BECQUEREL INSTITUTE
Strategy Consulting in Solar PV

Solar Performance Data for Next-Generation Improvements

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3rd December 2025

PVMODULETECH CONFERENCE EUROPE

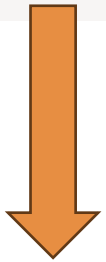
Industry reality check

What industry claims to have VS Reality

The introduction of novel technologies and novel PV system design makes the need of increased field performance and reliability a continuous industry demand. Solutions and services which are already available in the market or close to the market will need to be continuously updated and redefined to capture innovation trends. Moreover, new technologies can introduce new degradation modes once in the field.

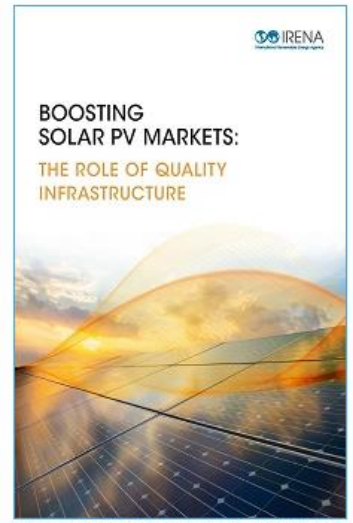
Bankable solar PV

Warranty and contractual terms are not well standardized in the PV industry. There is no total transparency on how the manufacturers and contractors define internally their risks corresponding to their specific warranties and contractual terms.



It is quite impossible for developers and investors to quantify the risk assumed in each individual project because the benchmarking is not possible with the mentioned lack of transparency.

THE QUEST FOR QUALITY



Boosting global PV markets: The role of quality infrastructure

SolarPower Europe

ETIP Photovoltaics

IEA PVPS

IRENA
International Renewable Energy Agency

Initiatives to follow in EU

Funded by the European Union

SUPERNOVA

PVOP

SOLARIS

Developing tools and components for different sensor technologies to be adaptable to different environments

Using robotic solutions to reduce costs, increase data collection, and automate the process

Connect physical solutions for automated monitoring, inspection, and rapid response to streamline PV system maintenance.

Initiatives to follow outside of EU

The Durable Module Materials Consortium (DuraMAT) brings together **DOE national lab** and **university** research capabilities with the photovoltaic (PV) and **supply-chain industries** through **five core objectives** (above), with the goal to accelerate rapid deployment of low-cost electricity.

Comprehensive information available at www.duramat.org

DuraMAT Goals for FY22-27

- Which materials and module designs will enable sustainable, high-energy yield 50-year modules, and how do we ensure that these new modules are not going to fail prematurely?
- What triggers wear out, defined as a rapid increase in degradation at end of life, and what are the characteristics, rates, and mechanisms of long term degradation in PV modules?

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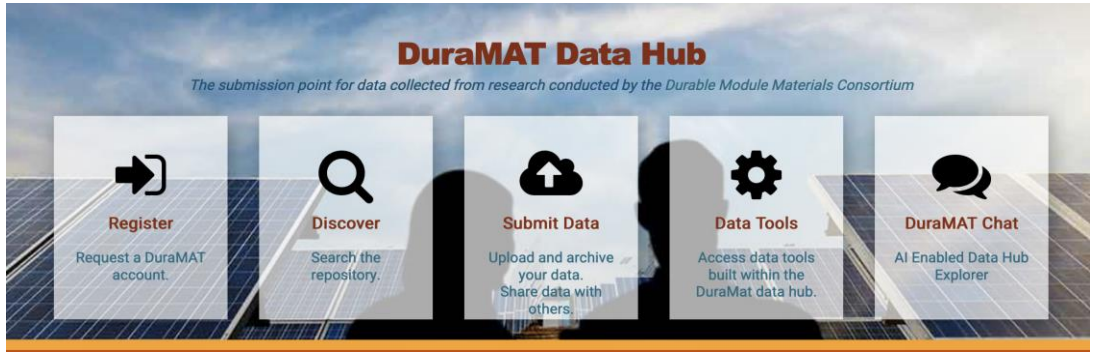
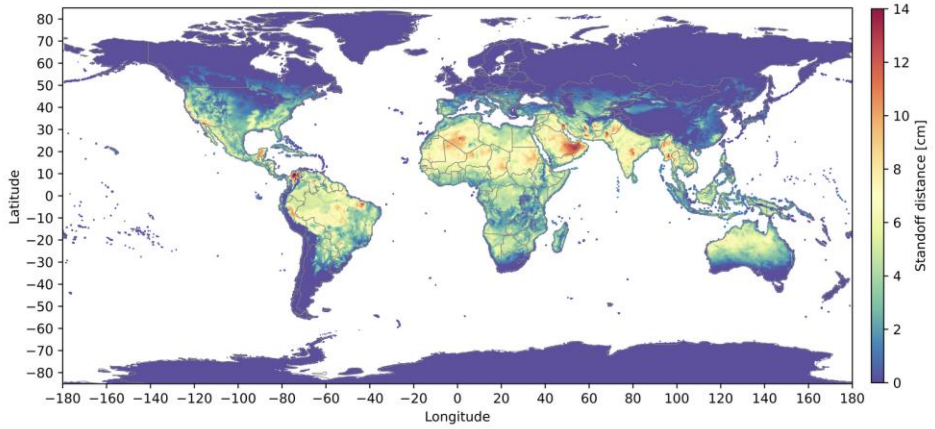
DuraMAT
Durable Module Materials Consortium

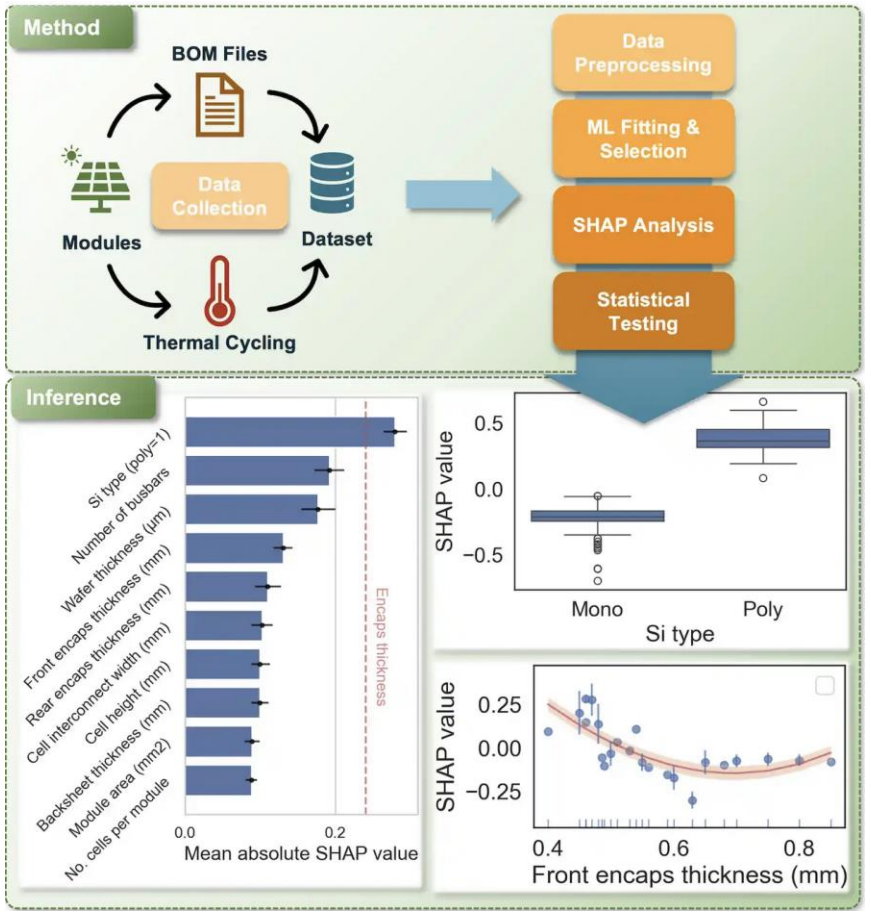
www.DuraMAT.org and other Data Sources

- https://datahub.duramat.org/



- https://github.com/NREL/PVDegradationTools





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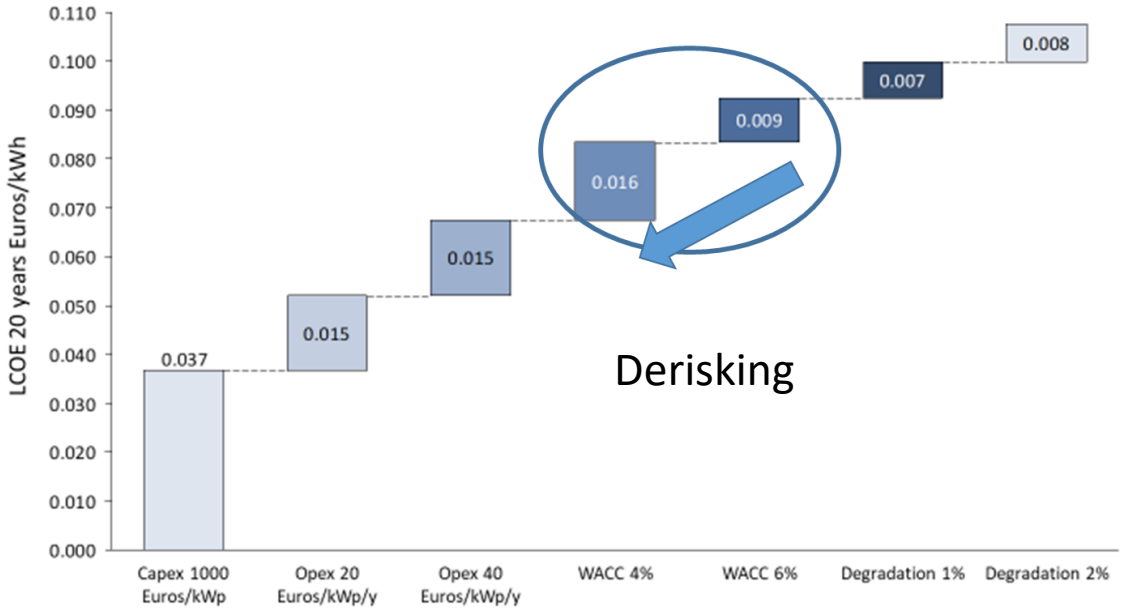
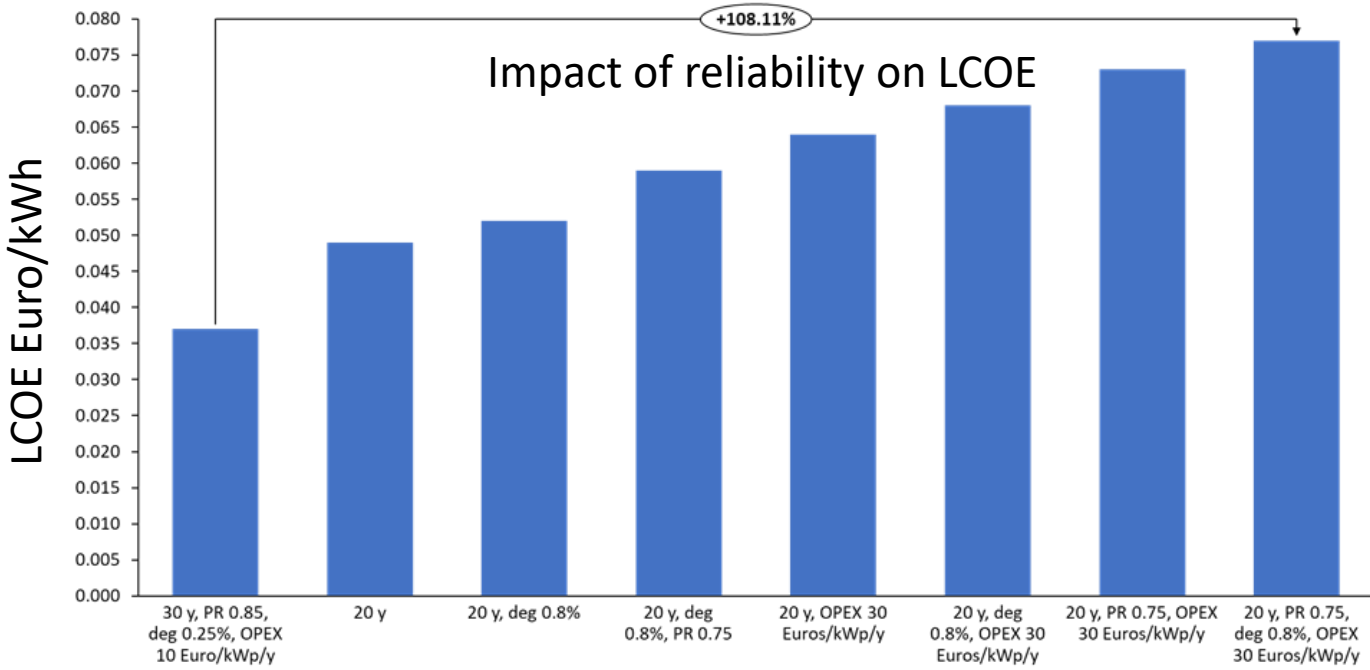
QUANTIFYING QUALITY





Drivers for cost-effective increase of performance and reliability:

- Risk framework and guidelines (lower risk, lower WACC)
- A value-chain approach

