

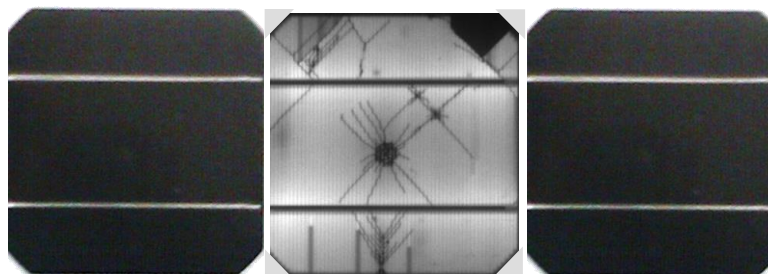


SCUOLA  
ALTI STUDI  
LUCCA



# **Durabilità e materiali innovativi per il fotovoltaico**

Una sfida dall'impatto  
industriale, economico e sociale



**Marco Paggi**

*IMT School for Advanced Studies Lucca*

Campus Party, 20 Luglio 2017, Milano

**IMT School for Advanced Studies Lucca** is a public graduate school and research institute that focuses on the analysis of economic, societal, technological and cultural systems



- 12 permanent faculty members
- Thematic research units
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- **Analysis and Management of Cultural Heritage (AMCH)**
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- **Computer Science and Systems Engineering (CSSE)**
- **Economics, Networks and Business Analytics (ENBA)**



# Multi-scale Analysis of Materials MUSAM Research unit



**MUSAM team**



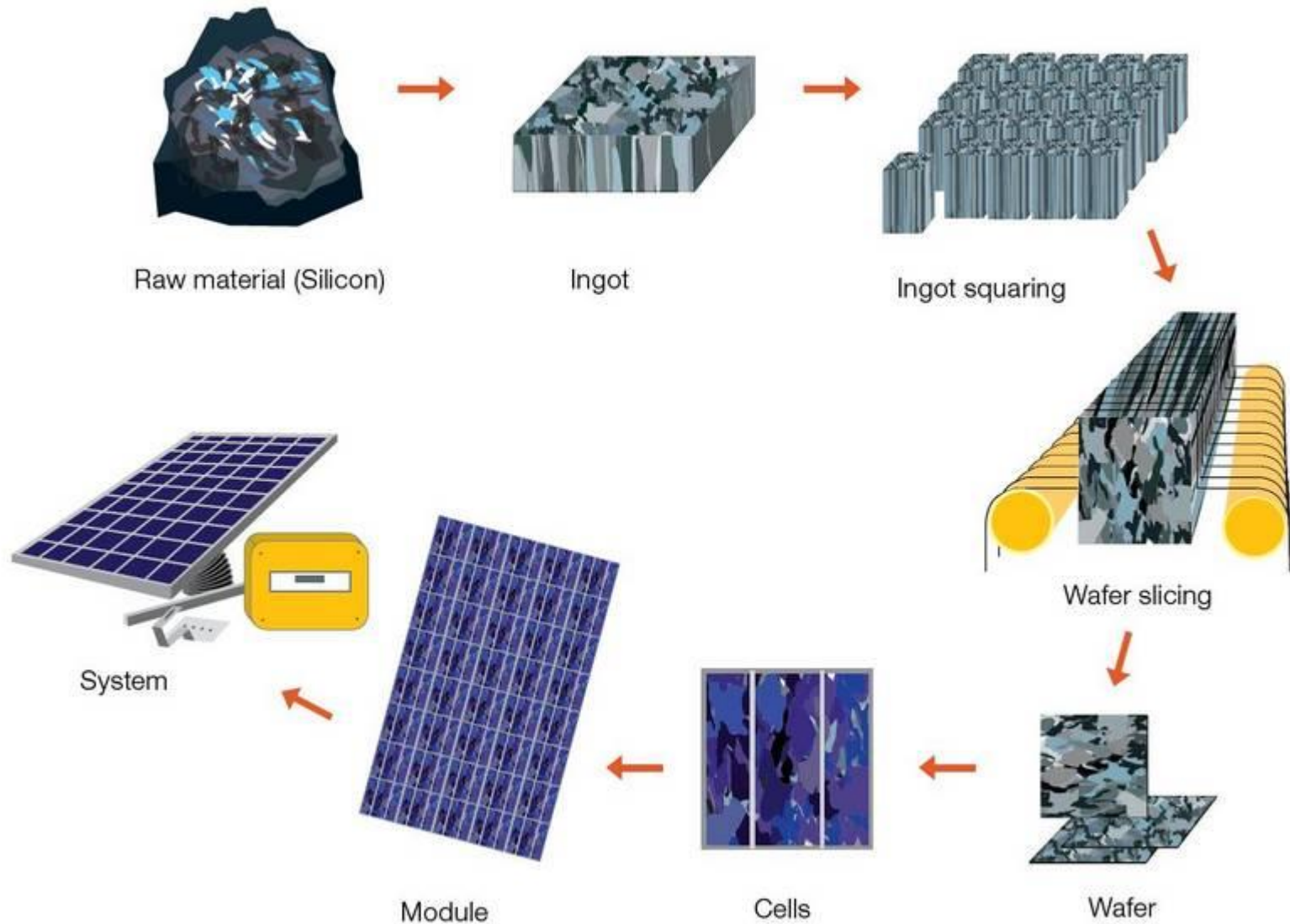
**International  
visiting professors**



**MUSAM-Lab**

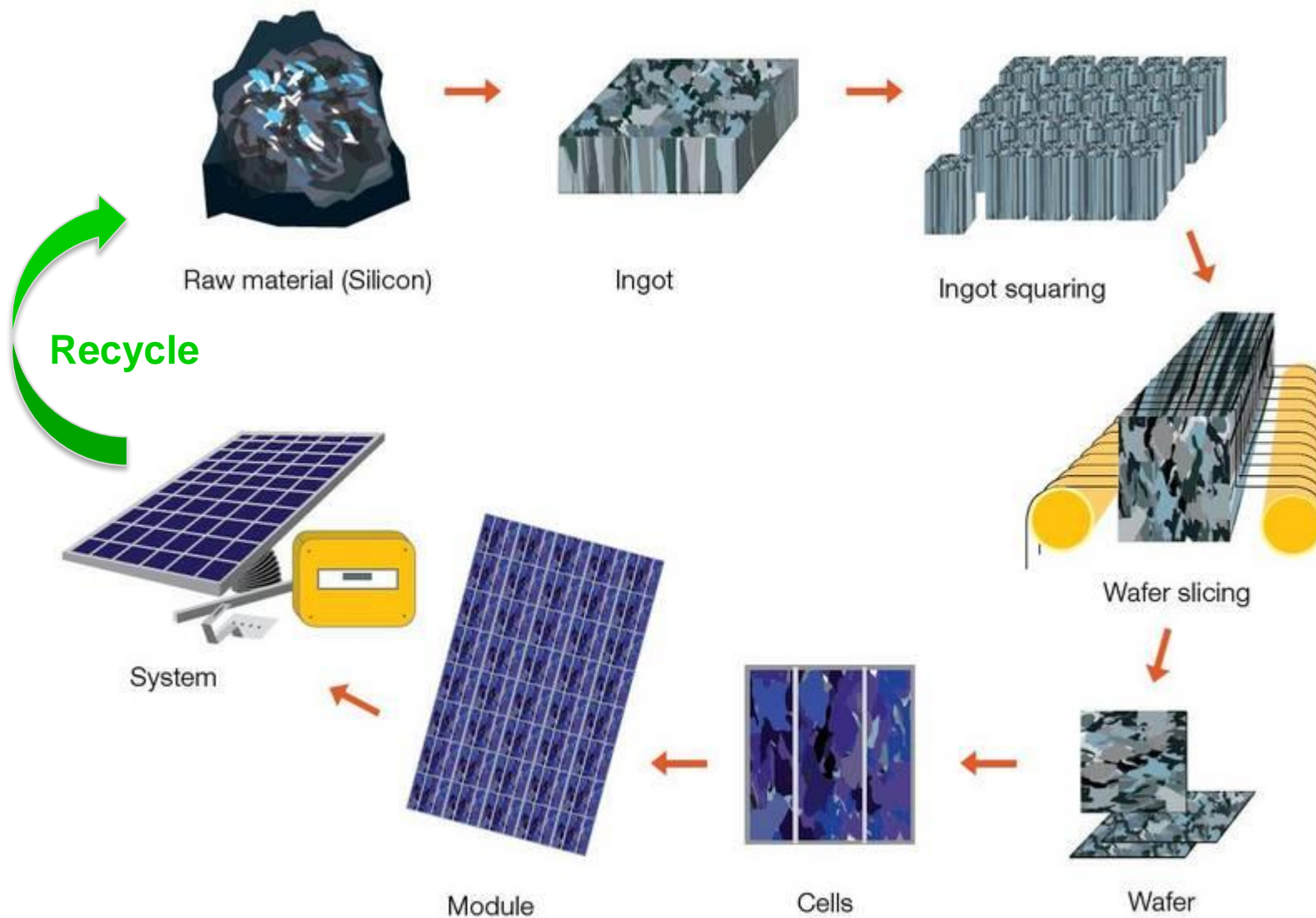
# **Photovoltaics: a technology for renewable energy production**

