system** and **string** level, down to **module** and **submodule/cell** level :
  - Detection, diagnosis.
  - Root-cause analysis possible.
  - Time- and labor- efficient.
  - 1.5x up to 4x higher “diagnostic capacity”

Year 2020

0 1 km

Aerial inspections **in a nutshell**



IR imagery-based

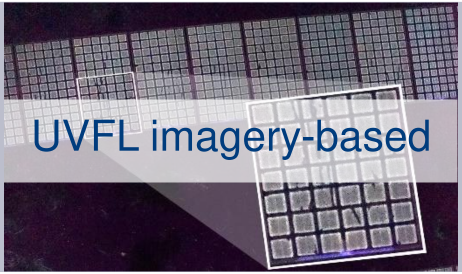
- Thermal signatures of faults from system to (sub)module level.
- Minimal instrumentation.
- Highly compatible with UAVs
- Standardized, commercialized, proved time-/cost- efficiency.

- High dependence on weather.
- Lower resolution vs EL / UVFL.
- Misinterpretations, false negatives.
- Qualitative (mostly).

EL imagery-based

- NIR luminescence signatures of faults down to cell/sub-cell level.
- Highest spatial resolution.
- More reliable interpretation.
- Suitable for evaluating propagation of certain faults.

- Complex deployment requirements. No turnkey solutions
- Need for high exposure times = challenging for aerial inspections.
- Higher cost & time vs IR.
- Qualitative (mostly).



UVFL imagery-based

- Fluorescence signatures of defects at material/component level.
- Spatial resolution comparable to that of EL imagery.
- High potential for materials evaluation and in-depth forensics.

- Complex deployment requirements. No turnkey solutions
- Need for high exposure times = challenging for aerial inspections.
- Higher cost & time vs IR.
- Strictly qualitative.

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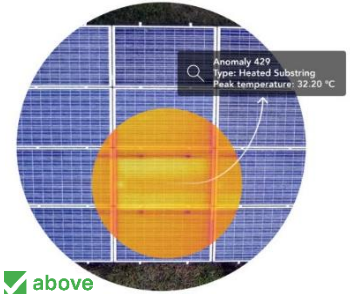
IR inspections: **State-of-Play**

Profile of commercial solutions

- Turnkey services, including AI-based data analytics and fault diagnostics.
- Reporting & maintenance recommendations.
- "Per-schedule" or "on-demand" aerial scans (preventive maintenance or reactive troubleshooting) ; commissioning or asset transfer.



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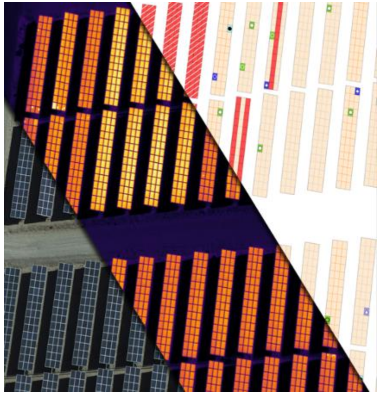
Two (very) different approaches

- *Aircraft-mounted IR imagery*

  100-150 MW/hour, focus on system/DC failures, higher cost

- *UAV/drone IR imagery*

  12 MW/day (~3 MW/hour), IEC compliance, system to module failures, lower cost



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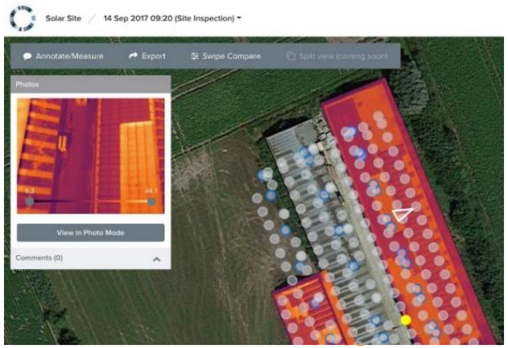

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Experience feedback

- Extensive increasing IR inspection portfolios → rich libraries of faults, proprietary imagery analysis & mapping software.
- Fast ROIs: >10% lower preventive O&M; recovery of an average 1-2% PV power losses.