For all these drivers digitalisation is key

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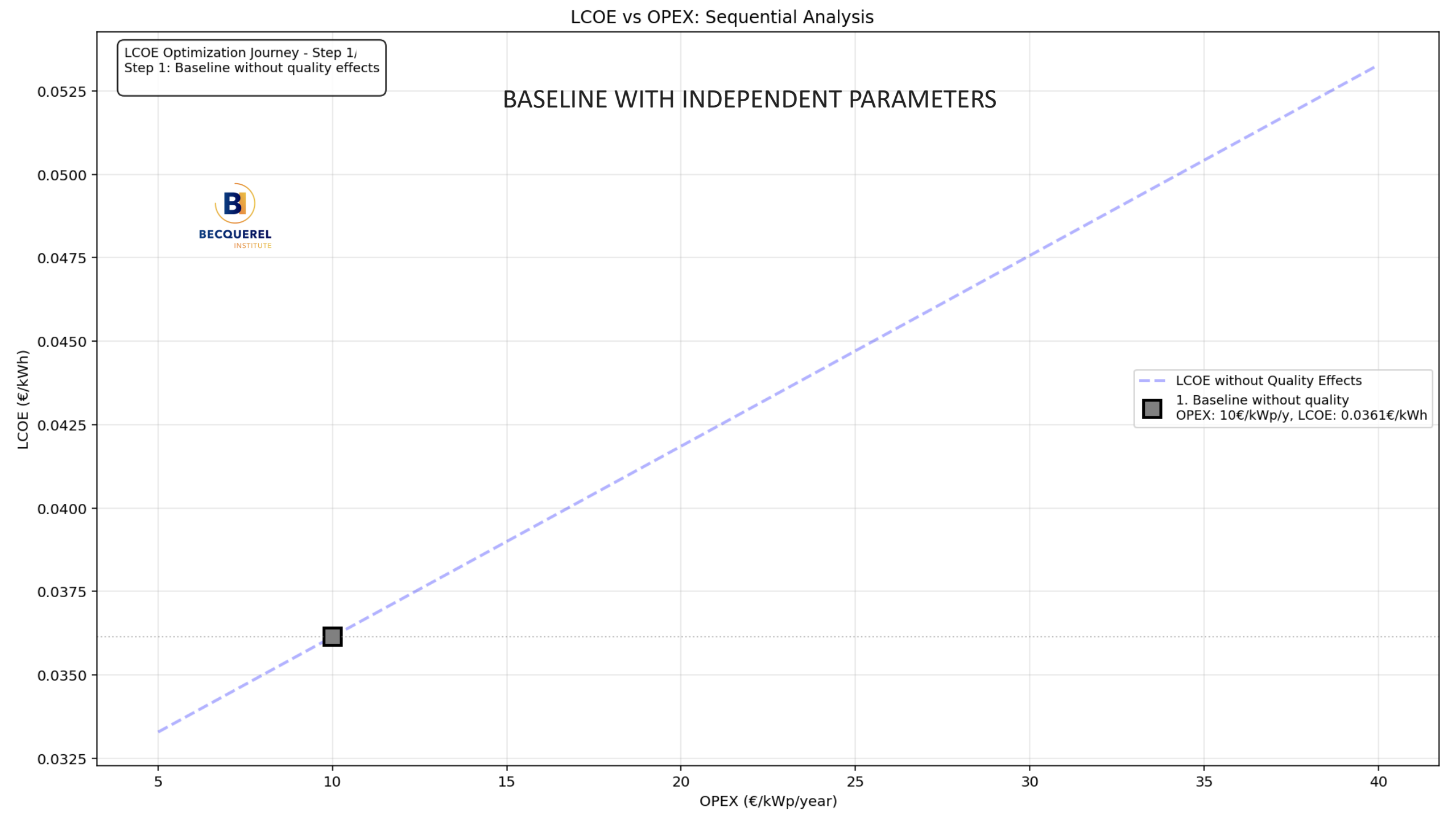
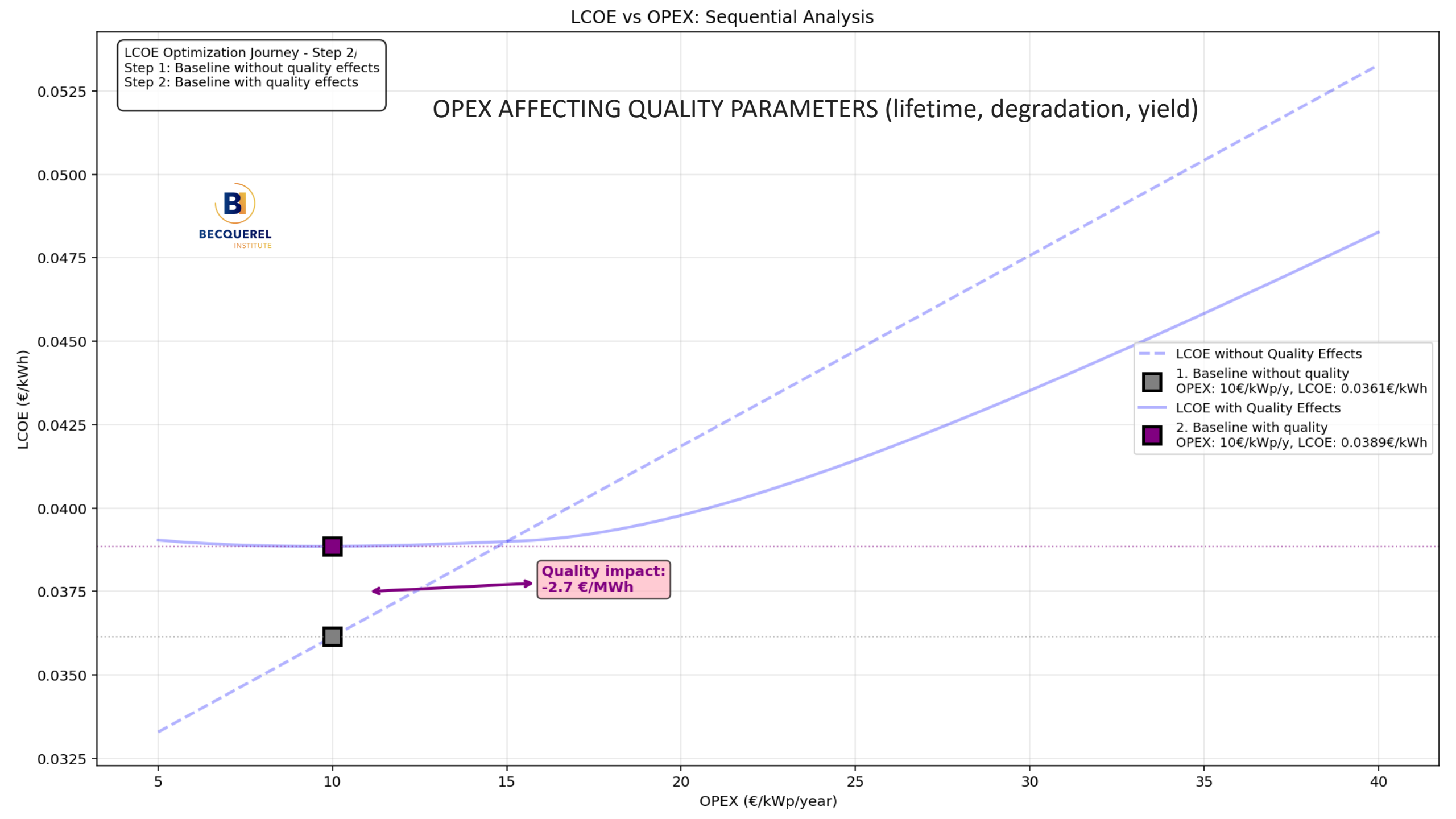
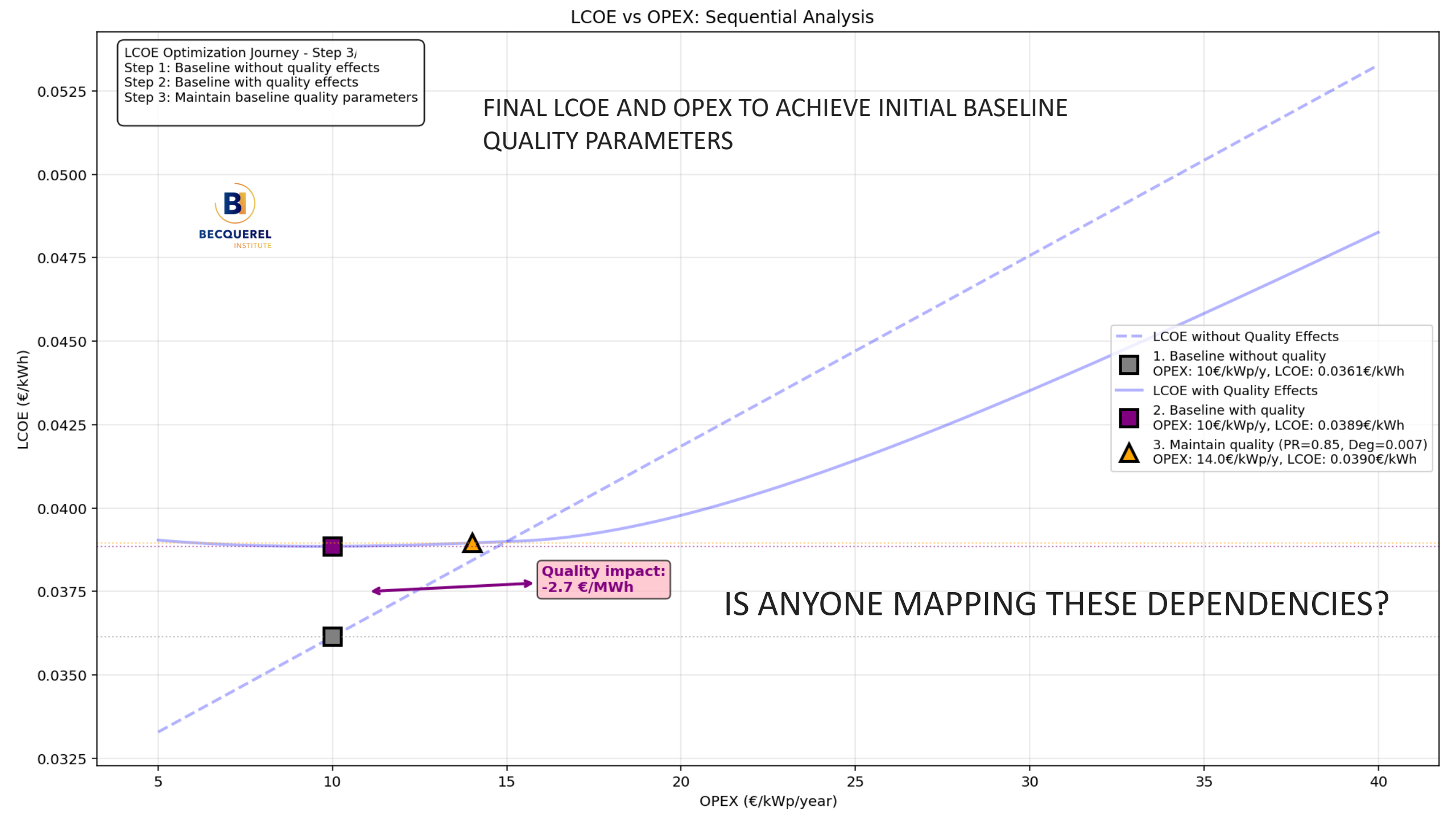
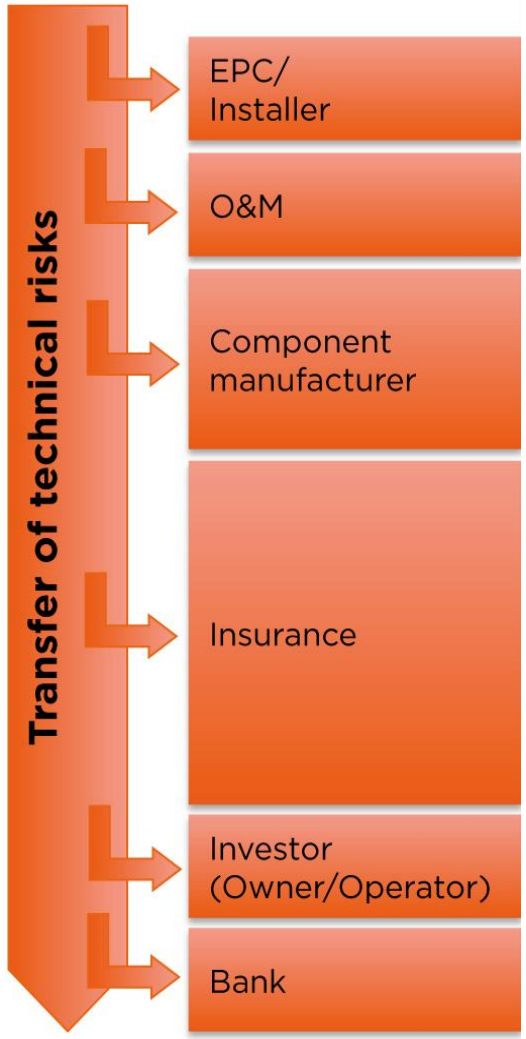

LCOE vs OPEX: Sequential Analysis
LCOE Optimization Journey - Step 1
Step 1: Baseline without quality effects
BASELINE WITH INDEPENDENT PARAMETERS
BECQUEREL INSTITUTE
LCOE without Quality Effects
1. Baseline without quality
OPEX: 10€/kWp/y, LCOE: 0.0361€/kWh
LCOE (€/kWh)
0.0525
0.0500
0.0475
0.0450
0.0425
0.0400
0.0375
0.0350
0.0325
OPEX (€/kWp/year)
5
10
15
20
25
30
35
40


LCOE vs OPEX: Sequential Analysis
LCOE Optimization Journey - Step 2/
Step 1: Baseline without quality effects
Step 2: Baseline with quality effects
OPEX AFFECTING QUALITY PARAMETERS (lifetime, degradation, yield)
BECQUEREL INSTITUTE
LCOE without Quality Effects
1. Baseline without quality
OPEX: 10€/kWp/y, LCOE: 0.0361€/kWh
LCOE with Quality Effects
2. Baseline with quality
OPEX: 10€/kWp/y, LCOE: 0.0389€/kWh
Quality impact:
-2.7 €/MWh
LCOE (€/kWh)
0.0525
0.0500
0.0475
0.0450
0.0425
0.0400
0.0375
0.0350
0.0325
5
10
15
20
25
30
35
40
OPEX (€/kWp/year)


LCOE vs OPEX: Sequential Analysis
LCOE Optimization Journey - Step 3
Step 1: Baseline without quality effects
Step 2: Baseline with quality effects
Step 3: Maintain baseline quality parameters
FINAL LCOE AND OPEX TO ACHIEVE INITIAL BASELINE QUALITY PARAMETERS
BECQUEREL INSTITUTE
LCOE without Quality Effects
1. Baseline without quality
OPEX: 10€/kWp/y, LCOE: 0.0361€/kWh
LCOE with Quality Effects
2. Baseline with quality
OPEX: 10€/kWp/y, LCOE: 0.0389€/kWh
3. Maintain quality (PR=0.85, Deg=0.007)
OPEX: 14.0€/kWp/y, LCOE: 0.0390€/kWh
Quality impact:
-2.7 €/MWh
IS ANYONE MAPPING THESE DEPENDENCIES?
LCOE (€/kWh)
0.0525
0.0500
0.0475
0.0450
0.0425
0.0400
0.0375
0.0350
0.0325
5
10
15
20
25
30
35
40
OPEX (€/kWp/year)

STAKEHOLDERS' NEEDS



short defect warranty periods, minimum of additional guarantees and warranties, high sale price with low OPEX (short time horizon)

manage all the conflicting requirements for a long period of time. The best condition for O&M operators is in fact in the presence of long defect warranty period and low sale price to allow for higher OPEX.

Limit their liability to product guarantees and warranties

limit their liability to failures PV plants, which meet technical market standards and are maintained on a regular basis

long defect warranty periods, performance guarantees, reasonable low CAPEX and OPEX, high long-term plant performance and lifetime (ideally above the initial prediction).

projects with a 10-15 year financing period and PV plant performance which can also be slightly below prediction.

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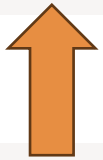
Quality assurance to increase lifetime and reliability: procurement and project development

Photovoltaic module manufacturers have experienced a rapidly growing market along with a dramatic decrease in module prices

Develop and implement new module designs to either increase performance and/ or lifetime of the modules or decrease the cost to produce them. Many of these innovations include the use of new and novel materials in place of more conventional materials or designs.