# Silicon-based solar cells production

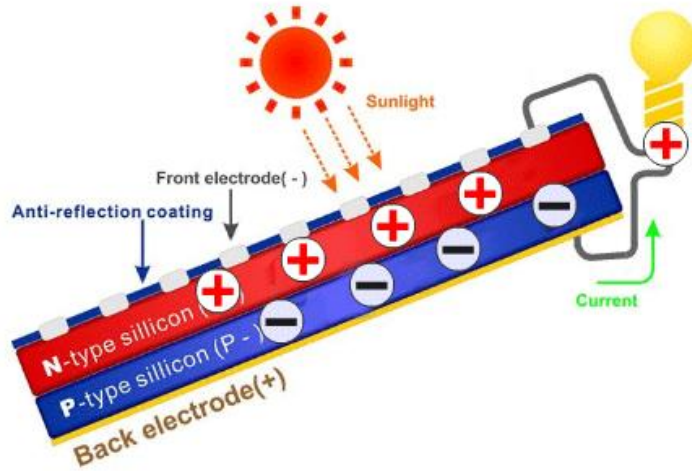




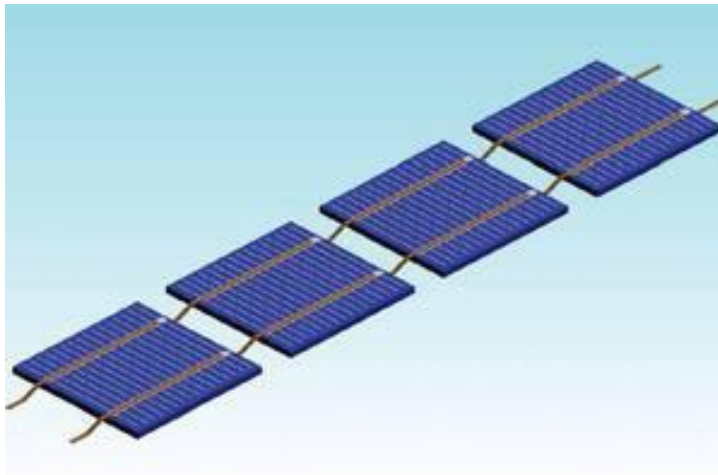
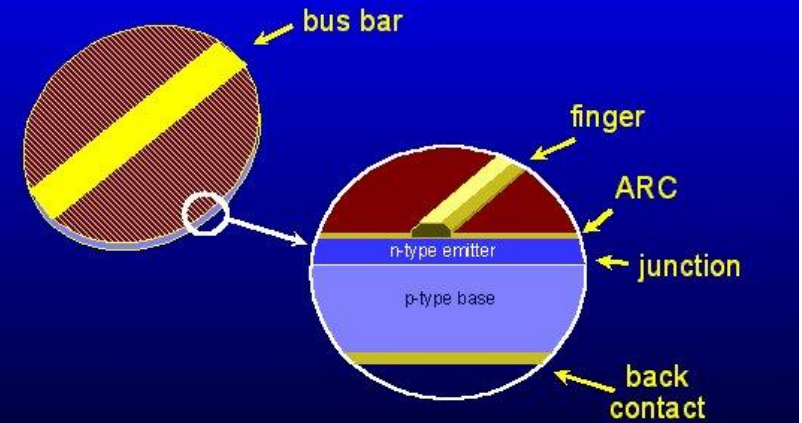
# Silicon-based solar cells production



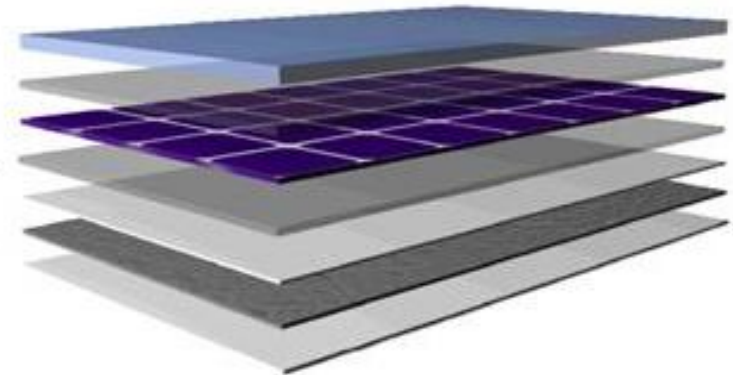
# Physical principles of photovoltaics



## The silicon solar cell



Glass  
EVA  
Solar cells  
EVA  
Tedlar  
Aluminum  
Tedlar





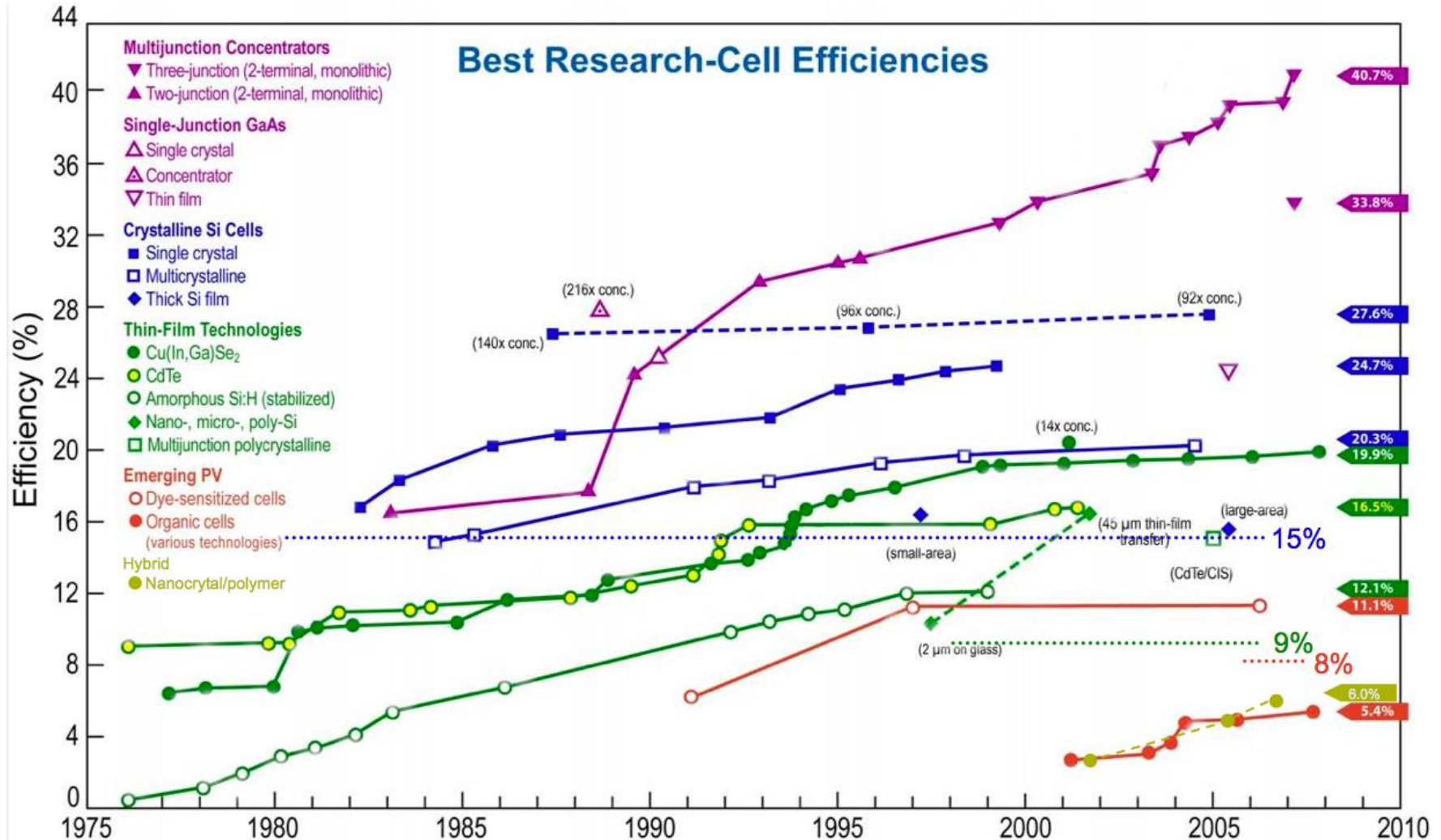
# Applications: from parks to building-integrated PV



# **Challenges: efficiency, durability, reliability**



# Increasing solar energy conversion: new semiconductors





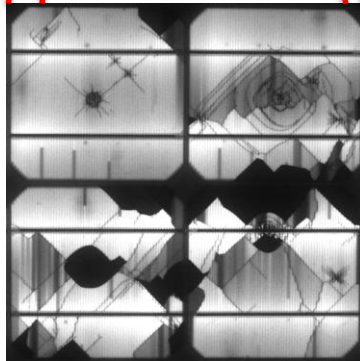
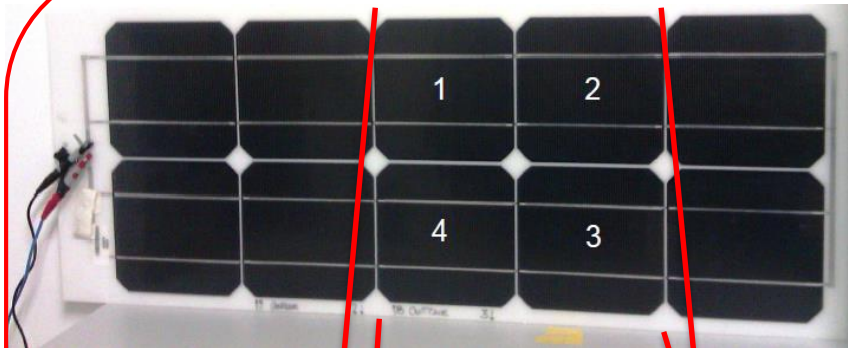
# Increasing durability and lifetime