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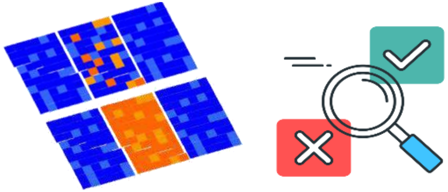
IR inspections: **Standardization** and **Best practices**

IEC TS 62446-3 released by the IEC TC82, in 2017. Groundwork by Task 13 experts.
→ test procedures and requirements. No pass/fail criteria. Not specific for aerial IR.

Recommended TS for hardware (IR camera, etc)

Requirements related to ambient/meteo conditions

Inspections configuration
Site conditions and preparation



Failure modes classification
Reporting / recommendations

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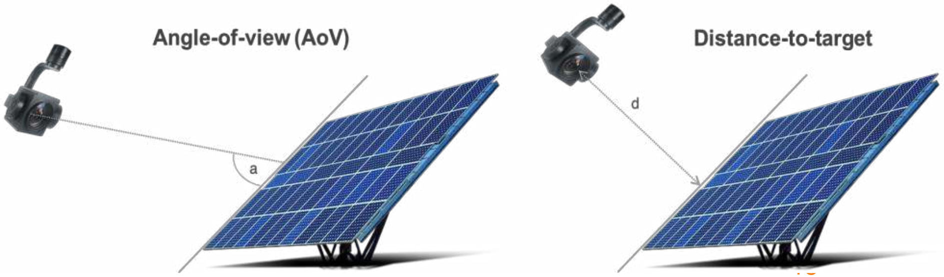
IR inspections: **Standardization** and **Best practices**

In a nutshell (for aerial IR inspections)

Parameter	Condition/Requirement – Remark(s)
Global Plane-of-Array Irradiance (G_{PoA})	**≥ 600 W/m²** , for PV module/array inspection ≥ 300 W/m² , for inspection of other BOS components
Wind Speed (S_W)	**≤ 4 Bft** or **≤ 8 m/s**
Cloud Coverage	**clear-sky** recommended ; if not possible, then two cases: • cumulus type : **≤ 2 okta** → to avoid any reflection effects • sirrus type **< 10% / min.** ; otherwise, ≥15 min. waiting time, to reach **steady-state**
Air/ambient temperature (T_{amb})	No limiting conditions or requirements. Recommendation: If the IR camera/equipment has any calibration function to limit the measurement uncertainty from atmospheric transmission effects/losses (for example: "ambient compensation value (ACV) function"), then the T_{amb}, RH are required, thus should be recorded.
Relative humidity (RH)	
Soiling	On modules : zero or low-uniform soiling on module plane (pre-cleaning required or ensure less than 10% of losses in current output) Atmosphere: avoid measurements after rain-dust or after soiling inducing activities

Parameter	Condition/Requirement – Remark(s)
Spectral response	**8-14 µm (optimal range)** or 2-5 µm (for electrical parts only)
(corresponding) Temperature range	**-20°C…+120°C** (*at least*)
Noise-equivalent temperature difference (NETD) or Thermal sensitivity	**≤ 0.1 K**
Accuracy or absolute uncertainty/error	**≤ ± 2%** or **≤ 2 K**
Optical resolution / array size	≥ **640×480 pixels**
Other/adjustable functions	Emissivity correction, ambient temperature, focus/netting, temperature level and range, measurement spot and region-of-interest (ROI), output image and/or video file format with radiometric data (e.g. *.RTIFF, *.RAVI)

- Environmental conditions; hardware TS requirements.
- Angle-of-View, Distance-to-Target and DeltaT definitions.
- PV plant under operating (i.e. at MPPT) conditions, electrical/thermal steady-state, free of partial shading.
- Soiling: pre-check and cleaning prior to inspection.
- Intermittent faults: diagnosed at an individual inspection? Bi-annual (at least) inspections recommended.
- Recommended applicable safety regulation: EN 50110-1



IR inspections: **Deployment**

Data acquisition [1]

- Flyover(s) and logging of radiometric data. Georeferencing and/or 3D modelling of the PV plant (opt).
- UAV equipped or interoperating with auxiliary sensors. (e.g. temperature, irradiance, etc).
- Flight paths: typically pre-programmed and optimized:
  → repeatability, IEC compliance, diagnostic accuracy.