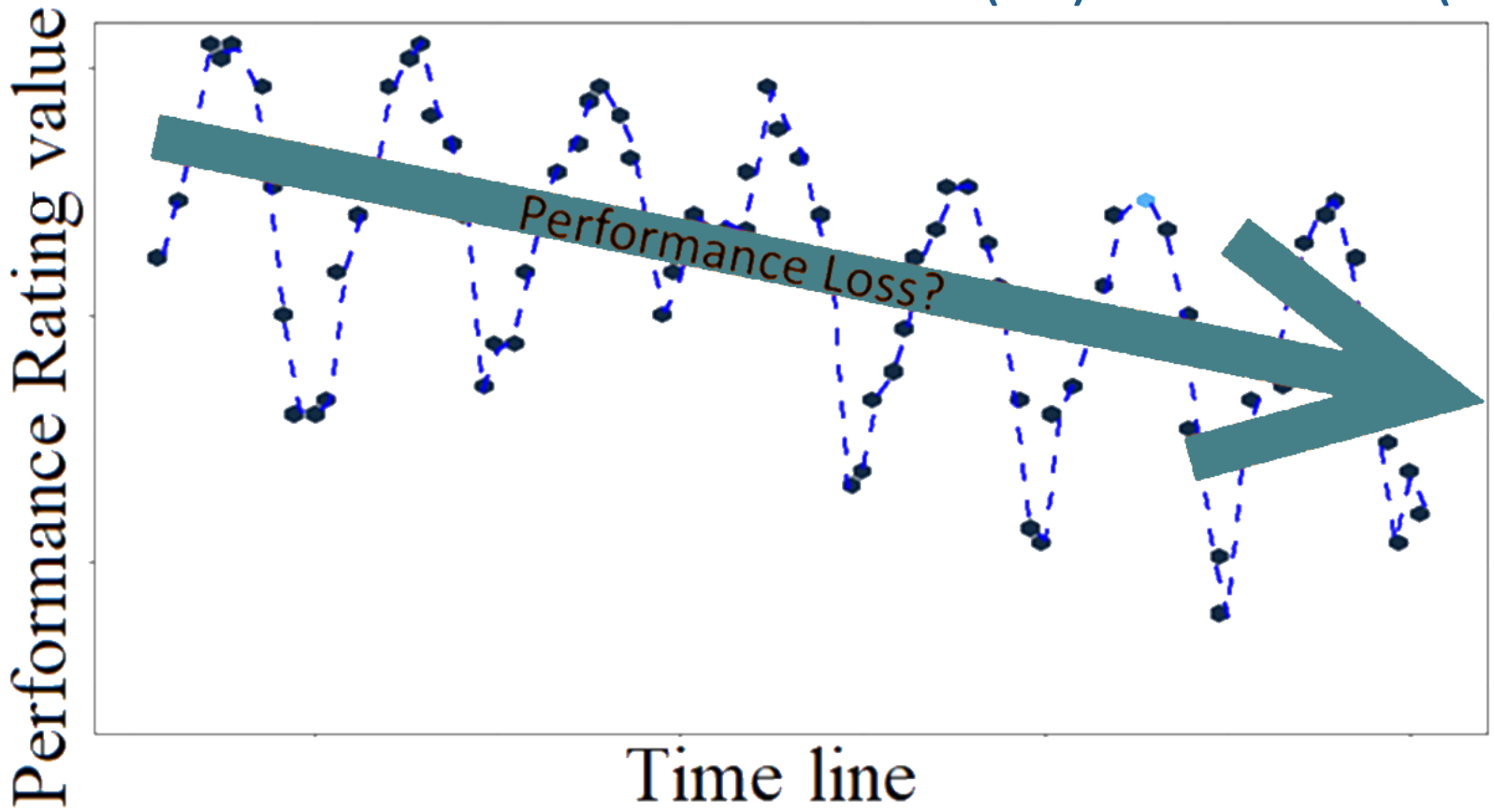
PV modules are being produced and sold without a long-term understanding about the performance and reliability of these new materials. This presents a technology risk for the industry.



In the past, several unexpected degradation mechanisms appeared after a few years of operational time in the field although they were not detected in any laboratory accelerated testing (Potential Induced Degradation (PID), Light and elevated Temperature Induced Degradation (LeTID), back sheet cracking).

What is a Performance Loss Rate?

Parameter, which indicates the decline of the power output of a PV system over time. Can be absolute (PL) or relative (PLR)



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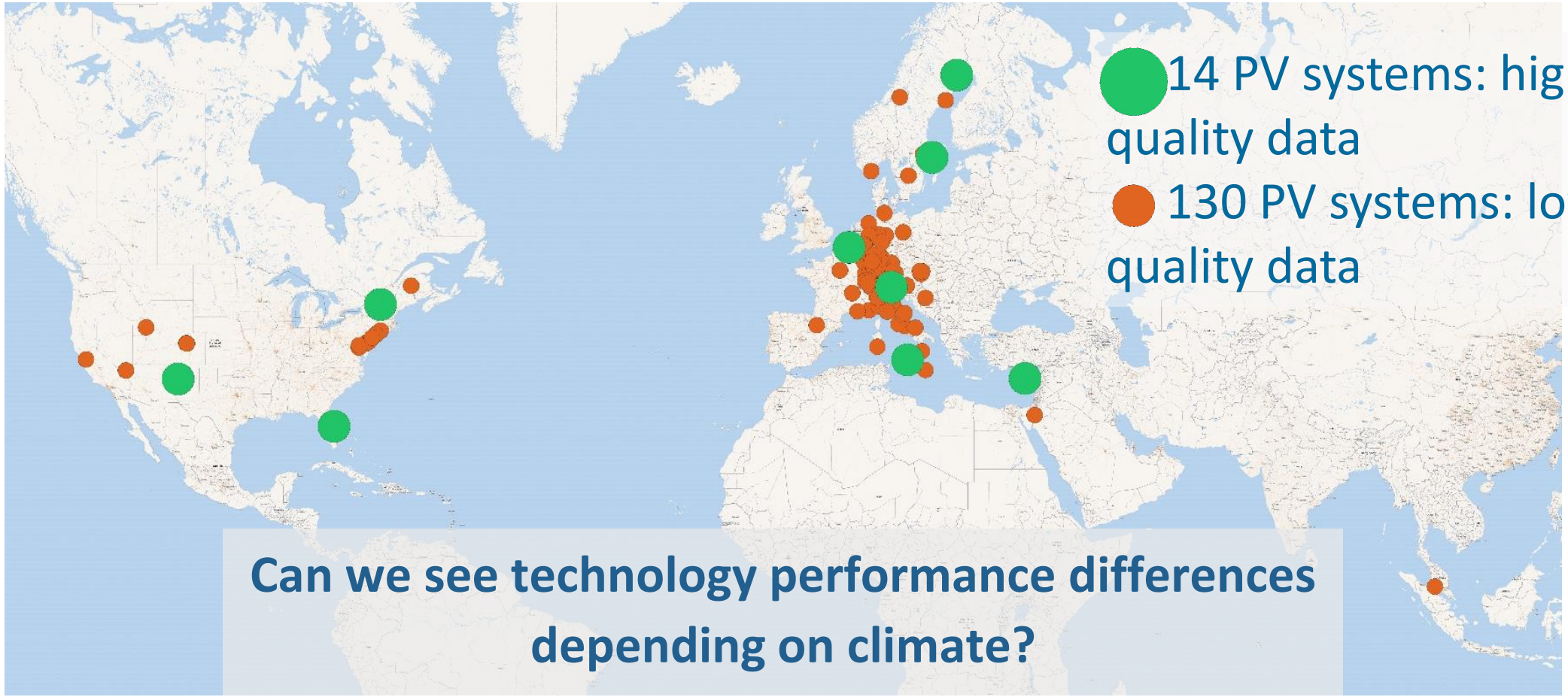
Datasets and benchmarking



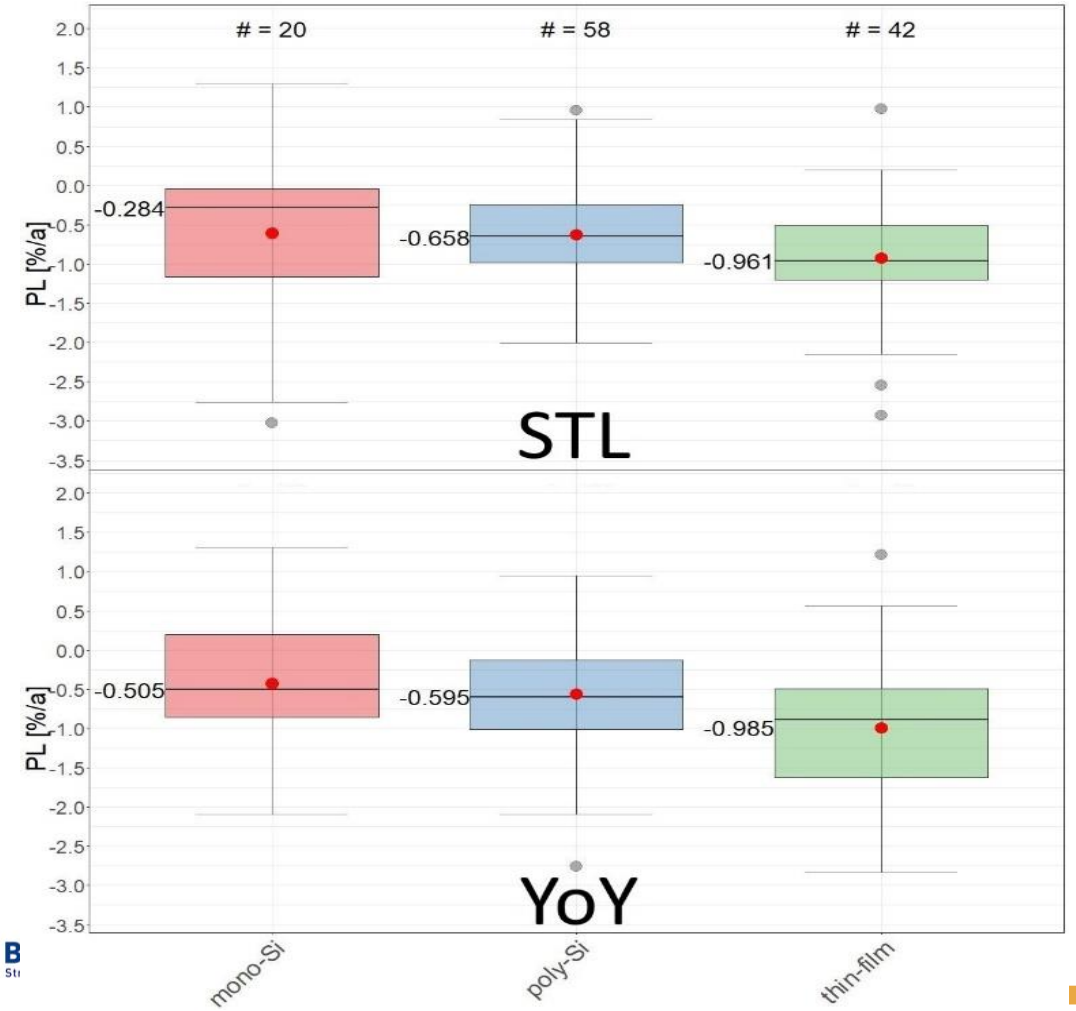
Can we see technology performance differences depending on climate?

C	Warm temperature climates	
Cfa	Fully humid	Hot summer
Cfb	Fully humid	Warm summer
Csa	With dry summer	Hot summer
Csb	With dry summer	Warm summer
D	**Snow Climates**	
Dfb	Fully humid	Warm summer