## Material-related failure modes:

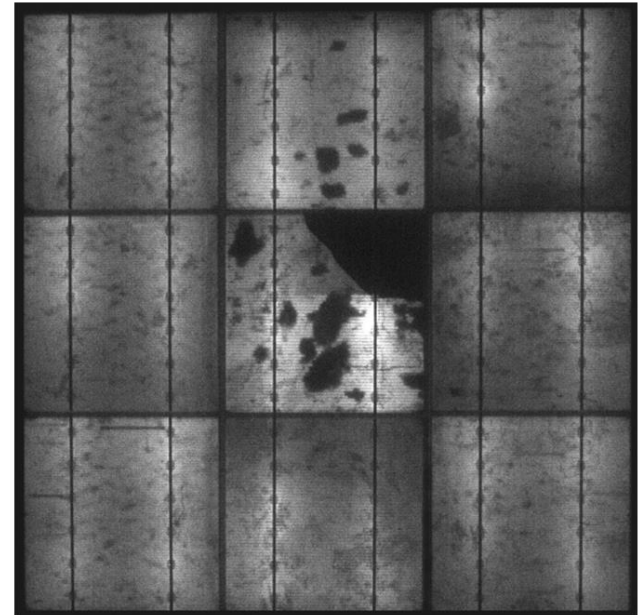
1. **Cracks**
2. **Decohesion of the encapsulant**
3. **Moisture-induced degradation**



2

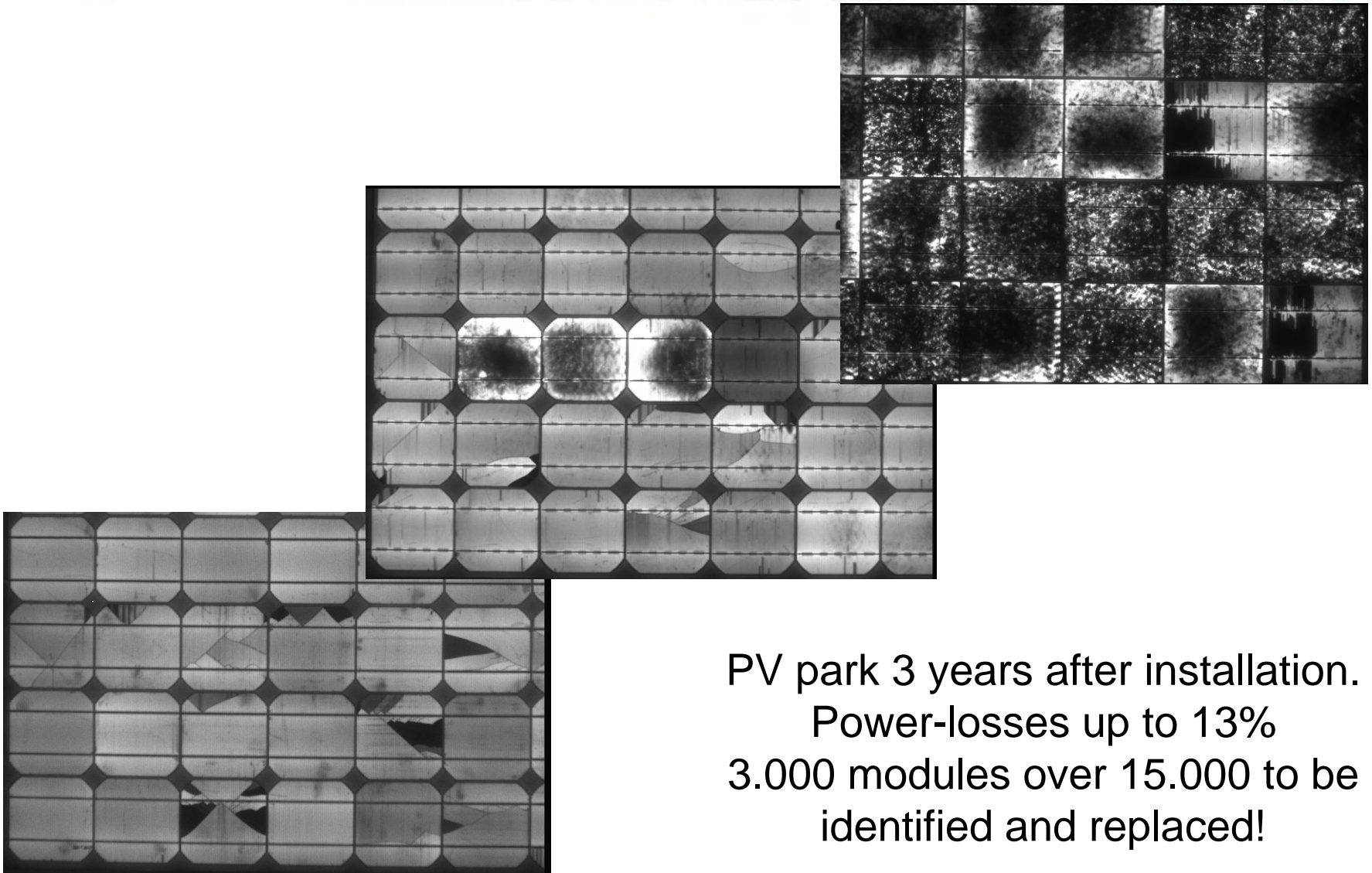


1



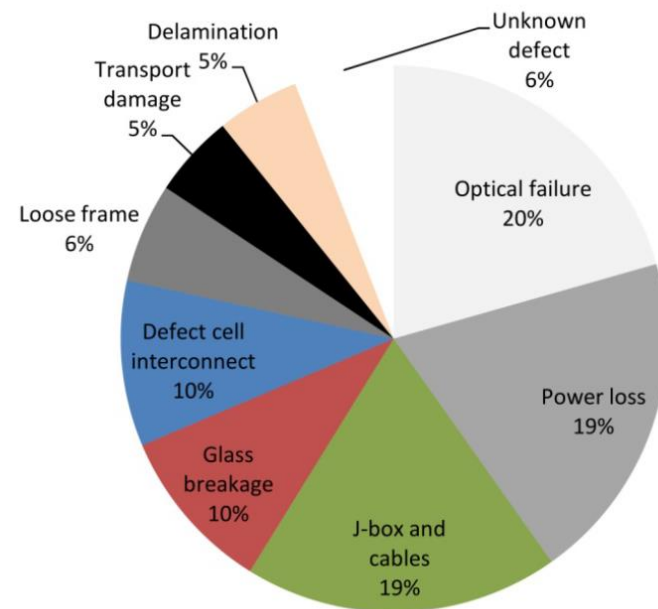
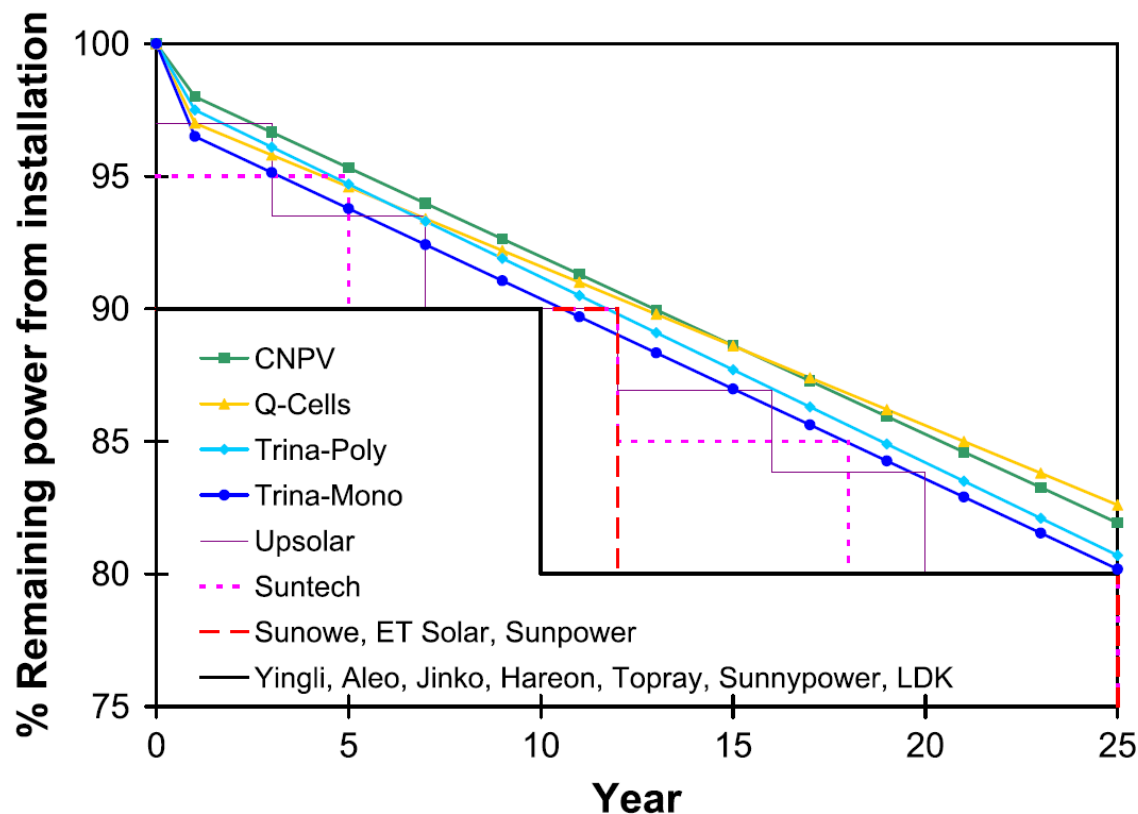
3

# Defects do really matter?



PV park 3 years after installation.  
Power-losses up to 13%  
3.000 modules over 15.000 to be  
identified and replaced!