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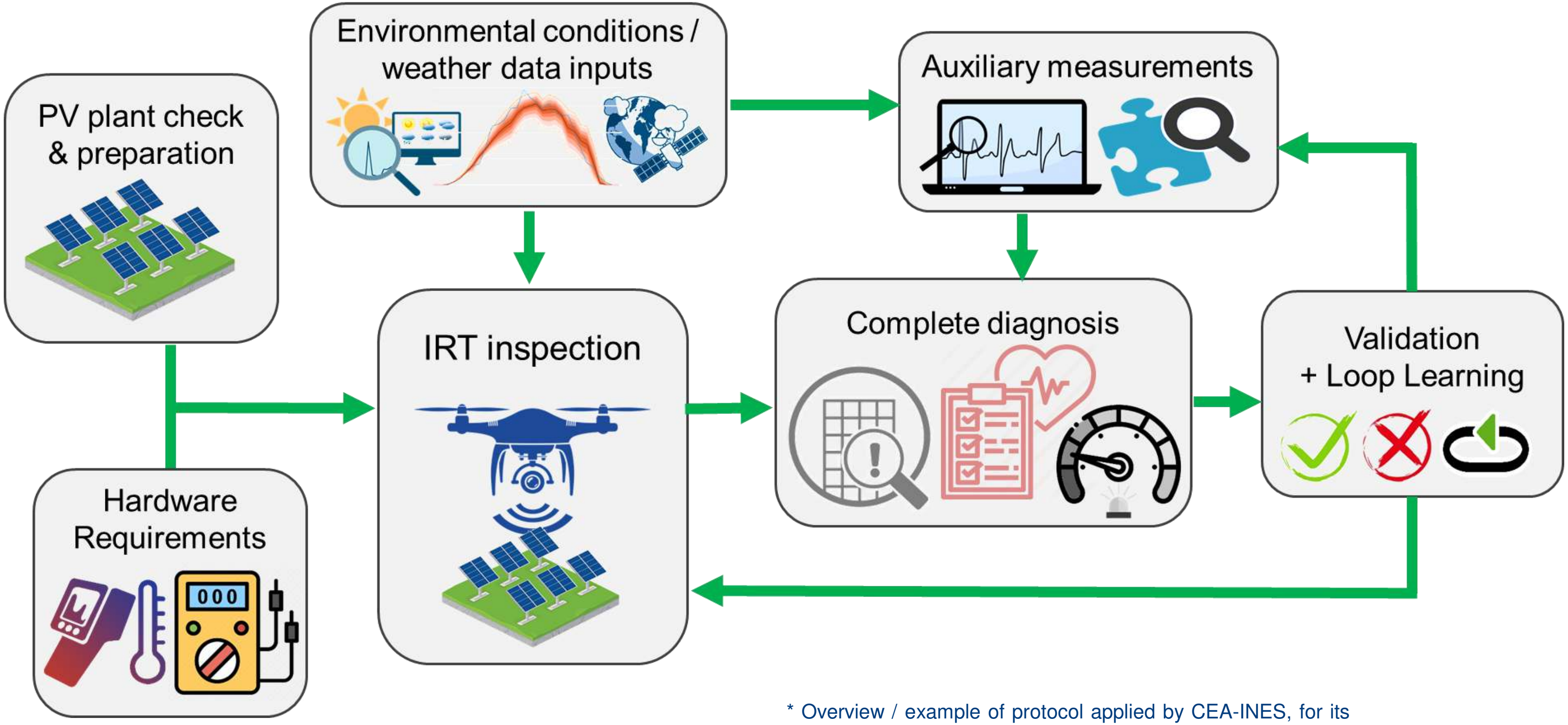
Post-processing [1]

- Geolocation of PV modules
- Thermal anomalies detection and classification
- PV module failure analysis
- Data analytics
- Maintenance implementation plan
- Reporting

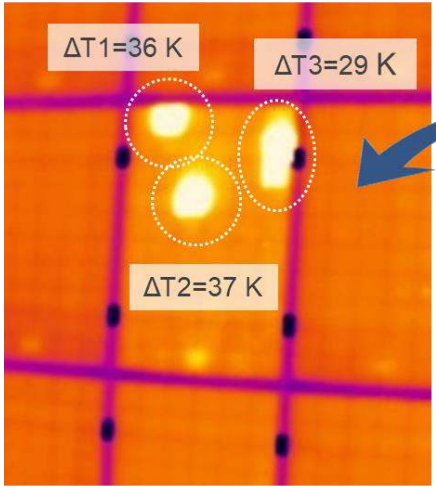
1. Solar Power Europe, O&M Best Practice Guidelines Version 4.0, 2020.