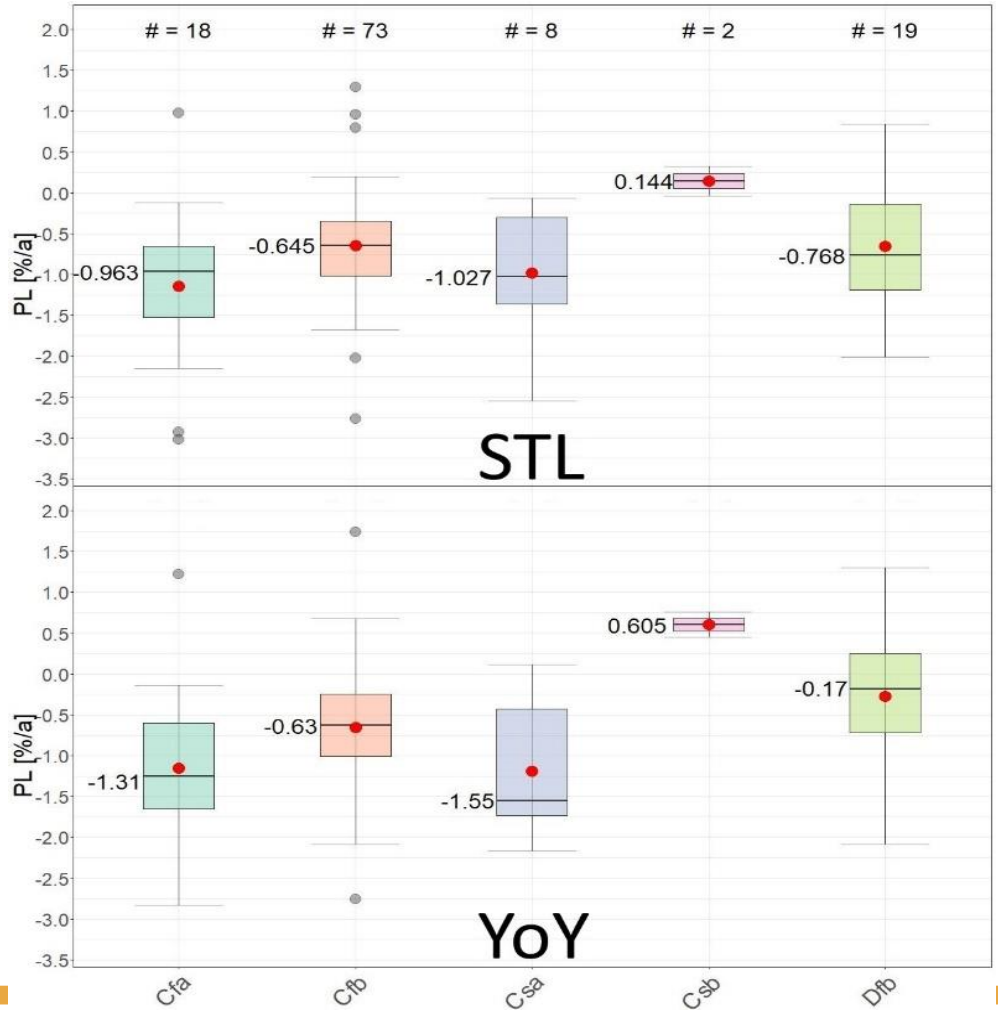
Task 13 Performance Database

IEA PVPS

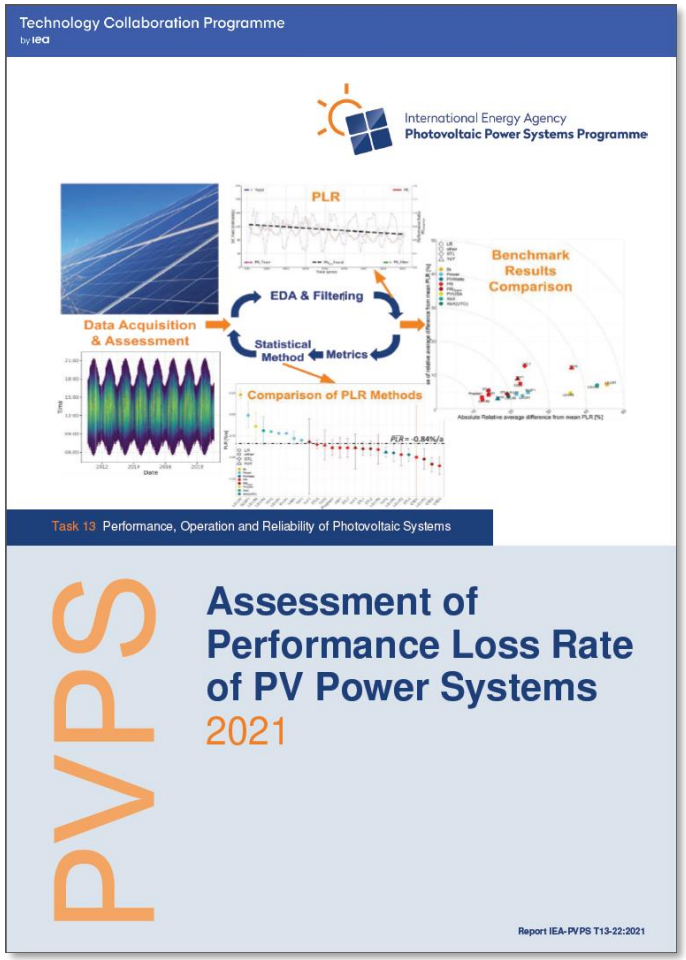
Technology



Climate



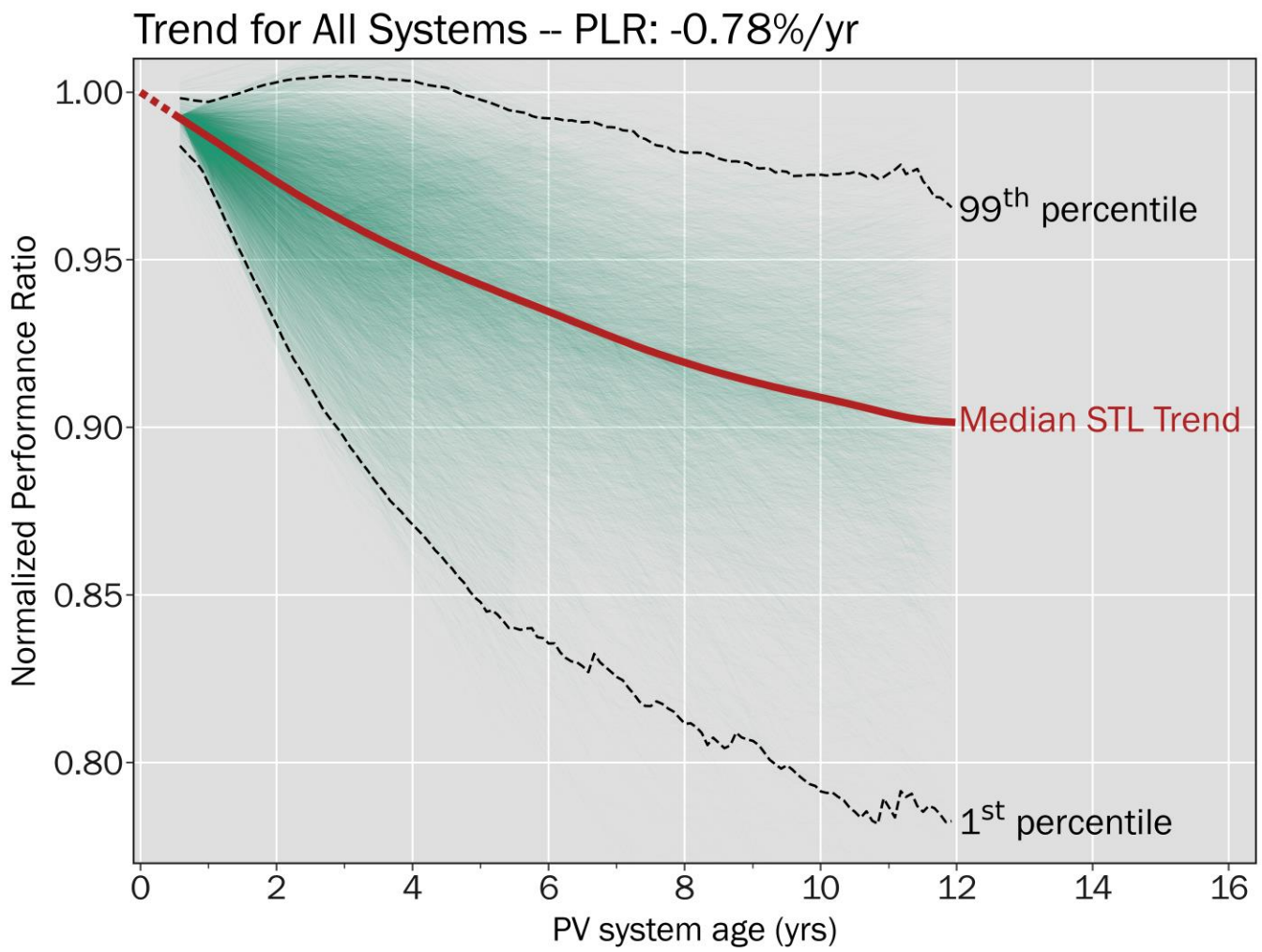
Report IEA-PVPS T13-22:2021

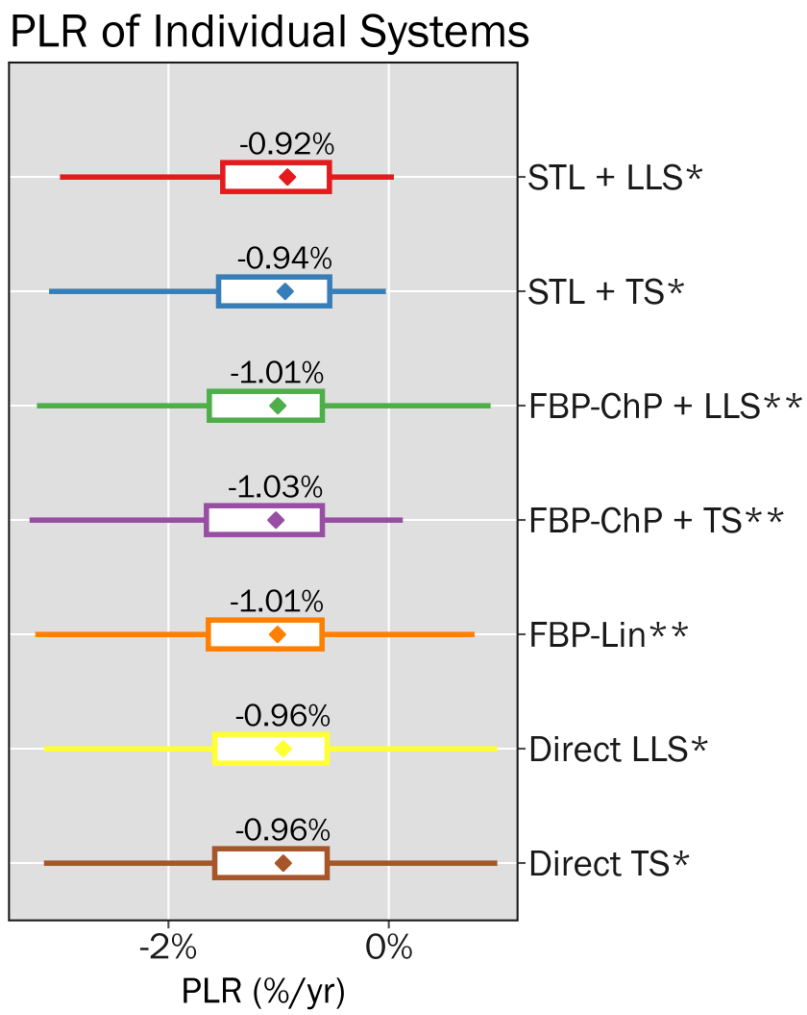


- Definition performance loss rates
- Critical review of existing calculation methodologies
- Best practice guidelines
- Development of data quality grading scheme

TÜVRheinland
RSE Ricerca Sistema Energetico
EDF
Fraunhofer ISE
SERIS
NREL National Renewable Energy Laboratory
University of Cyprus Electromagnetics and Novel Applications Lab
eurac research
Sandia National Laboratories
AIT Austrian Institute of Technology
Stanford University
zhaw
Case Western Reserve University

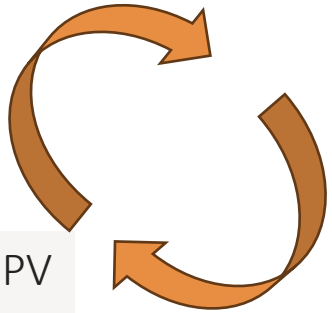
Climate and Technology Dependent Performance Loss in a Fleet of 10,000 PV Systems





Quality assurance to increase lifetime and reliability: operation

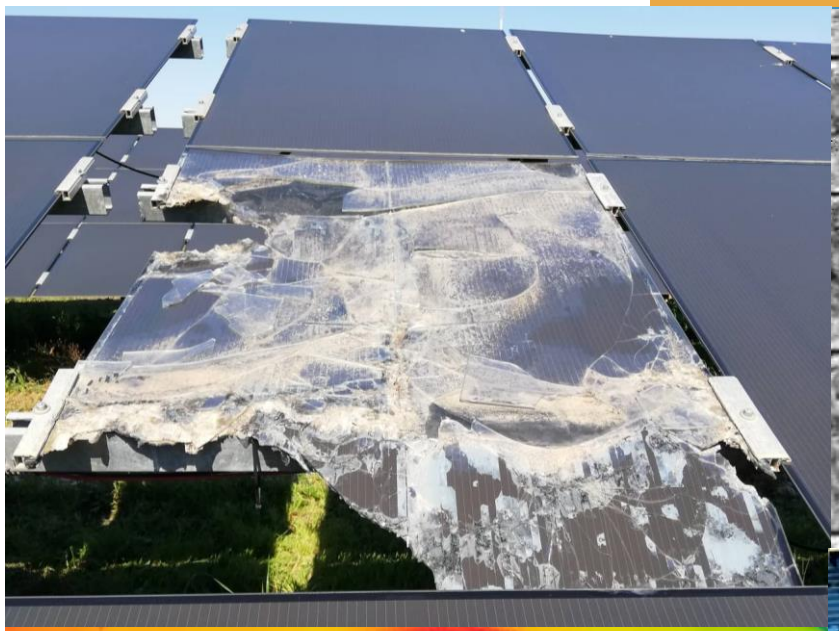
The PV sector must ensure that the installed power capacity in GW can also reliably generate TWh of electricity for an extended lifetime.



The introduction of novel technologies and novel PV system design makes the need of increased field performance and reliability a continuous industry demand. Solutions and services which are already available in the market or close to the market will need to be continuously updated and redefined to capture innovation trends. Moreover, new technologies can introduce new degradation modes once in the field.

Monitoring-based fault analysis and diagnosis are time-consuming, expert dependent and often of insufficient spatial granularity. As a result, several underperformance issues and failure modules – especially on PV module level – may either remain undetected, trigger “false alarms” or their root cause stays unidentified.

Losses

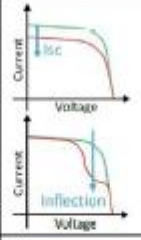
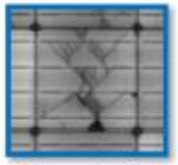
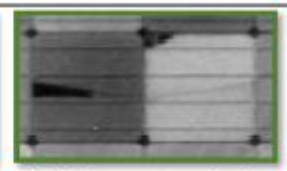
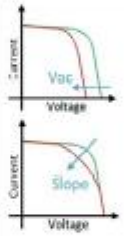
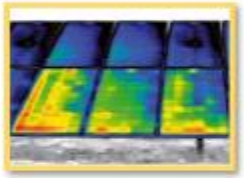
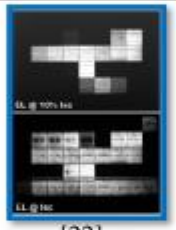
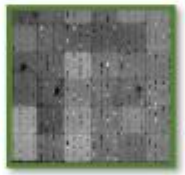
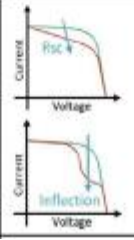


Courtesy of Guillermo Oviedo Hernández

MODULE LOSSES

SYSTEM LOSSES

Review of failures in the field

Performance reducing observations	*CPL/DR* Commonly described	I-V Affected parameters (from [22])	Inspection Method Inspection methods with a possibility of detecting one respective observation, degradation mode or failure in the corresponding categories. Images are example appearances.
Fractured Solar Cell	*CPL* up to 1-15 % [28]		VI IR-T **EL** dPL **UV-F**  Snail Trail  Type-C crack [22]  Type-A, -B and -C cracks  Visible type-A and –C cracks  Crack type not clear [9]
PID	*CPL*: up to 100 % [22] *DR*: 1-4 %/a [55] up to 20 % in first year [29]		- IR-T **EL** dPL -  [22]  [22]  [77]
Glass Breakage	Module failure (exchange necessary)	Depending on severity	VI IR-T **EL** dPL **UV-F**  Breakage of glass and module parts  Glass breakage caused hot spots [7] Similar pattern as in dPL  Fragmented glass Zero signal due to photo bleaching
Quick Connector Failure	*CPL*: up to 100 %		VI IR-T (EL) (dPL) -  Burned quick connector [16]  Module in open circuit [22] No signal due to missing connection No signal due to missing connection