# Reliability: warranties and failure rates



Failure rates  
due to customer complaints  
in the first 2 years after delivery  
(2M PV modules)

**Report IEA-PVPS T13-01:2014**



## Criticalities

- Standard qualification tests reproduce failure modes never observed in the field
- Lack of simulation tools for durability assessment in any environmental condition
- Lack of guidelines for PV monitoring in the field

## Challenges & innovation

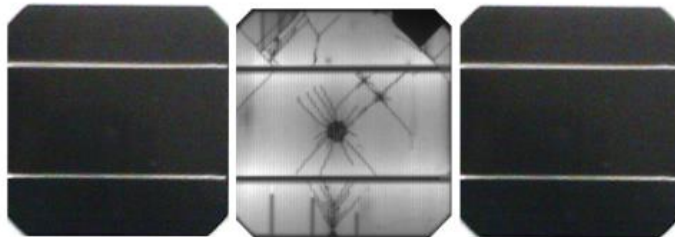
- Move from the solar cell to the PV module laminate exposed to the environment
- Multi-physics approach to degradation requiring an interdisciplinary approach
- New testing protocols; new image analysis techniques for PV inspection
- New design criteria for PV modules insensitive to cracking; material savings for ultra-thin solar cells; semi-flexible PV modules; stretchable electronics.

## Impact

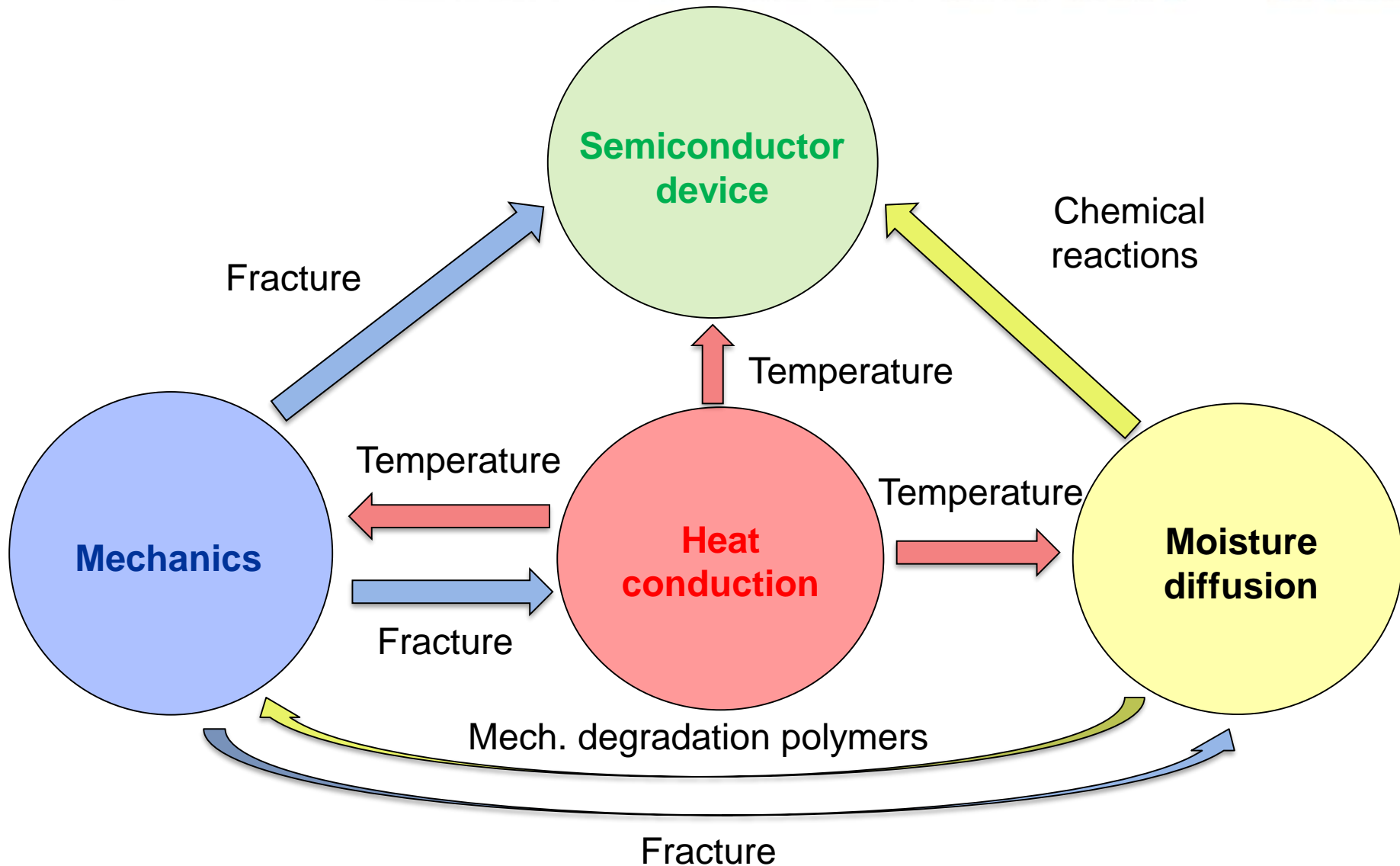
- More reliable expectation on PV lifetime and assessment of O&M costs
- Better quality control and rating of PV productions
- Scalability of the PV market to non EU countries with other climate zones

# Research achievements in a nutshell

**Multi-field and multi-scale Computational Approach to design and durability of Photovoltaic Modules – CA2PVM**



# Multi-physics modelling & simulation





# Length and time scales

## Time scale

Moisture  
diffusion

20 yrs

Temperature  
cycles

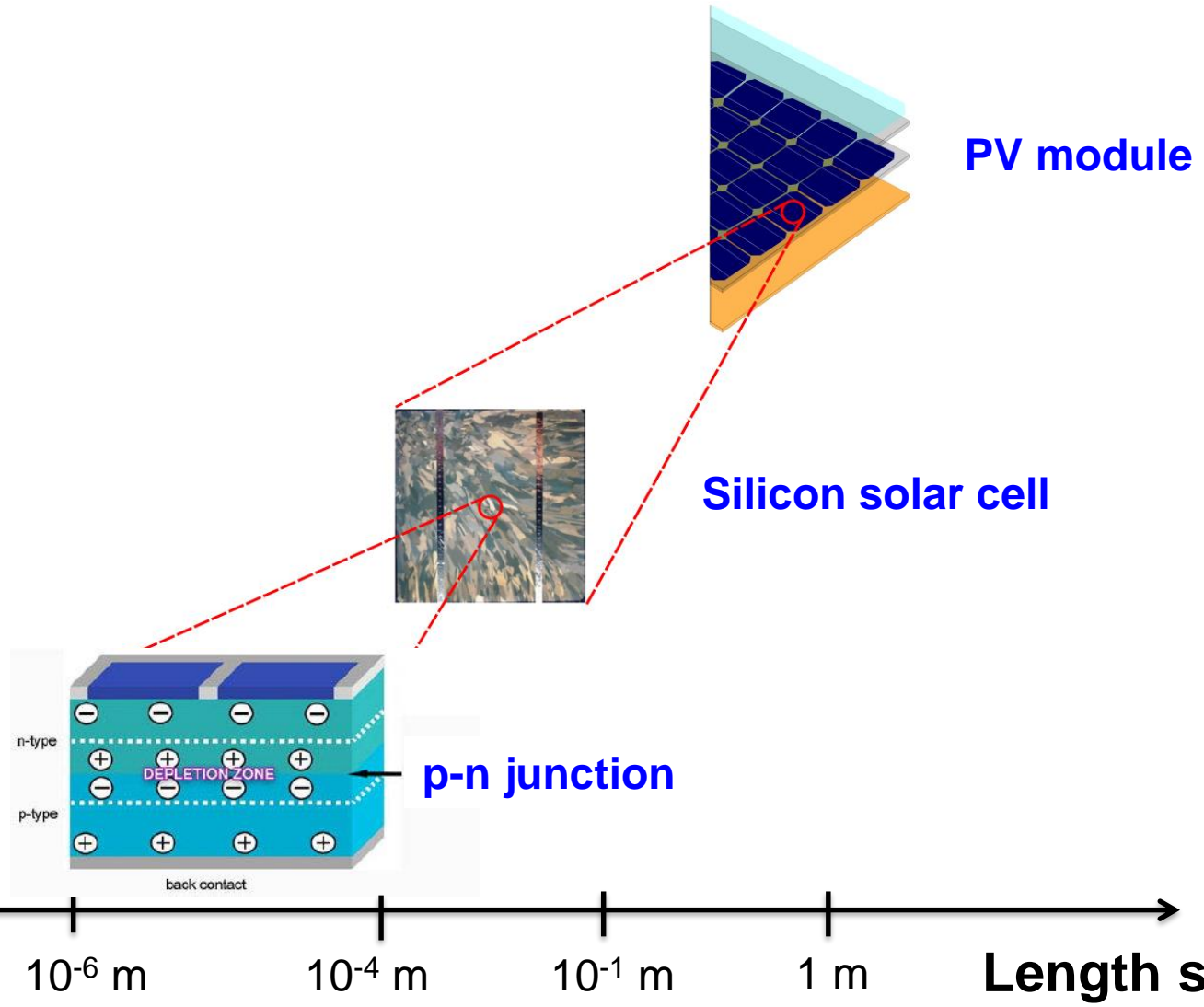
1 day

Brittle  
fracture

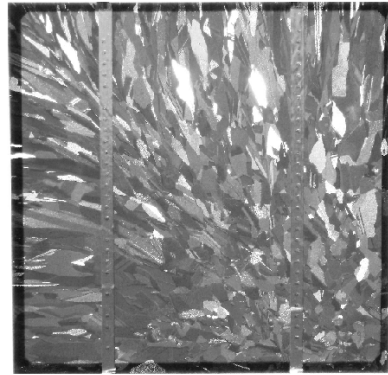
1 s

Recombination  
effects

1  $\mu$ s

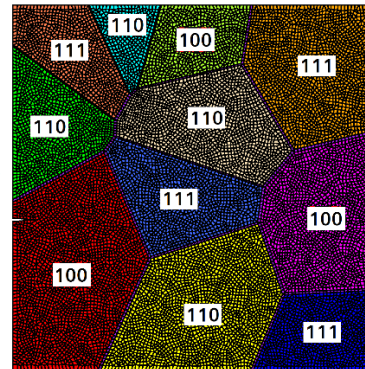
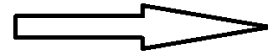