Example of applied **IR inspection protocol** *



* Overview / example of protocol applied by CEA-INES, for its patented “ASPIRE” IR-diagnostic methodology and software.

IR inspections: **Case study examples**



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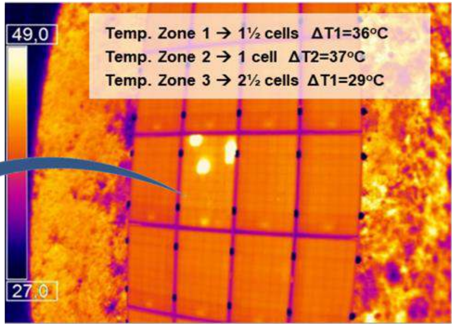
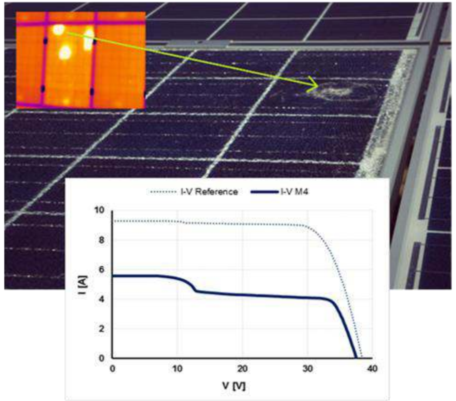
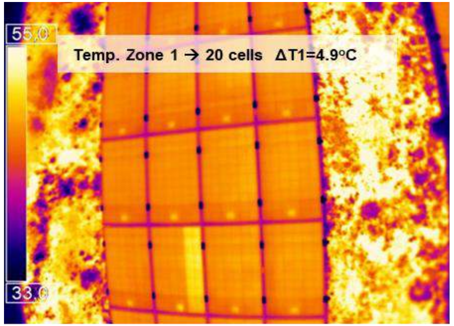
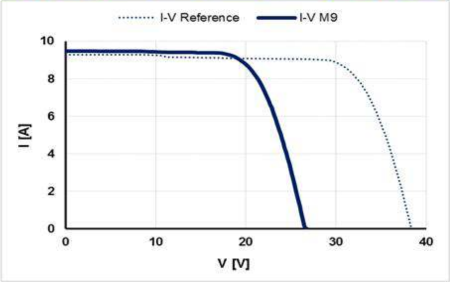


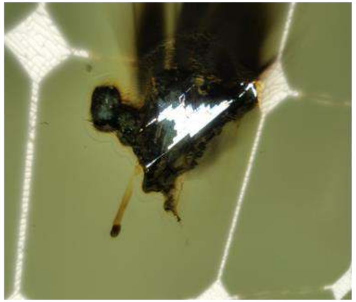


Total estimated **ΔP=125.9 W** or **-48.4%**
Total measured **ΔP=128.3 W** or **-49.35%**
Accuracy = 98.1%





Severe, not-mitigated hot spots: follow-up failures



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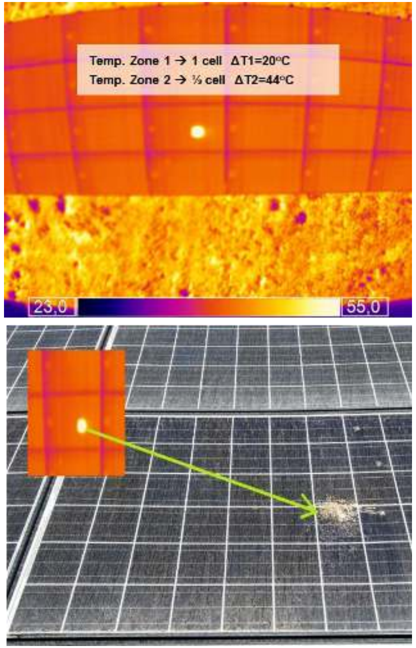
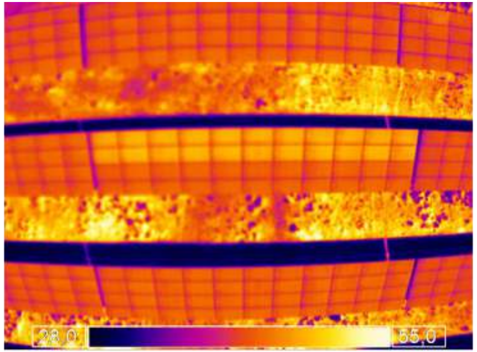
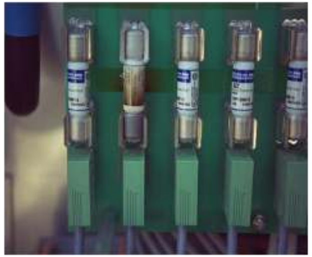
IR inspections: **Case study examples**