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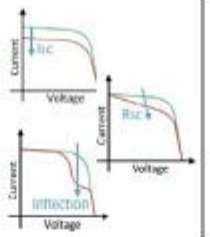
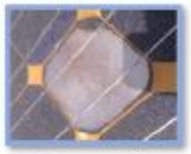
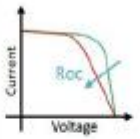
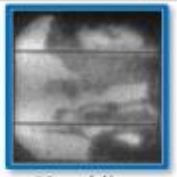
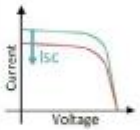
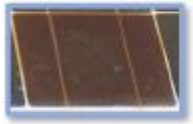
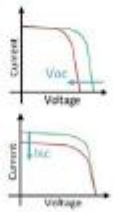
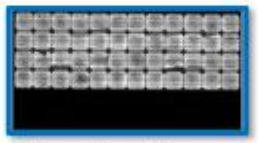
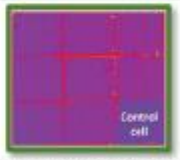
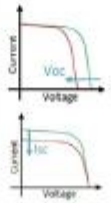
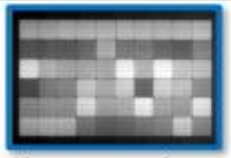
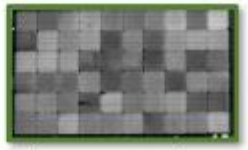
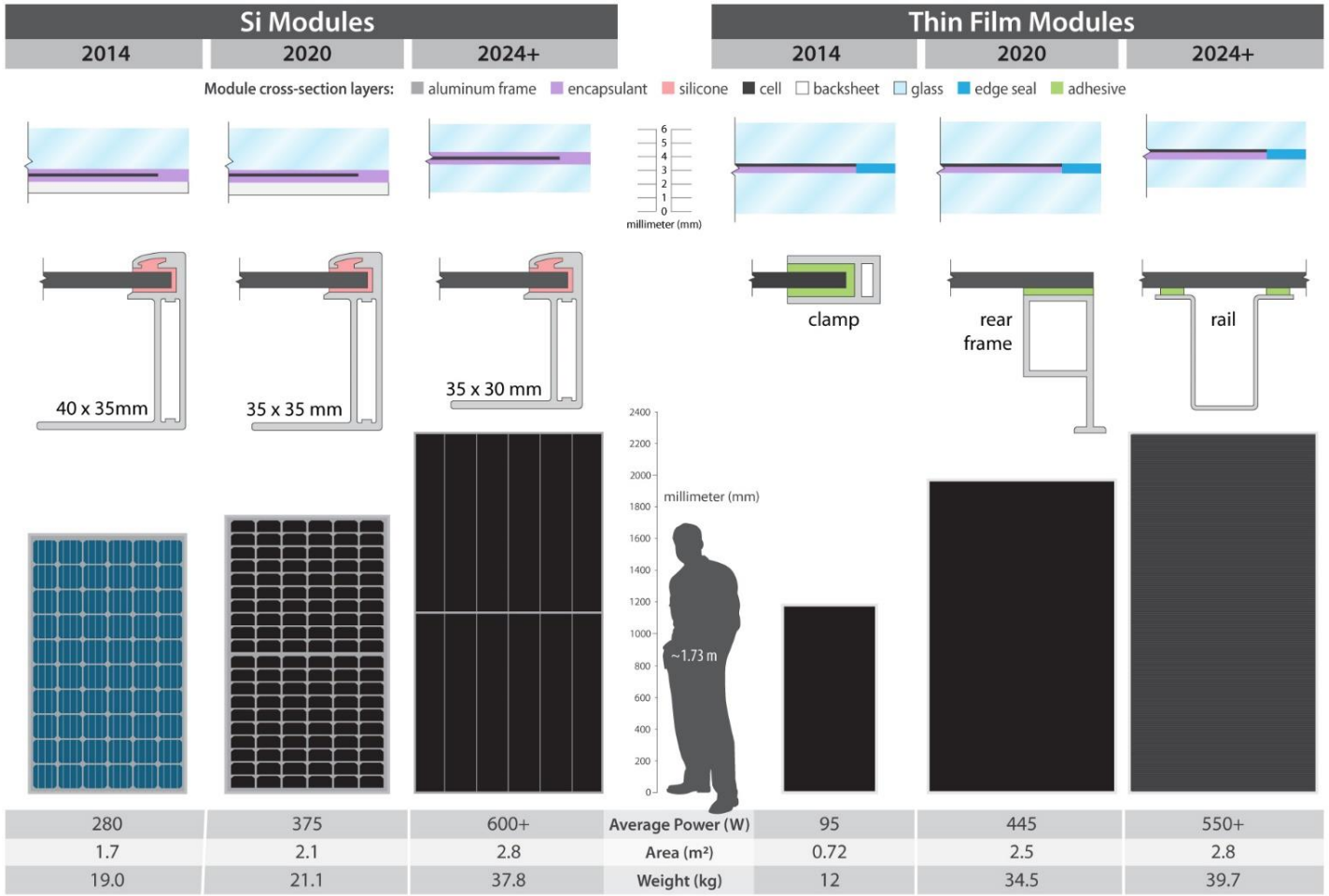
Review of photovoltaic module degradation, field inspection techniques and techno-economic assessment, https://doi.org/10.1016/j.rser.2022.112616

Review of failures in the field

Delami-nation	CPL: 0-4 % [22]		VI - - - -	 Front cell delamination [28]  Backsheet delamination [16]
Internal Circuitry Discoloration	*DR*: 1 %/a [17]		VI - EL - -	 Corrosion string interconnect [29]  Humidity corrosion [22]
Encapsulation Discoloration	*CPL*: up to 45 % [52] *DR*: 0.5-1 %/a [29]		VI IR-T - - UV-F	 EVA browning [22] Hot spot as possible root Increased fluorescence signal [9]
Junction Box / Bypass diode	*CPL*: up to 100 %		(VI) IR-T EL dPL -	 Junction box missing lid [29]  Short circuit bypass diode [22]  Short circuit bypass diode [22]  Short circuit bypass diode [13] ©JohnWiley & Sons, Inc.
LID / LeTID	*CPL*: up to 6 % (LID [61]) or 16 % (LeTID [64])		- - EL dPL -	 Chess pattern due to LeTID [66]  Chess pattern due to LeTID

Review of photovoltaic module degradation, field inspection techniques and techno-economic assessment, https://doi.org/10.1016/j.rser.2022.112616

Growing Panes: Investigating Sudden Increase in Early Failures



280	375	600+	Average Power (W)	95	445	550+
1.7	2.1	2.8	Area (m²)	0.72	2.5	2.8
19.0	21.1	37.8	Weight (kg)	12	34.5	39.7

Trends

Thinner glass

Glass-Glass

Heat treatment variability

Smaller frames

Larger areas

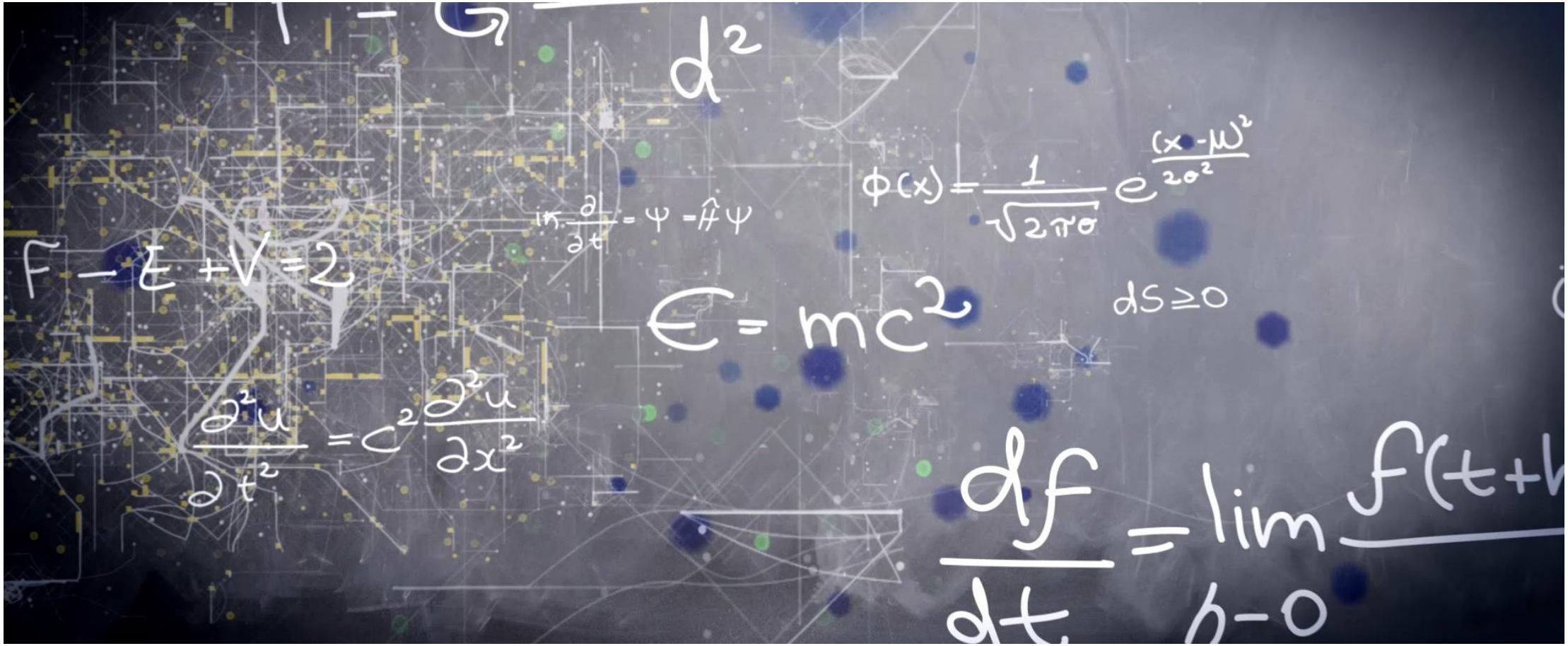
Single-axis trackers

Current qualification testing appears ineffective for catching early failures in these new module designs

There is insufficient reliability information on these designs to inform module buyers

Growing Panes: Investigating the PV Technology Trends Behind Frequent Early Failures in Modern Glass–Glass Modules
DOI 10.1109/JPHOTOV.2025.3526170

Technical risks framework: towards a standardised approach to quality



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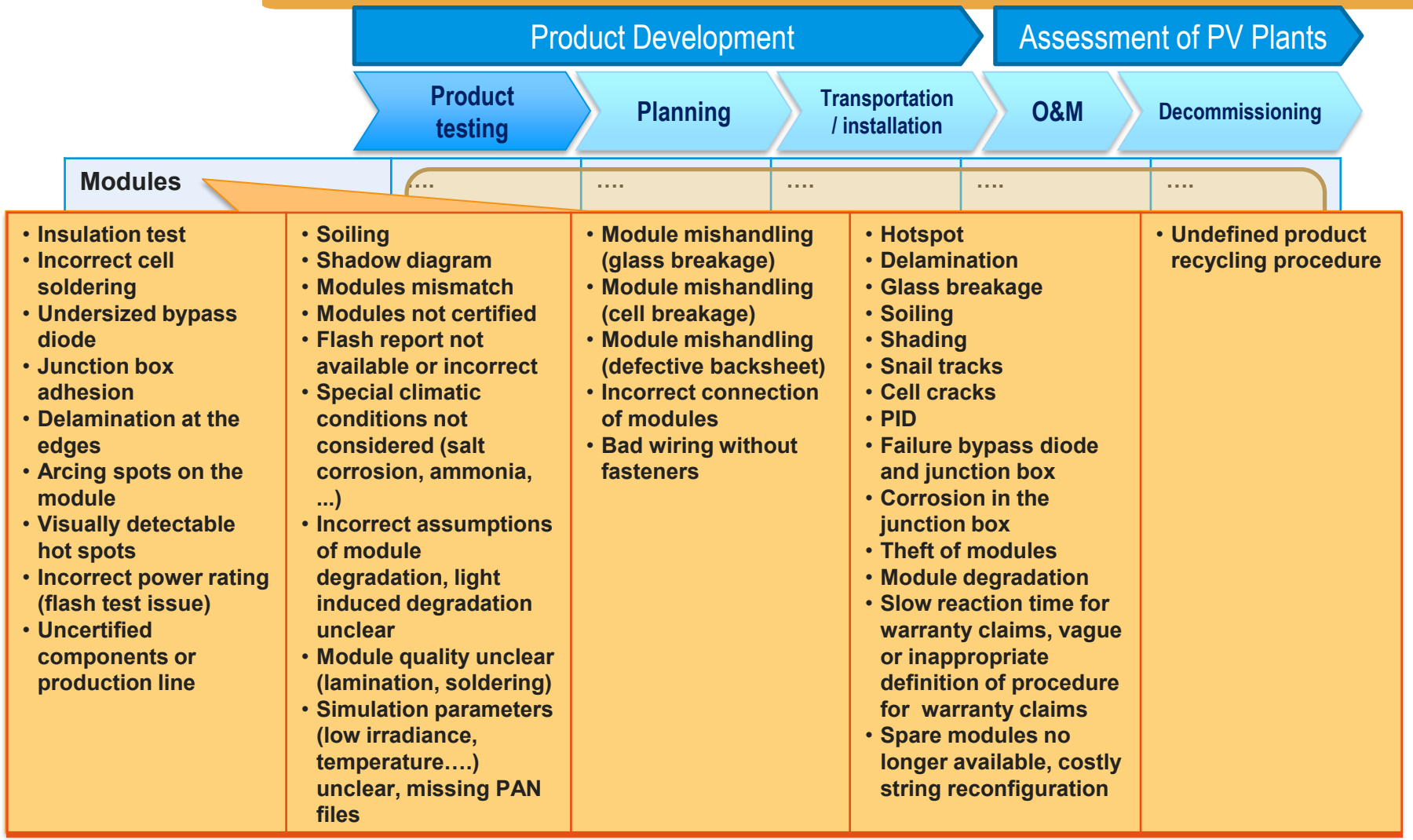
Risk matrix and common taxonomy



Product testing	Planning	Transportation / installation	O&M	Decommissioning
• Insulation test • Incorrect cell soldering • Undersized bypass diode • Junction box adhesion • Delamination at the edges • Arcing spots on the module • Visually detectable hot spots • Incorrect power rating (flash test issue) • Uncertified components or production line	• Soiling • Shadow diagram • Modules mismatch • Modules not certified • Flash report not available or incorrect • Special climatic conditions not considered (salt corrosion, ammonia, ...) • Incorrect assumptions of module degradation, light induced degradation unclear • Module quality unclear (lamination, soldering) • Simulation parameters (low irradiance, temperature….) unclear, missing PAN files	• Module mishandling (glass breakage) • Module mishandling (cell breakage) • Module mishandling (defective backsheet) • Incorrect connection of modules • Bad wiring without fasteners	• Hotspot • Delamination • Glass breakage • Soiling • Shading • Snail tracks • Cell cracks • PID • Failure bypass diode and junction box • Corrosion in the junction box • Theft of modules • Module degradation • Slow reaction time for warranty claims, vague or inappropriate definition of procedure for warranty claims • Spare modules no longer available, costly string reconfiguration	• Undefined product recycling procedure

f failures

Cost-based Fa
and Effects An
(FMEA) for PV

a) Economic impact due to
to Euros)
- Failures might cause dow
- Time is from failure to rep
time to detection, respons
- Failures at component lev
(e.g. module failure might

b) Economic impact due to
- Cost of detection (field ins
etc)
- Cost of transportation of c
- Cost of labour (linked to d
- Cost of repair/substitution