# Computational fracture mechanics



Real polycrystalline  
Silicon microstructure

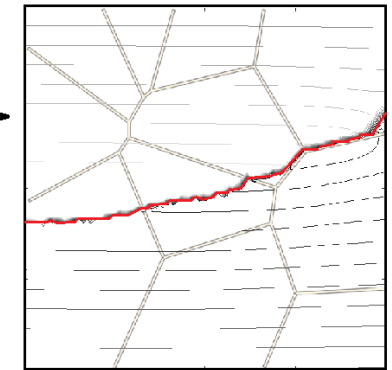
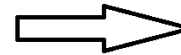
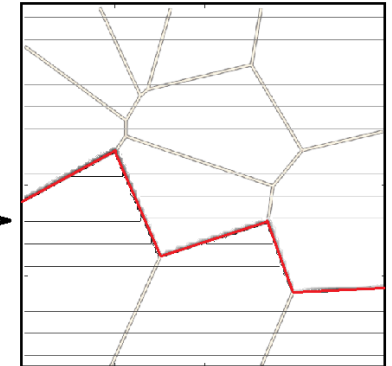
Identification  
of grain orientation  
distribution



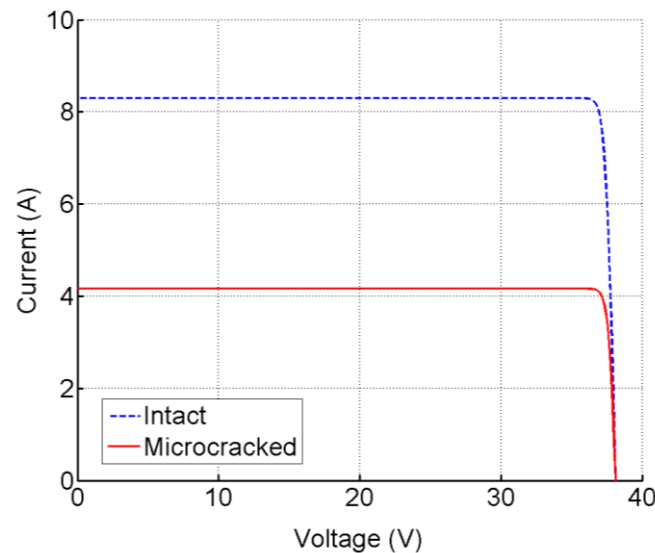
Finite element model



Intergranular fracture



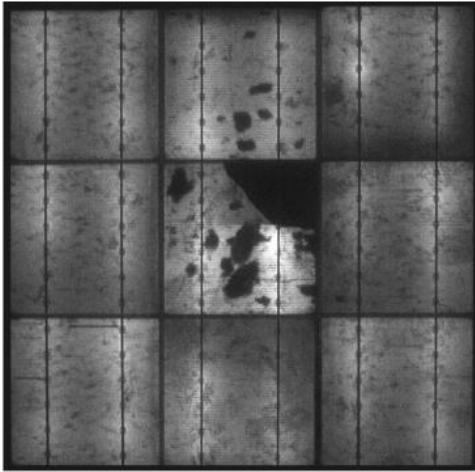
Transgranular fracture



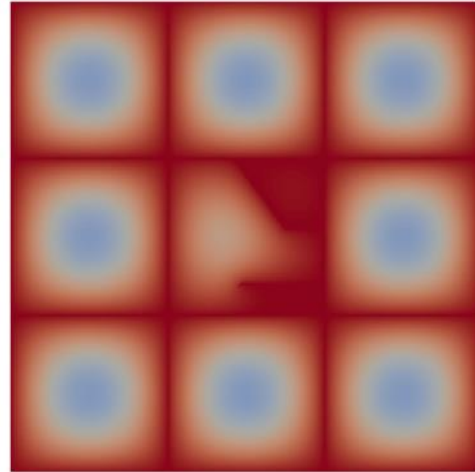
**Prediction of complex  
crack patterns,  
electrically inactive  
areas, power losses**

# Understanding & simulation of ageing towards new accelerated tests

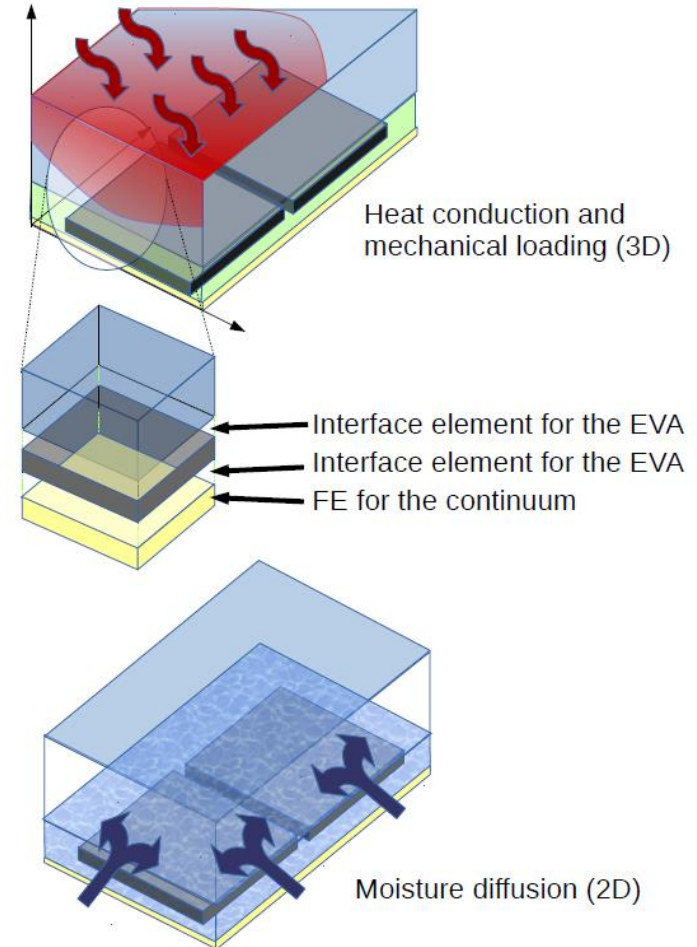
Simulation of moisture diffusion and  
chemical reactions inside the EVA layers



EL image from  
accelerated ageing  
(experiment)