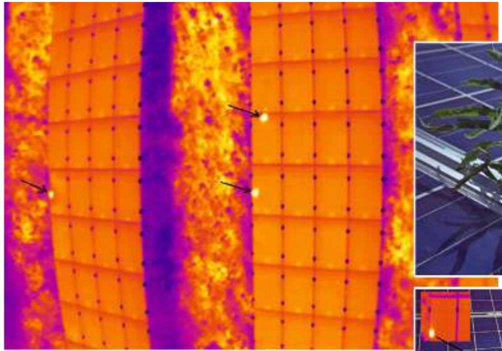


Soiling / dirt
(e.g. bird droppings)





Failures in connectors/cabling and combiner boxes (e.g. burnt fuses)



Shading losses
(poor vegetation management)

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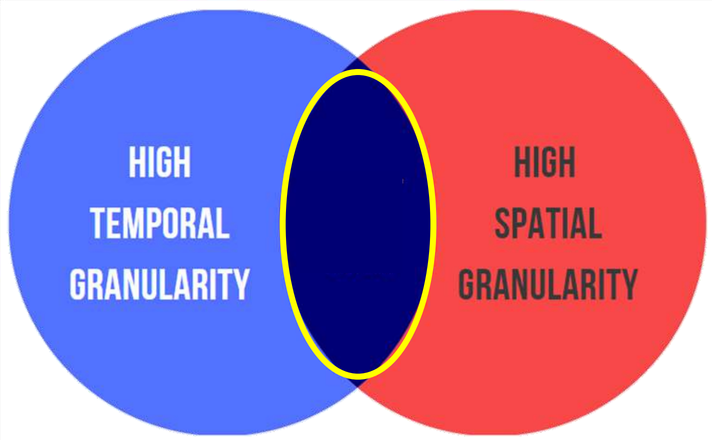
IR inspections+diagnostics "**roadmap**" : **future trends**[1,2]

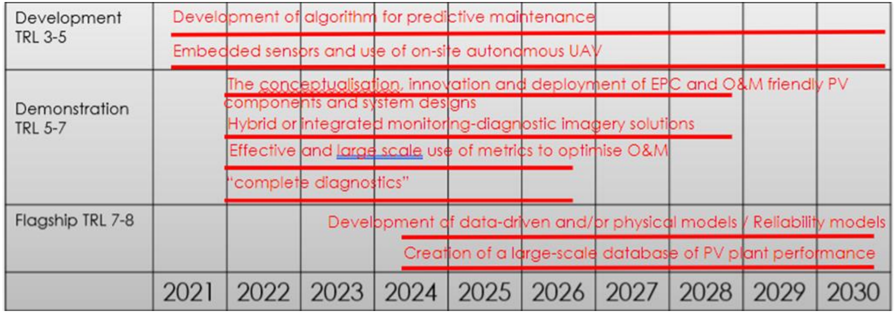
- Deployment and validation in emerging PV applications
- Hyperspectral imagery and 100% autonomous UAV
- "Complete" all-in-one imagery diagnostics
- "Data fusion" IoT enabled concept: Hybrid or integrated monitoring/diagnostic IR imagery solutions



PV monitoring Diagnostics

Aerial Imagery Diagnostics

Data-driven predictive maintenance



1. Solar Power Europe, O&M Best Practice Guidelines Version 5.0 (in progress)
2. ETIP PV : European Strategic Research and Innovation Agenda (SRIA) for PV, May 2021.

Thank you for your attention

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