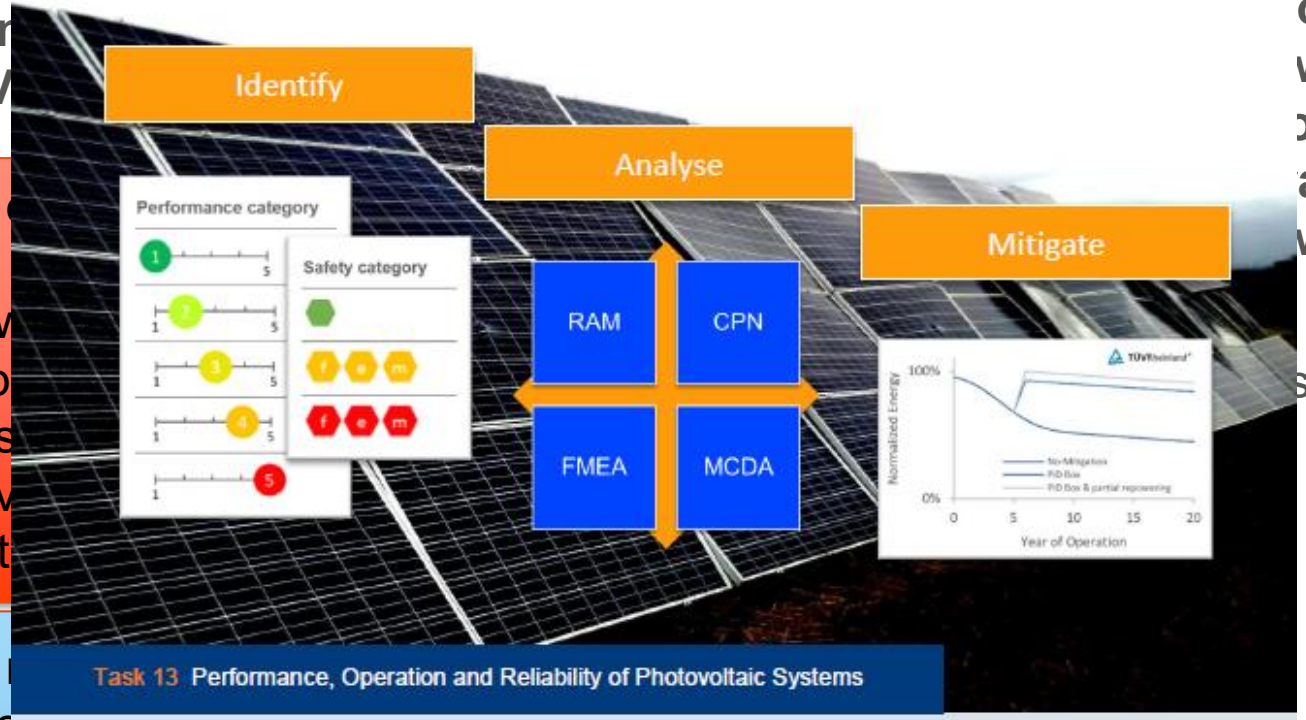
ows for
veen asset within the same
o (AM, O&M)
ategies in EPC, O&M
veen the various phases of

s reduction

ase
ase

Technology Collaboration Programme
by iea

International Energy Agency
Photovoltaic Power Systems Programme



Task 13 Performance, Operation and Reliability of Photovoltaic Systems

IEA PVPS

Quantification of Technical Risks in PV Power Systems 2021

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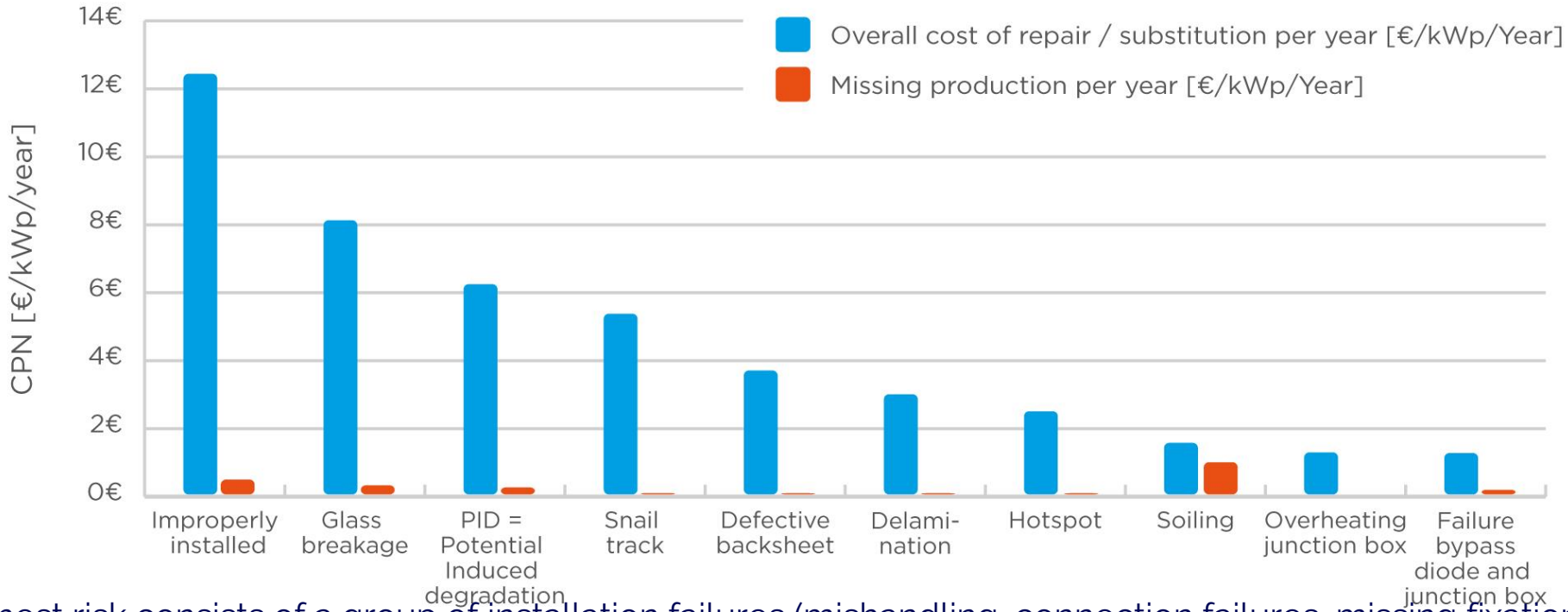
CPN Results - Components and Market Segments

- PV modules - Utility scale



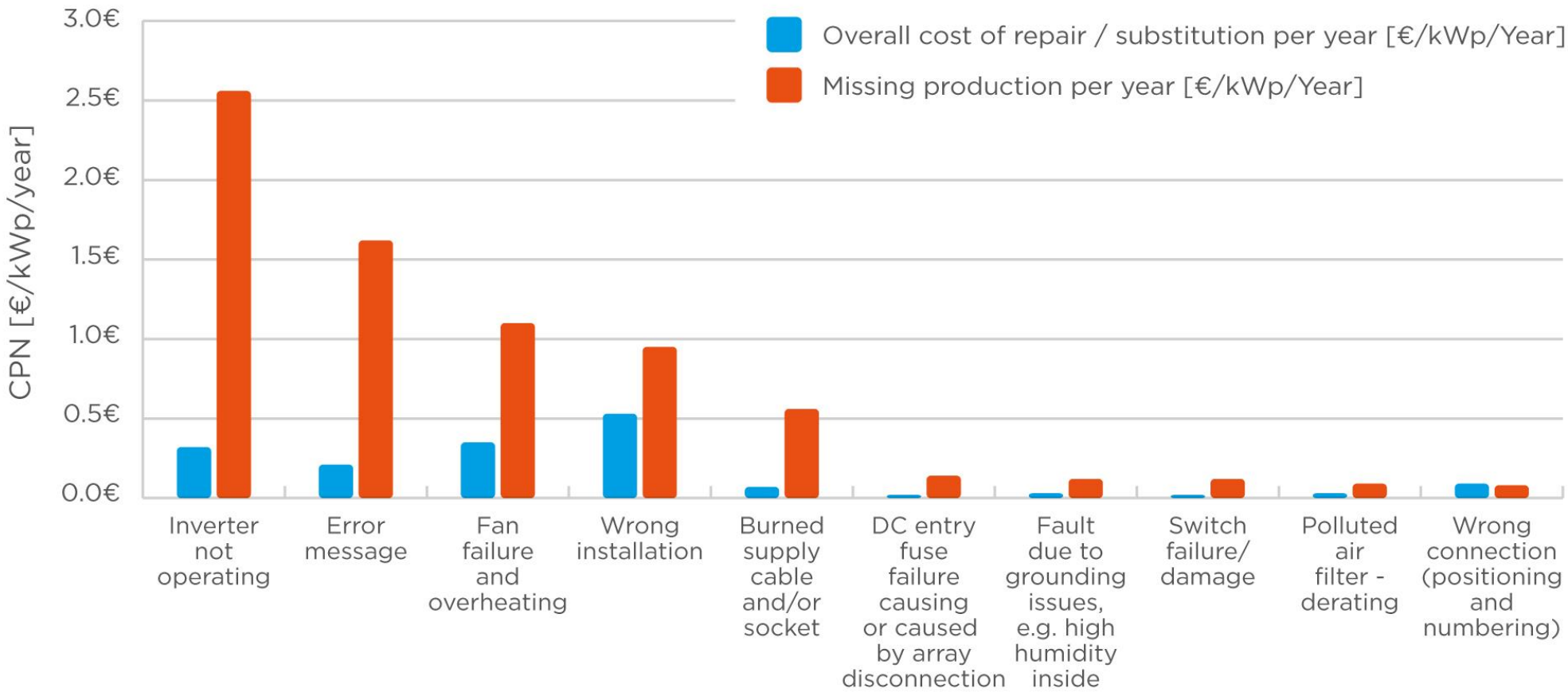
- Highest risk consists of a group of installation failures (mishandling, connection failures, missing fixation, etc.)
- Variety of failures detected by different techniques (VI, IR, EL, IV-Curves)

Scenario based results!

CPN Results - Components and Market Segments

- Inverters

Scenario based results!



Economic impact of failures and treaceability

When a failure occurs, e.g. performance deviation beyond allowed threshold or inverter error code generated.
An alarm is triggered

Acknowledgement of the fault by the O&M Contractor.
A maintenance ticket is opened

The technician arrives on-site with all the tools and spare parts needed to fix the problem

Problem fixed and acknowledged by the O&M Contractor.
The maintenance ticket is closed

failure time | acknowledgement time | intervention time | resolution time

Detection time

Time that it takes to detect the occurrence of a problem

Response time

Time that it takes to organise the repair or substitution

Repair time

Time that it takes the technician to fix the problem

CPN is the economic impact of a failure

Cost ownership is easy with CPN methodology once responsibilities are clear (AM, AO, O&M, insurance, warranty, etc)

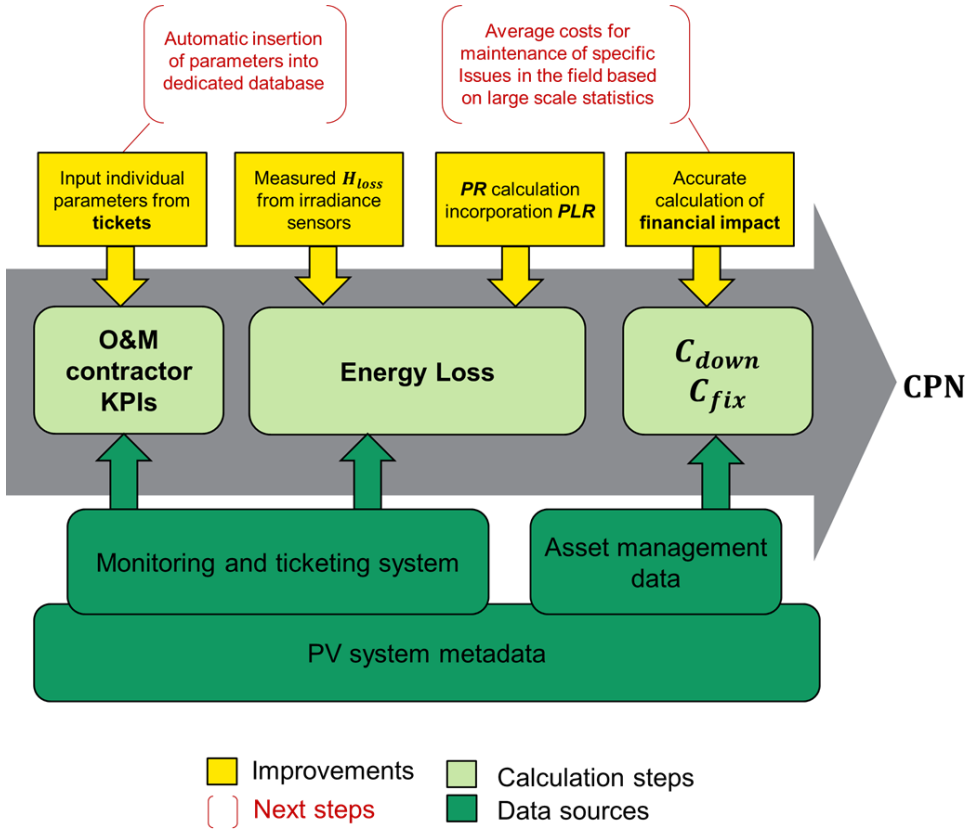
Digitalisation becomes a necessity!

OPTIMIZATION OF THE COST PRIORITY NUMBER (CPN) METHODOLOGY TO THE NEEDS OF A LARGE O&M OPERATOR, G. Oviedo Hernandez et al, EUPVSEC 2019, Marseille 5CV.4.19

Digitalisation as THE driver for quality

Process digitalisation

Full integration of monitoring platforms and ticketing systems



- Creation of standardised metadata (PV passport)
- Development of an automated and therefore time-efficient solution for extracting key parameters from maintenance tickets to gain statistical insights from a large number of PV plants.
- Development of a software tool for field technicians that would allow the precise and error-free recording of standardised parameters for the calculation of the O&M contractors KPIs necessary for an efficient implementation of the methodology
- The O&M field practices must definitely move away from a manual input of tickets in text format and adopt a more standardised approach when human intervention is limited

OPTIMIZATION OF THE COST PRIORITY NUMBER (CPN) METHODOLOGY TO THE NEEDS OF A LARGE O&M OPERATOR, G. Oviedo Hernandez et al, EUPVSEC 2019, Marseille 5CV.4.19

RISK MATRIX: TAXONOMY (OR ONTOLOGY)

Failure appearance in PV plant

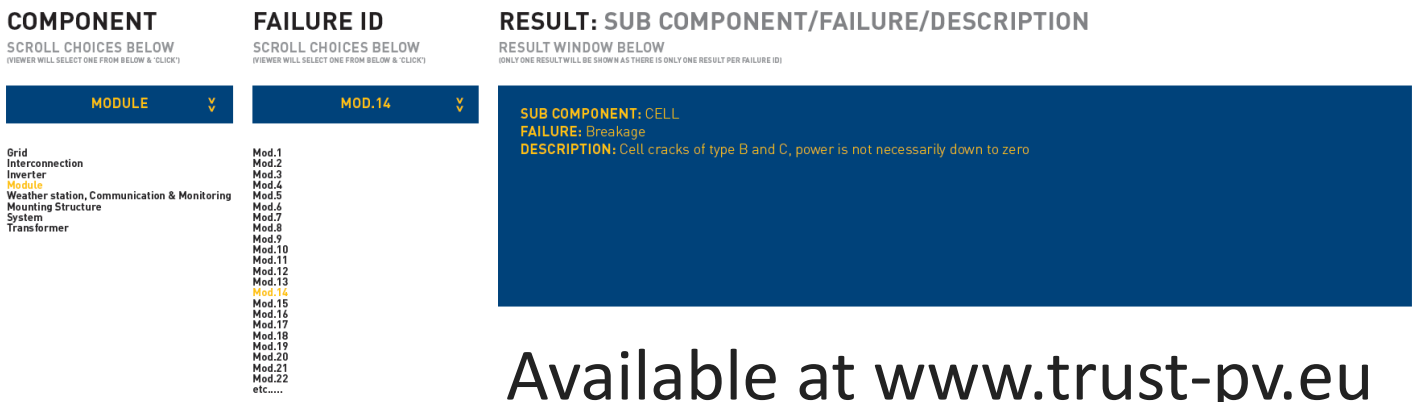
Creation of ticket in SCADA system

Classification of failure according to TRUST PV's Risk Matrix

Resolution of failure

Statistical analysis of failure (CPN)

Risk Matrix Update



Available at www.trust-pv.eu

Ticket Alignment

250,000s tickets of >100 PV plants aligned

INNOSEA An LDC Company · Statkraft · enel Green Power · BayWa r.e.