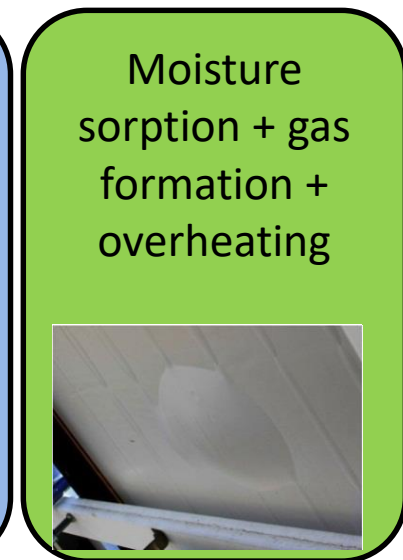
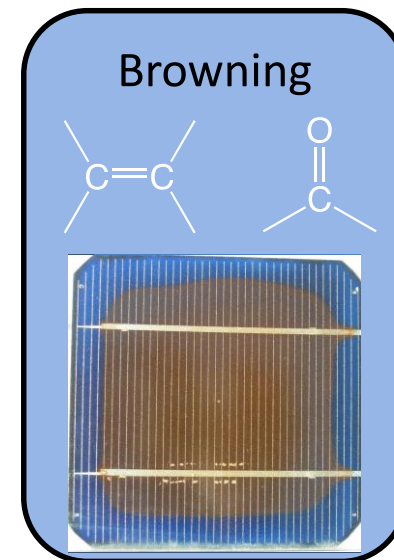
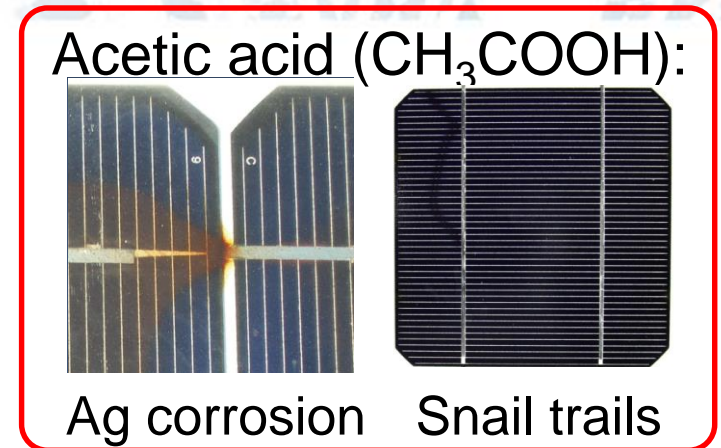
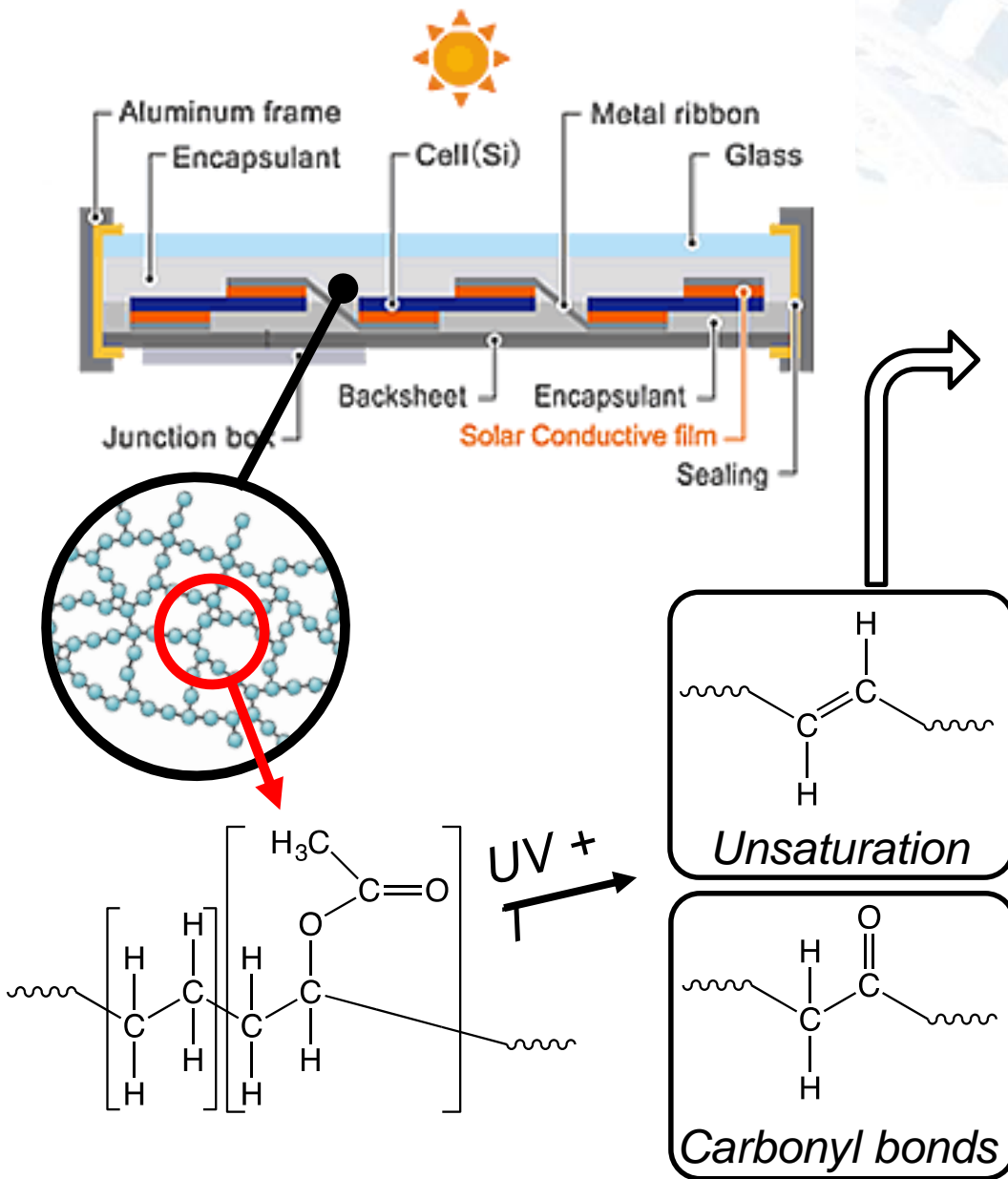


Predicted moisture  
concentration  
(numerical model)



P. Lenarda, M. Paggi (2016) A geometrical multi-scale numerical method for coupled hygro-thermo-mechanical problems in photovoltaic laminates. **Computational Mechanics**, 57:947-963



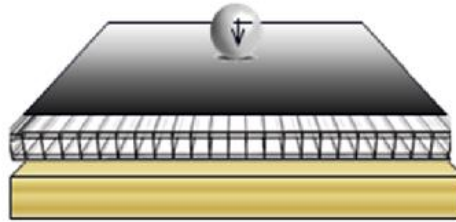


M. Gagliardi, P. Lenarda, M. Paggi (2017) Solar Energy Materials and Solar Cells, 164:93-106.

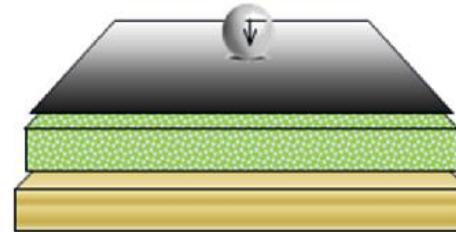
# Impact resistance of semi-flexible PV: towards new qualification tests



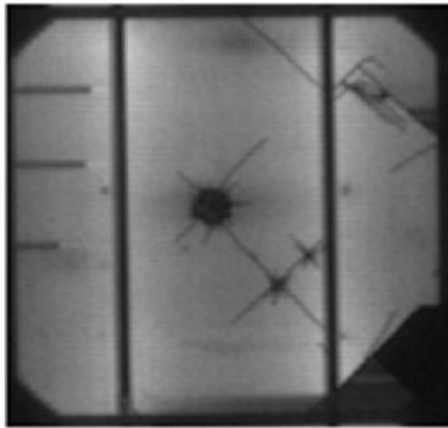
Wooden board



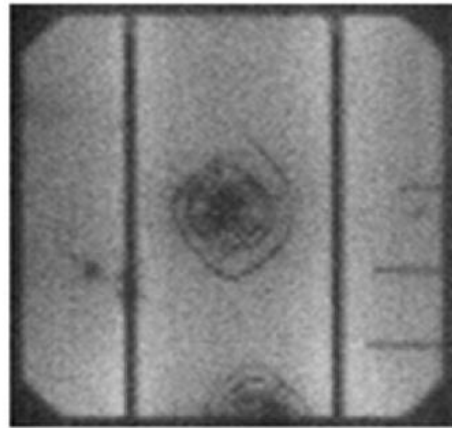
Alveolar PC +  
Wooden board



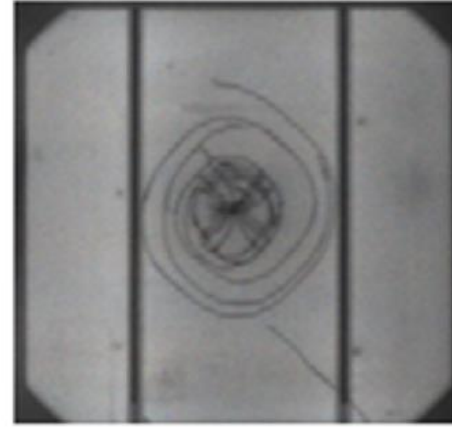
Polystyrene +  
Wooden board



Case A: Hard substrate



CaseB: Medium substrate

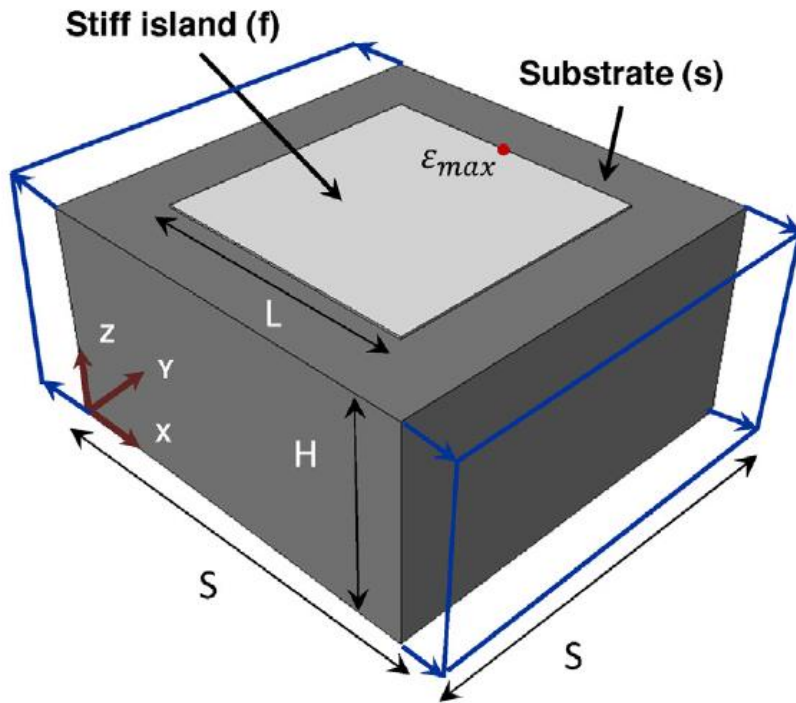


Case C: Soft substrate

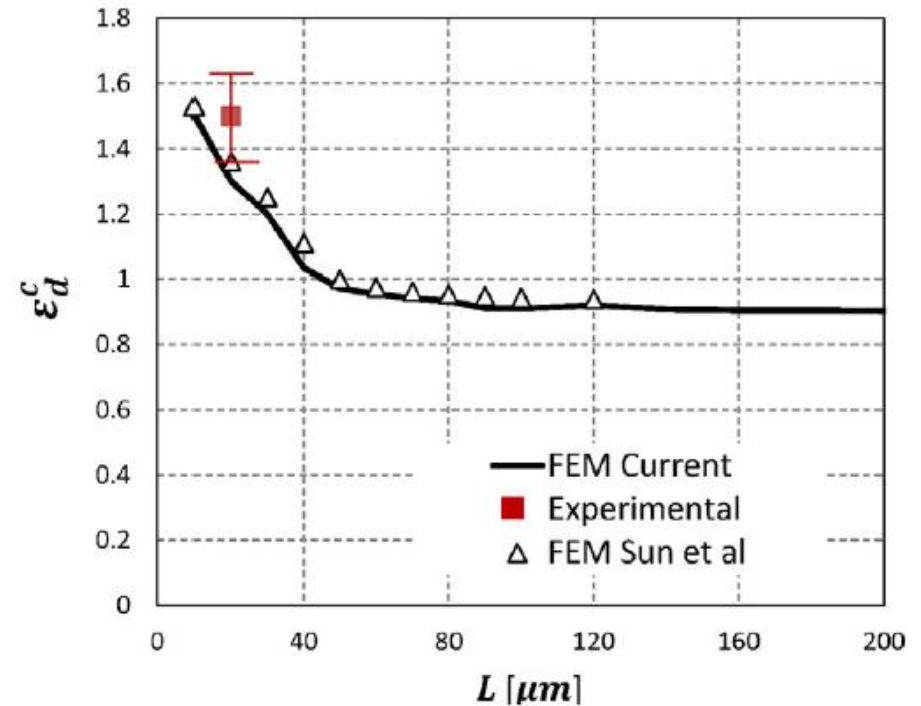
**The stiffness of the substrate plays a crucial role for flexible PV and should be considered depending on the application**

Corrado, Infuso, Paggi (2017) Simulated hail impacts on flexible photovoltaic laminates: testing and modelling. **Meccanica**, 52:1425-1439.

# Reliability of stretchable electronics



Are the two materials compatible?



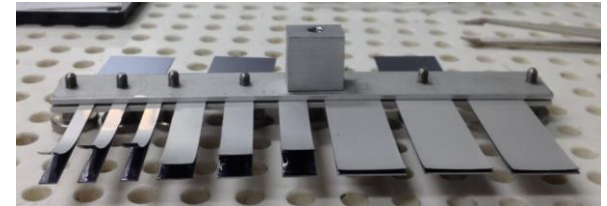
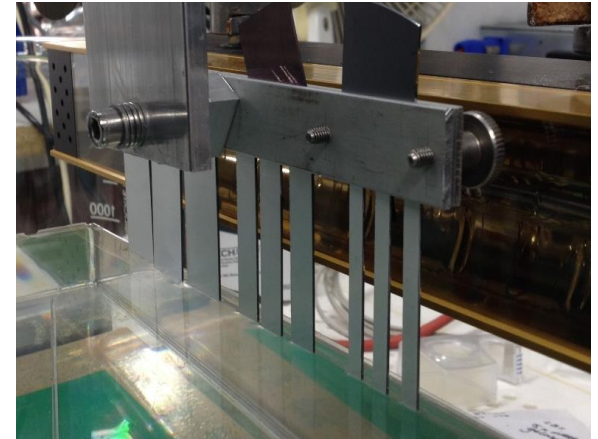
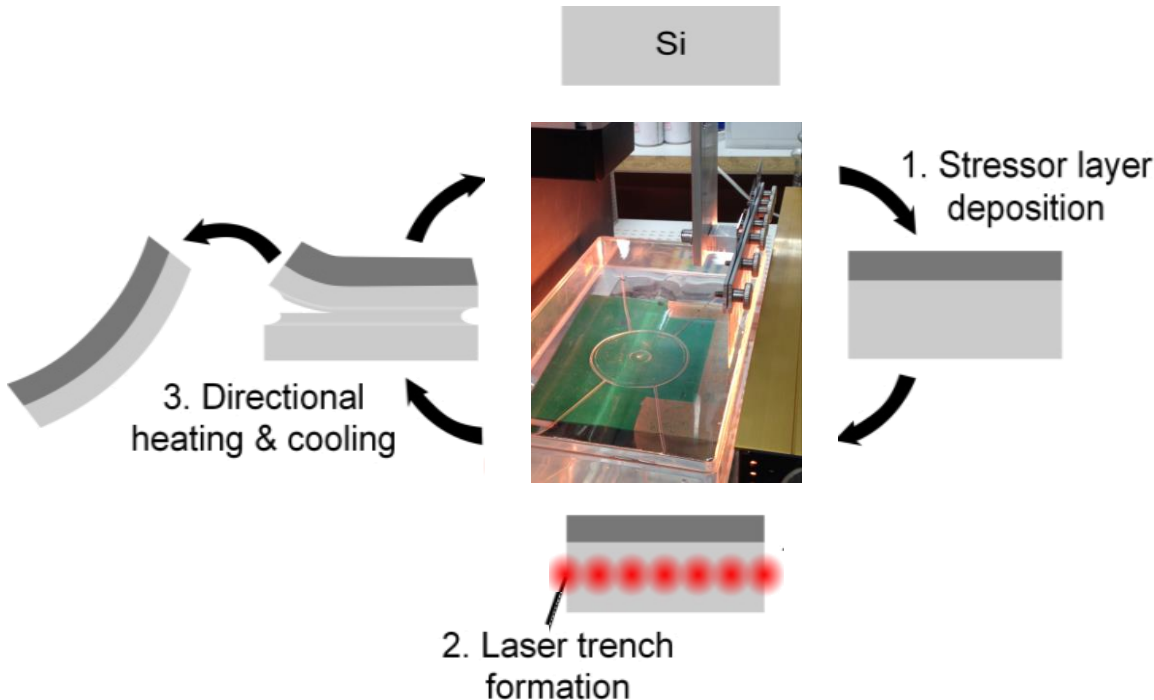
Critical stretching for the onset of island-substrate debonding

J. Reinoso, M. Paggi, P. Areias (2016) A finite element framework for the interplay between delamination and buckling of rubber-like bi-material systems and stretchable electronics, **J Eur Ceram Soc**, 36:2371-2382.



# New solutions: ultra-thin solar cells & material savings

## Low cost thin solar cells production by thermo-mechanical spalling

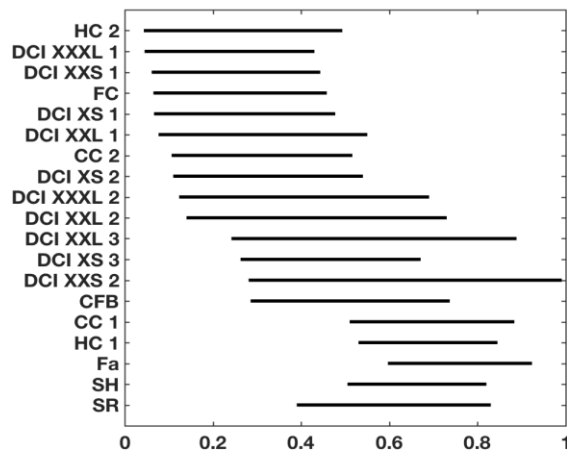
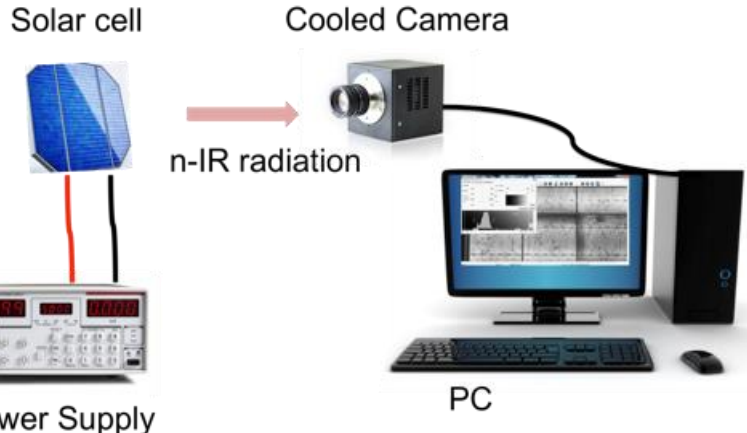


I. Berardone, S. Kajari-Schröder, R. Niepelt, J. Hensen, V. Steckenreiter, M. Paggi (2015) Numerical modelling and validation of thermally-induced spalling, **Energy Procedia**, 77:855-862.

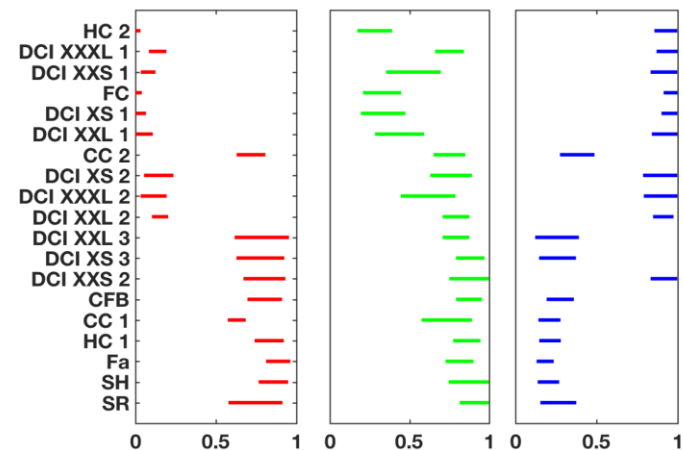
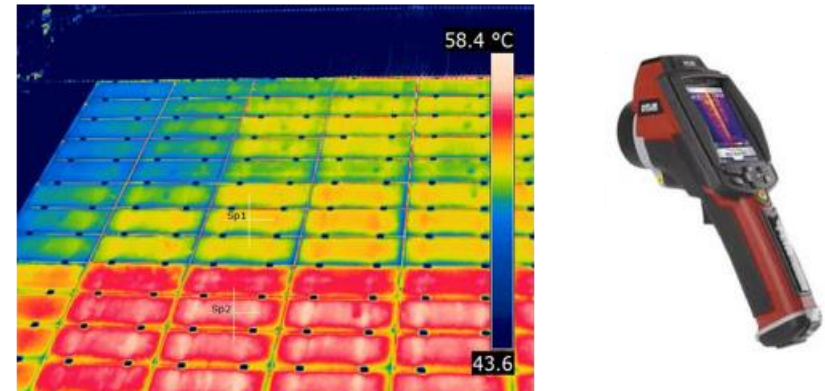
I. Berardone, J. Hensen, V. Steckenreiter, S. Kajari-Schröder, M. Paggi (2016) Simulation of spalling with a non-planar bi-layered interface due to the reuse of the substrate, **Energy Procedia**, 92C:764-772.