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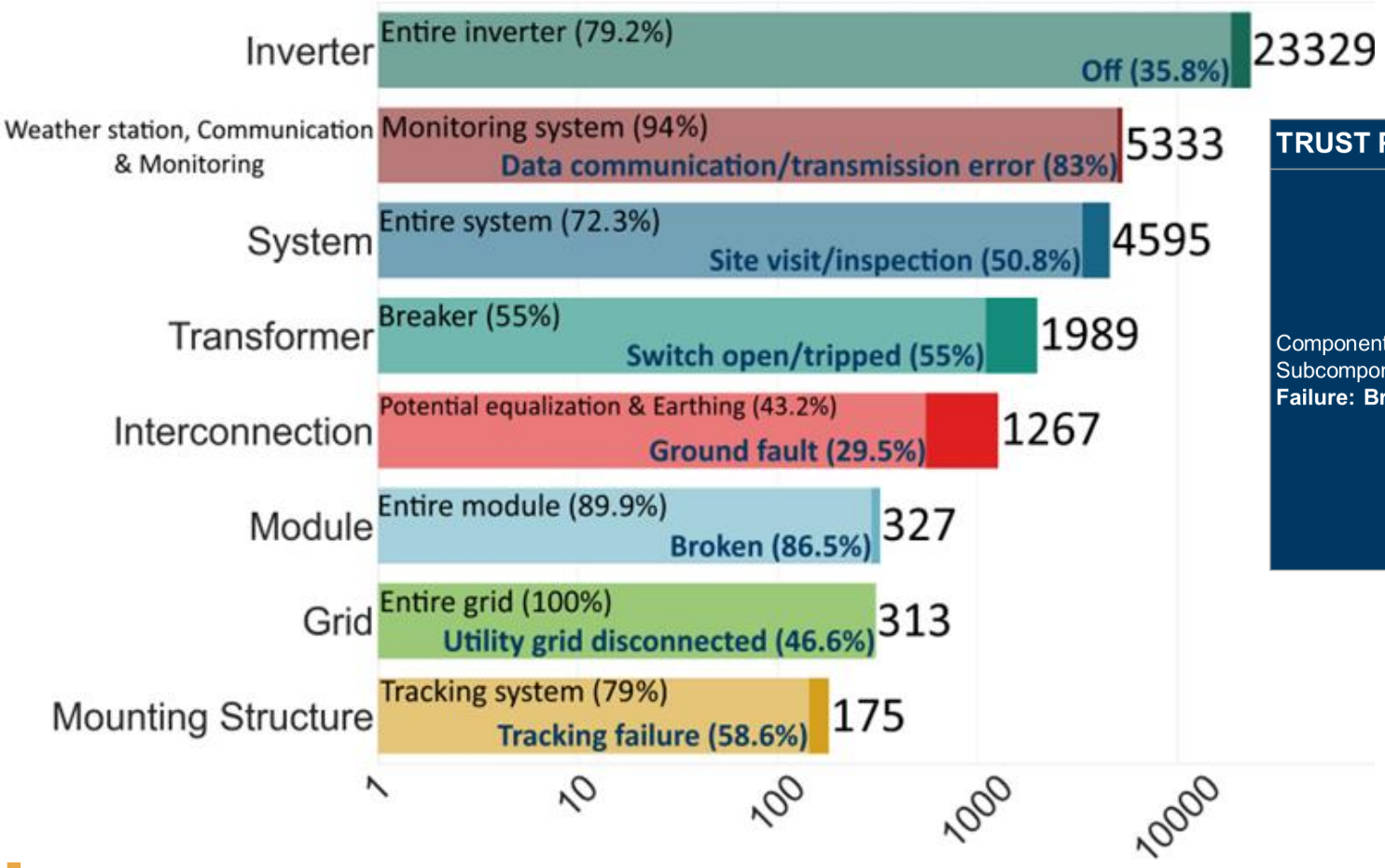
ANALYSIS OF MAINTENANCE TICKETS



TRUST PV's RISK MATRIX	O&M TICKETS
Component: Module Subcomponent: Entire Module **Failure: Broken module**	Damaged PV Module Found broken panel Faulty panel Isolated broken panels 2 broken panels found at string X PV panel outage String isolated due to broken panel Damaged panel Damaged module Broken module Faulty module Module broken Smashed module

What is the level of detail at component level? Need of common dictionary

Is this a true representation of reality or is it biased by the ease of detection?

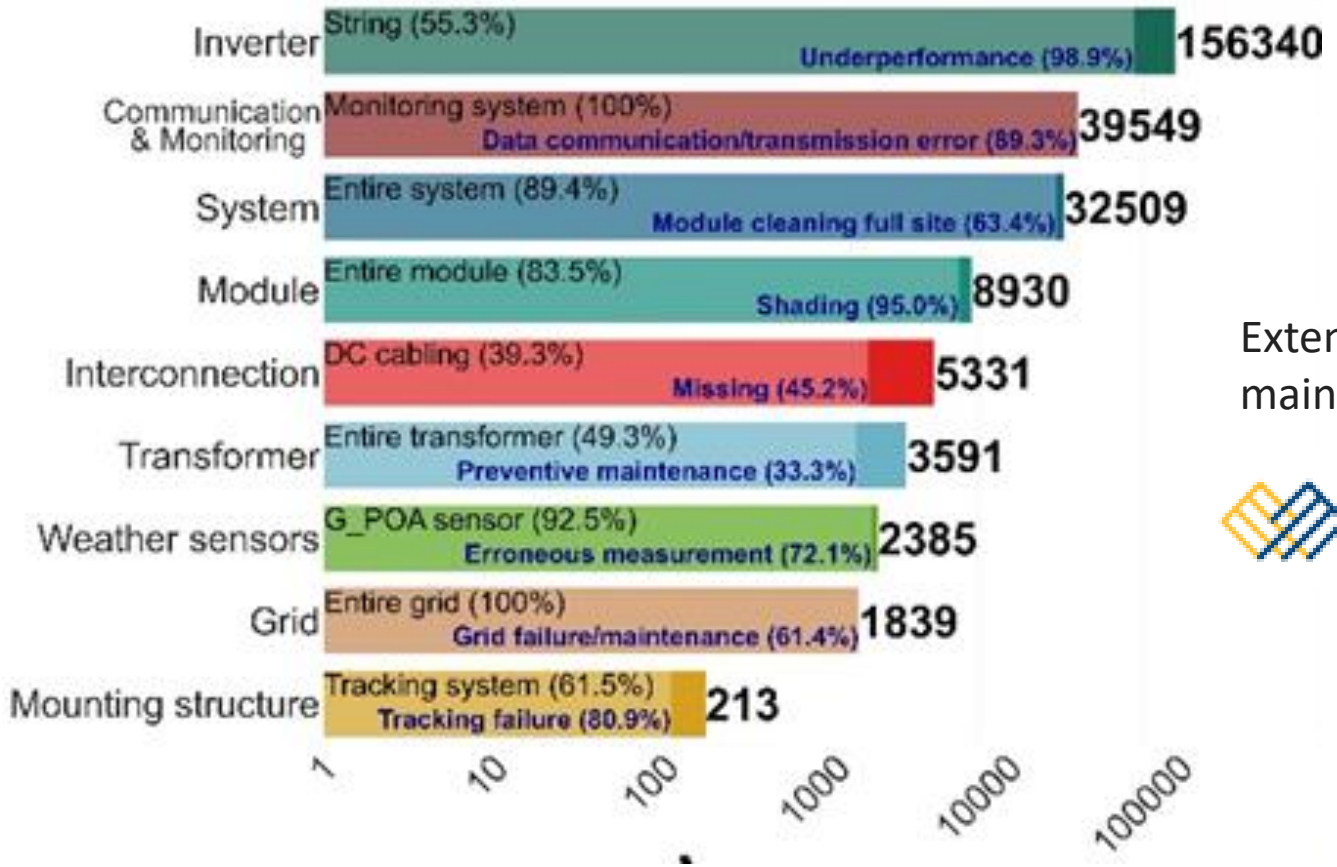
Towards the development of an optimized Decision Support System for the PV industry: A comprehensive statistical and economical assessment of over 35,000 O&M tickets

https://doi.org/10.1002/pip.3637

ANALYSIS OF MAINTENANCE TICKETS

60-65%

3-5%



Extended to 250,000 maintenance tickets

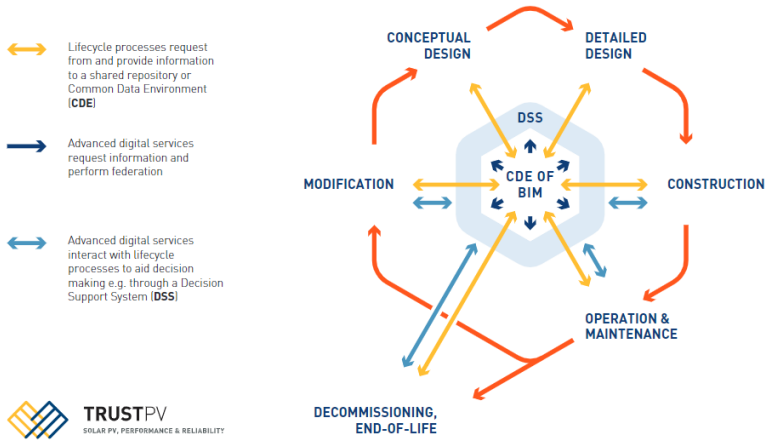
TRUSTPV

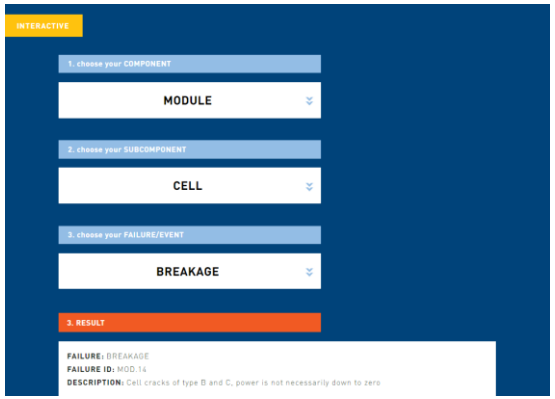
INGREDIENTS FOR AUTOMATION IN O&M and AM: State of the art

Management, sharing and federation of PV asset information throughout the lifecycle
DIGITAL TWIN AND UNIVERSAL MAPPING

TRUSTPV
SOLAR PV, PERFORMANCE & RELIABILITY

SUPERNOVA



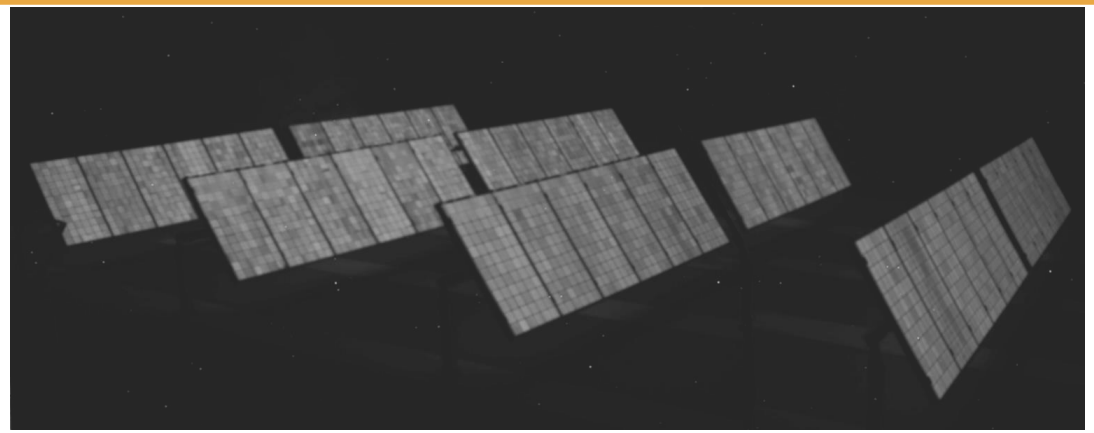


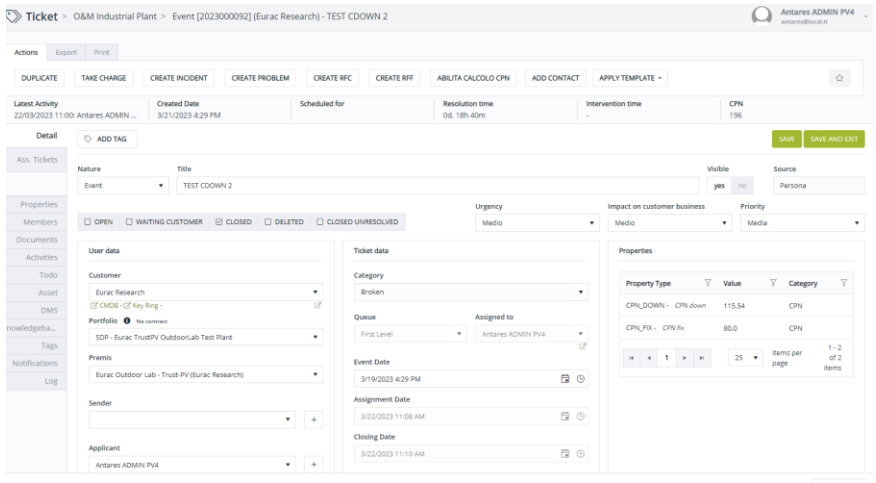
TRUSTPV
SOLAR PV, PERFORMANCE & RELIABILITY

Implement a RISK MATRIX in the ticketing platform to harmonise data coming from the field (independent from operator)

INGREDIENTS FOR AUTOMATION IN O&M and AM: State of the art

Identify failure through for e.g. advanced monitoring and semiautomated inspection techniques, and resolve the issue (SOLUTION MATRIX)





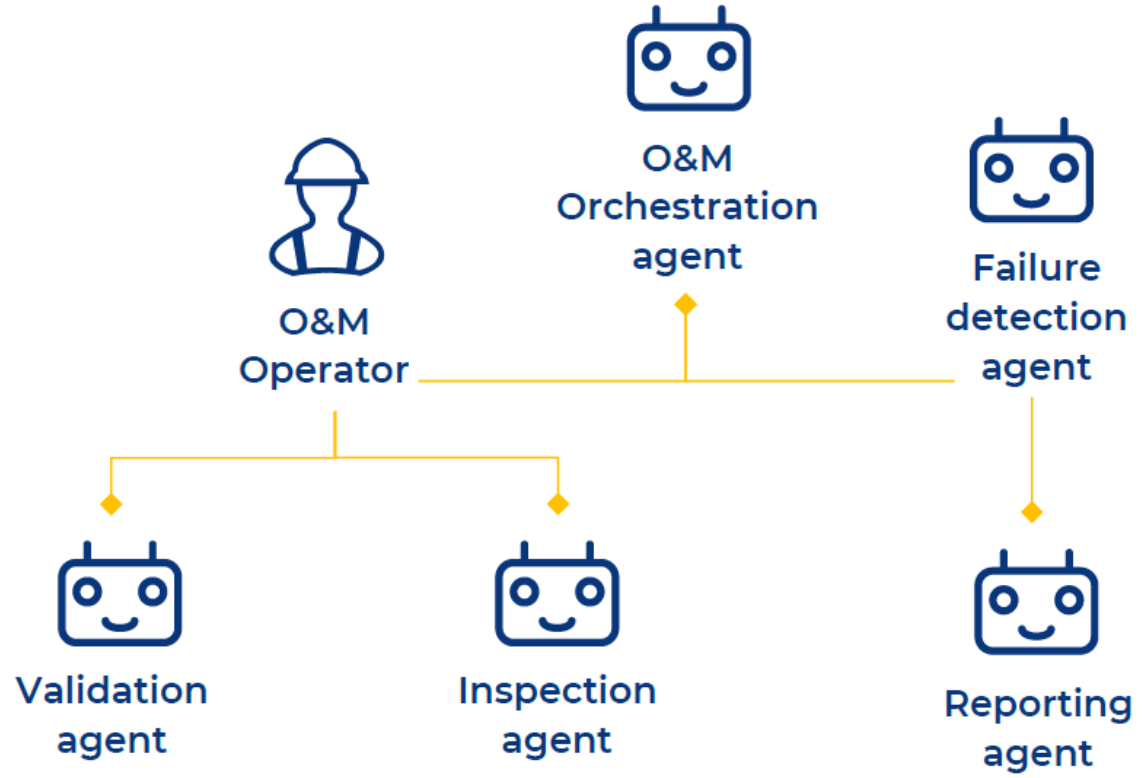
Calculate the final KPI and update a KNOWLEDGE BASE database