# In-situ inspection methods

## Electroluminescence (EL)



## Thermography (IR)



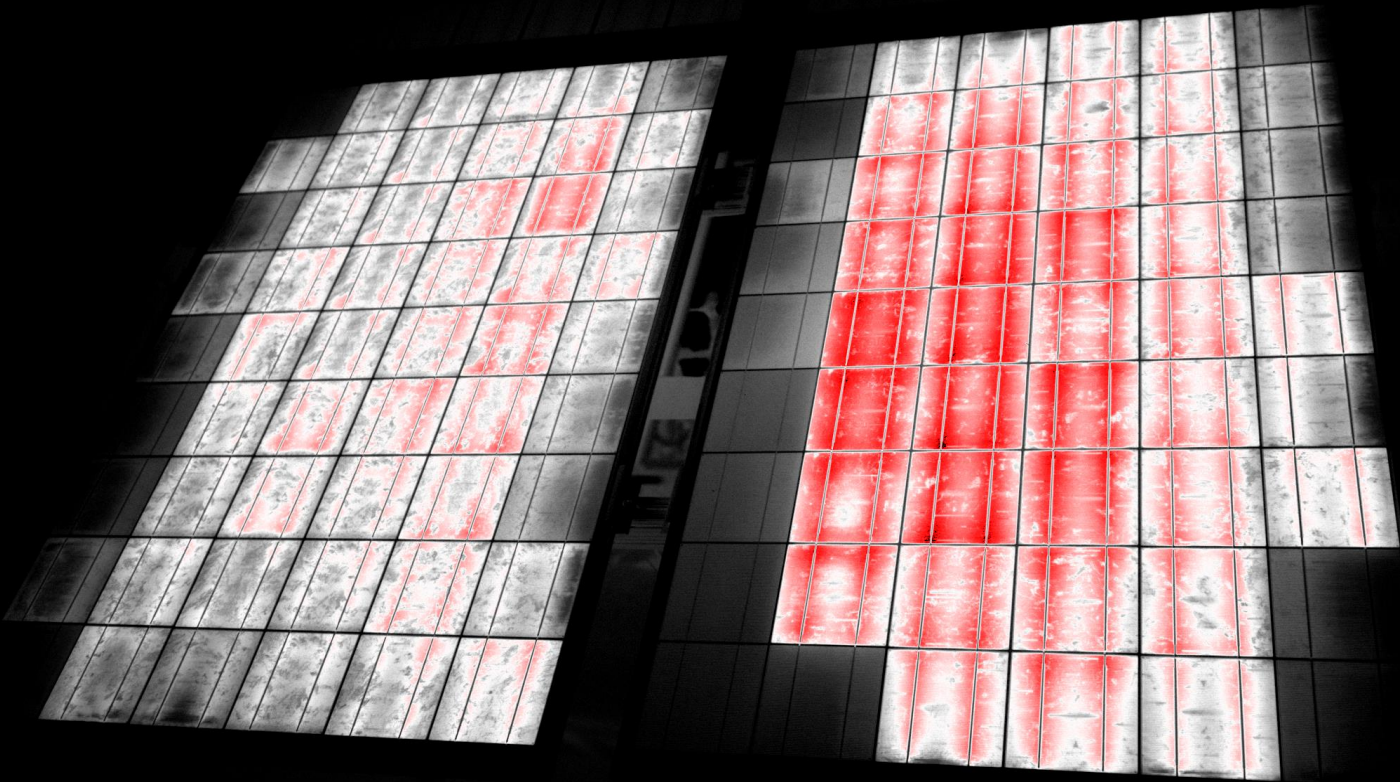
I Berardone, M Paggi, J Garcia (2017) Quantitative analysis of electroluminescence and infrared thermal images for aged monocrystalline silicon photovoltaic modules, **44th IEEE Photovoltaic Specialists Conference**, 25-30 June, Washington DC.

# Outreach and international cooperations

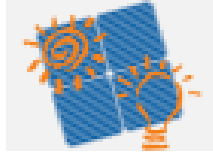


# Outreach in collaboration with the International Energy Agency

**GUIDELINES FOR EL OUTDOOR QUALIFICATION OF PV SYSTEMS**  
**Intersolar Europe Conference, 30 May 2017, Munich, Germany**  
**PV Reliability & Assessment of Technical Risks in PV Investments**

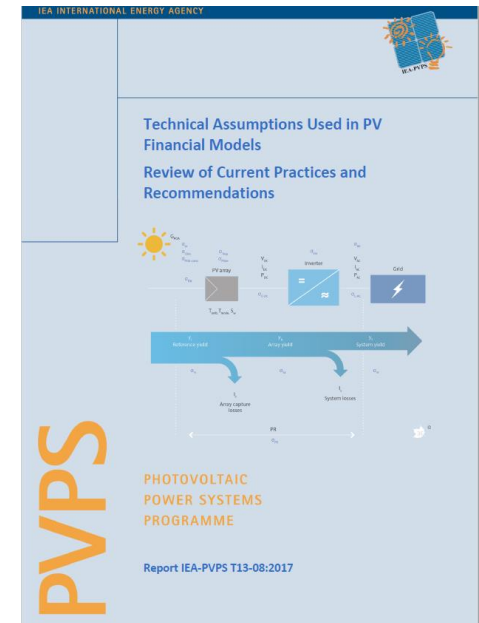
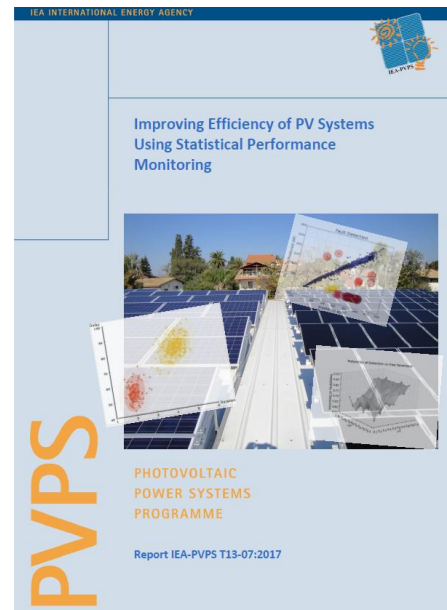
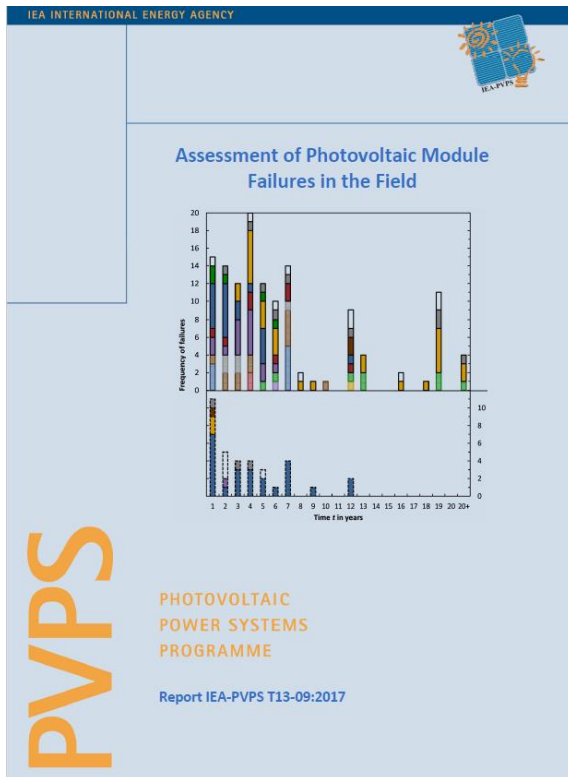


# Outreach in collaboration with the International Energy Agency



## International Energy Agency Photovoltaic Power Systems Programme (PVPS) Task 13 on Performance and Reliability of Photovoltaic Systems

See also from Task 13 experts:



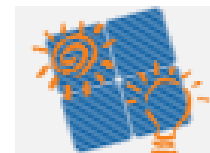
<http://iea-pvps.org/index.php?id=57>

# Endorsement and collaborations

## International Energy Agency

Photovoltaic Power Systems Programme (PVPS)

Task 13 on Performance and Reliability of Photovoltaic Systems



## Joint Research Centre

Institute for Energy and Transport



## Institute for Solar Energy Research

Hamelin, Germany



## Solbian Energie Alternative S.r.l.

Avigliana, Italy



## Applied Materials Italia S.r.l.

Olmi di S. Biagio di Callalta, Italy



## Jabil, Industrial and Energy

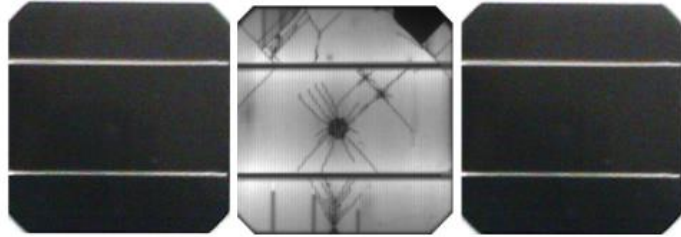
San Petersburg, Florida, USA





# Acknowledgements

**Multi-field and multi-scale Computational Approach to design and durability of Photovoltaic Modules – CA2PVM**



**ERC Starting Grant  
CA2PVM, 2012-2017**

**ERC Proof of Concept  
PHYSIC, 2017-2018**

<http://musam.imtlucca.it/CA2PVM.html>



<https://www.facebook.com/fanpagemusam>