A **DSS** system can provide suggestions based on statistics and previous field experience for the most effective solution

What's next? Robots, workflows and genAI

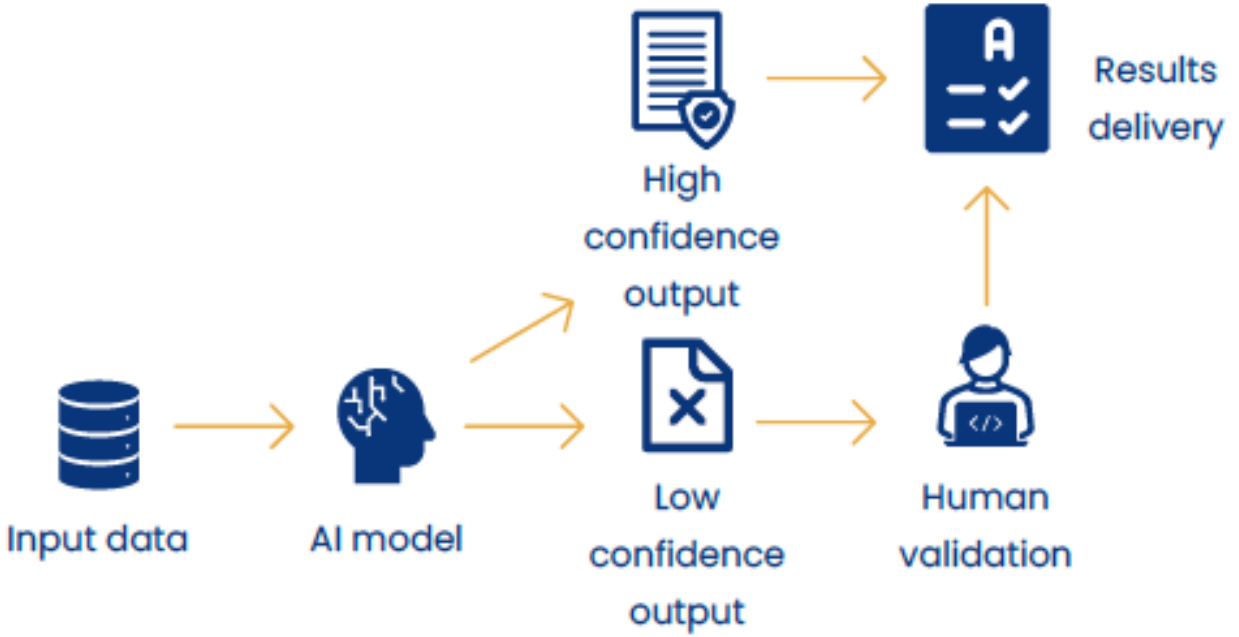
Hybrid teams

AI-Human Hybrid Teams are collaborative work arrangements where artificial intelligence systems and human workers operate together as integrated units, combining their complementary strengths to accomplish tasks.



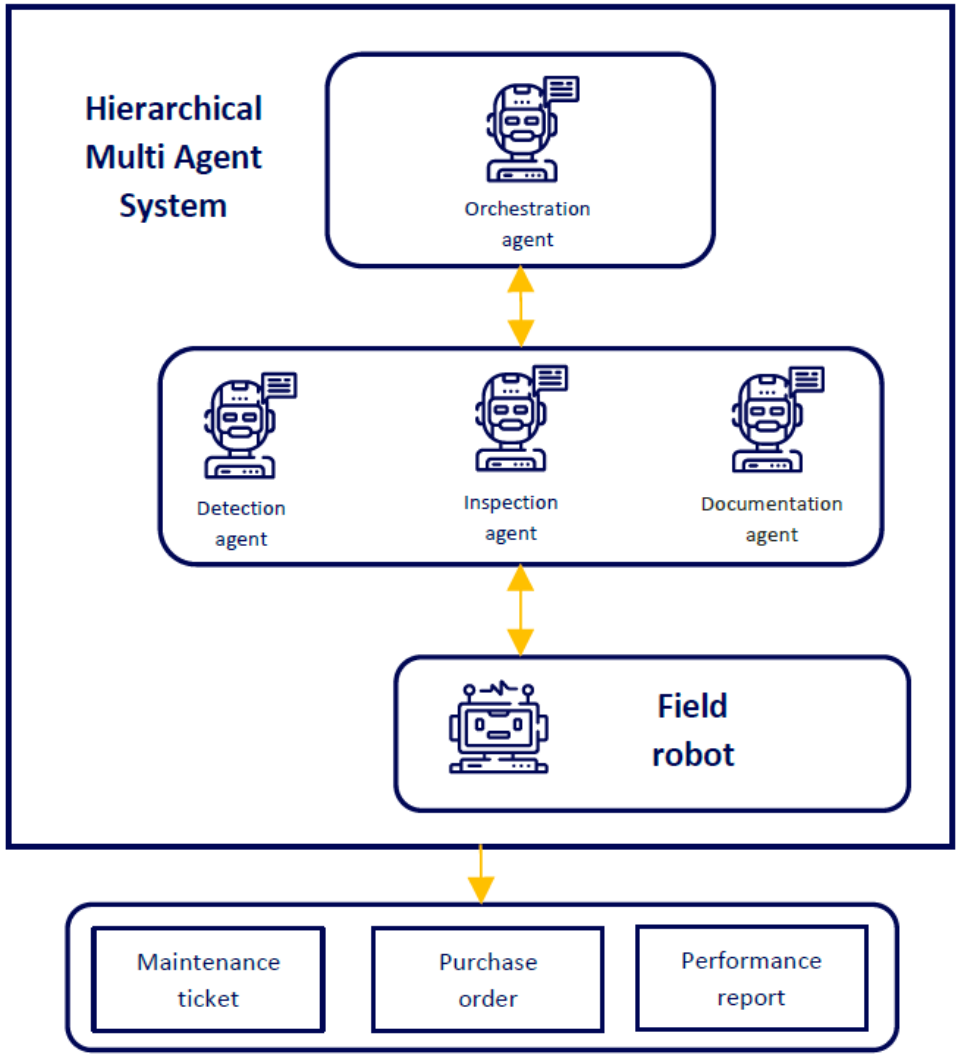
Human-in-the-loop

Human-in-the-Loop refers to a design approach where humans remain actively involved in AI system operations, particularly in critical decision points. Rather than fully automated processes, human-in-the-loop systems require human oversight, validation, or intervention at key stages. This ensures human judgment guides important outcomes while benefiting from AI's analytical capabilities.

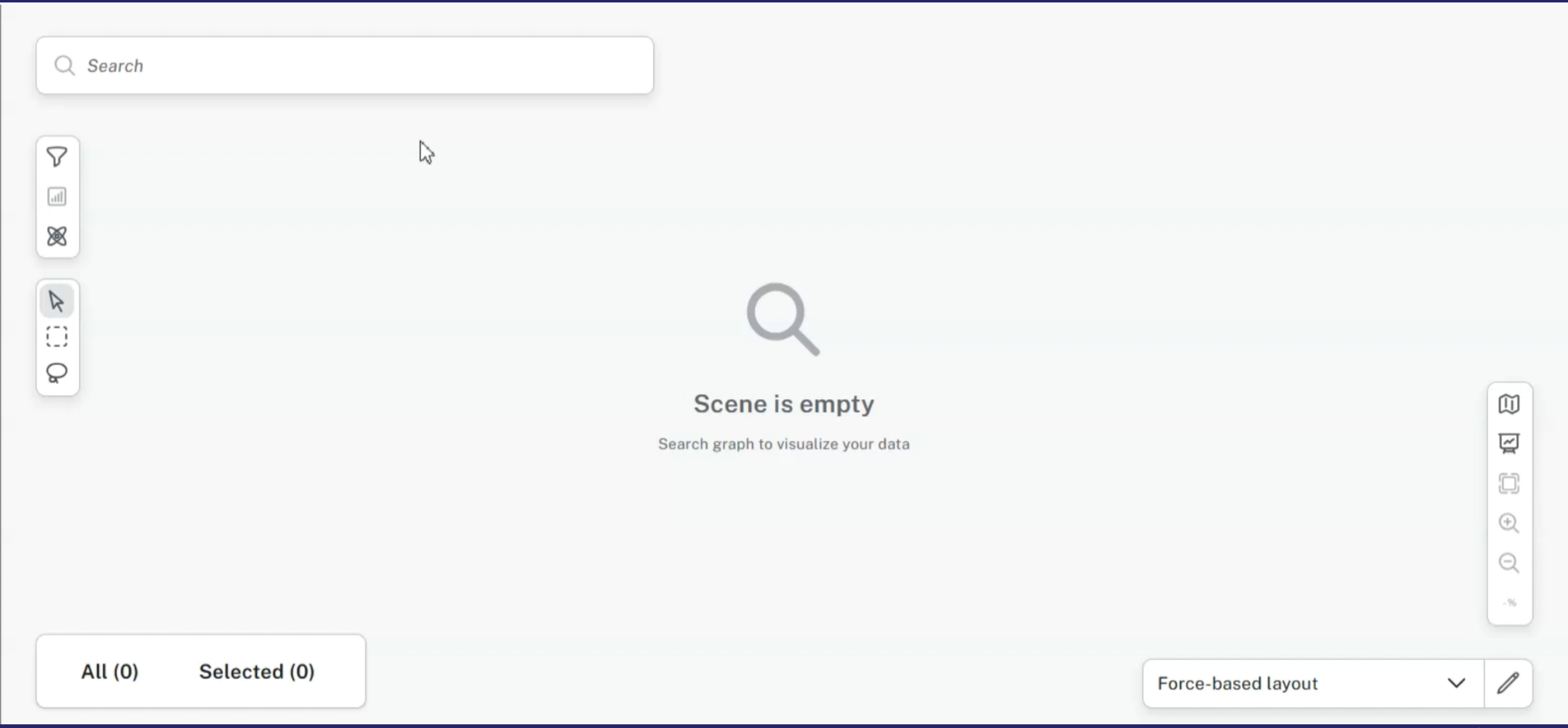


Multi-AI agents architecture

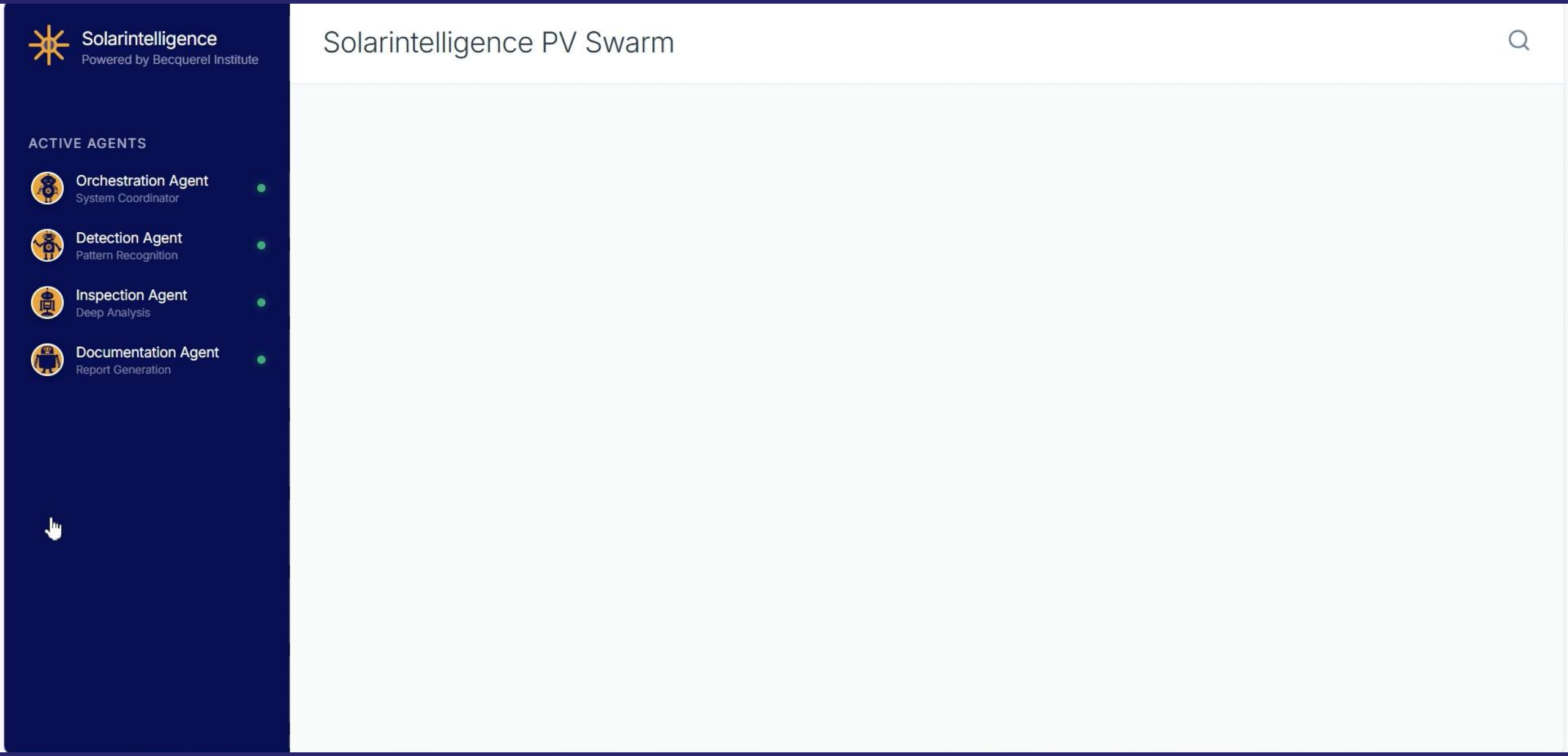
Multi-AI Agent Systems are composed of multiple specialized AI agents that collaborate to complete defined tasks by performing different actions within a shared workflow. Unlike single-agent systems,
which may struggle with complex or multi-step processes, multi-agent architectures distribute responsibilities across agents with distinct specialties.



PV O&M Ontology

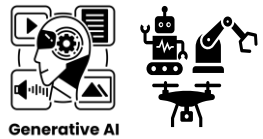


PV Swarm Demo



Automation along the value chain in 2030

Additional AI and Robotics automation



Component Manufacturing	Project Development & Engineering	Construction & Installation	Operation & Maintenance	Asset management & Trading
70-95%	70-90%	40-60%	60-80%	70-95%

Transforming the PV Sector: The AI & Robotics Revolution-Becquerel Institute
https://www.becquerelinstitute.eu/shop/transforming-the-pv-sector-the-ai-robotics-revolution-55

In the coming months, AI will drive a major leap in the PV industry, boosting efficiency, automation, and fundamentally transforming solar energy management.

The transition to generative AI requires the emergence of specialists to navigate its complex ethical and technological landscape

Solarintelligence.ai

AI-Powered Solar Market Intelligence Platform
The Industry's First Real-Time Intelligence Engine

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