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Module reliability: lessons learned for a smart tandem integration

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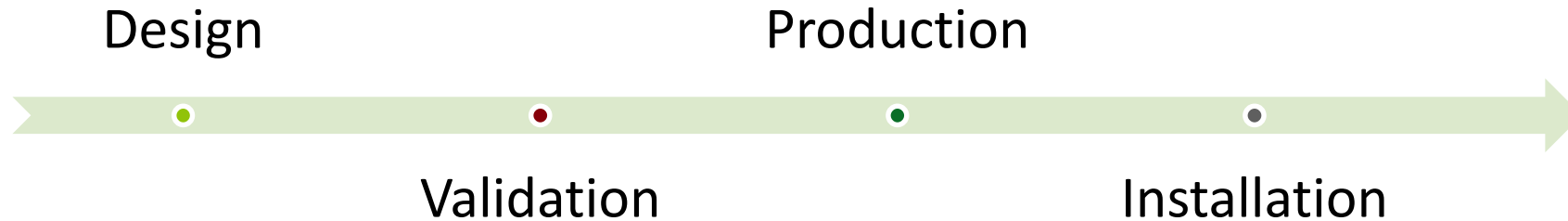
2nd International tandemPV Workshop, 1st June 2022

OUTLOOK

- 1. What is reliability**
- 2. Reliability in PV**
- 3. Challenges for reliability**
- 4. Challenges for Tandem**
- 5. Conclusions**

RELIABILITY...

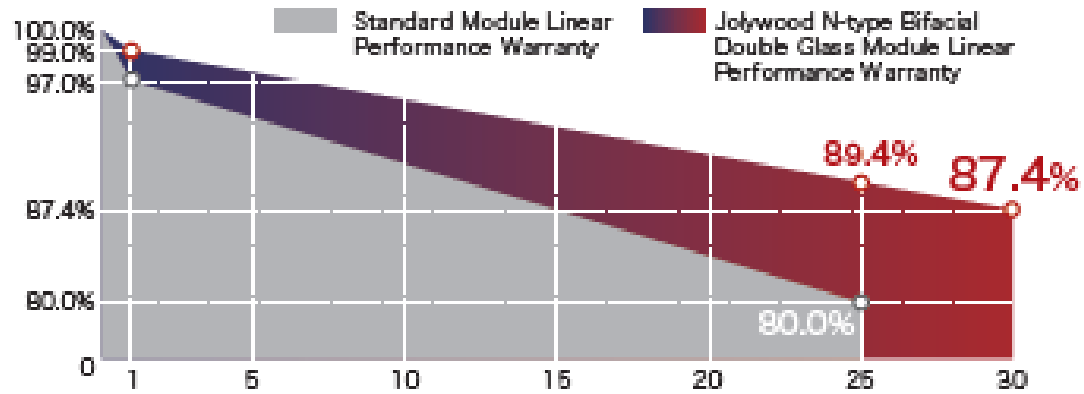
... the ability to perform as required, without failure, for a given time interval, under given conditions



Design for Reliability: detailed design techniques aimed at improving the product reliability in the whole life

RELIABILITY IN PV

-1.00% 1st-year Degradation | 15 Years Product Material & Workmanship
 -0.40% Annual Degradation | 30 Years Linear Performance Warranty



the <u>ability</u> to perform as required, without <u>failure</u>	80%
for a given <u>time interval</u>	25y
under given <u>conditions</u>	IEC61215



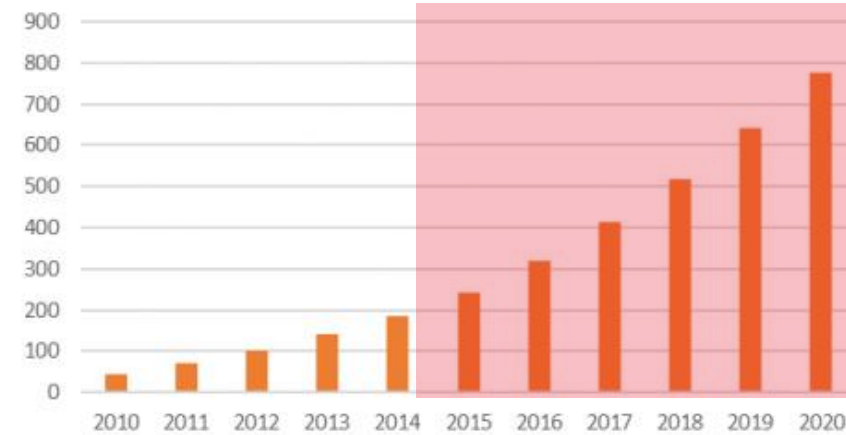
Need of modelling
 Need of accelerated testing
 Need of development for all environments
 Need of data in real conditions



Design for reliability in PV

85% of the world's installed solar PV capacity has operated for less than five years

Global solar PV installations - cumulative PV capacity (GWdc)



Source: IHS Markit, 2019

Copyright (c) 2019, IHS Markit



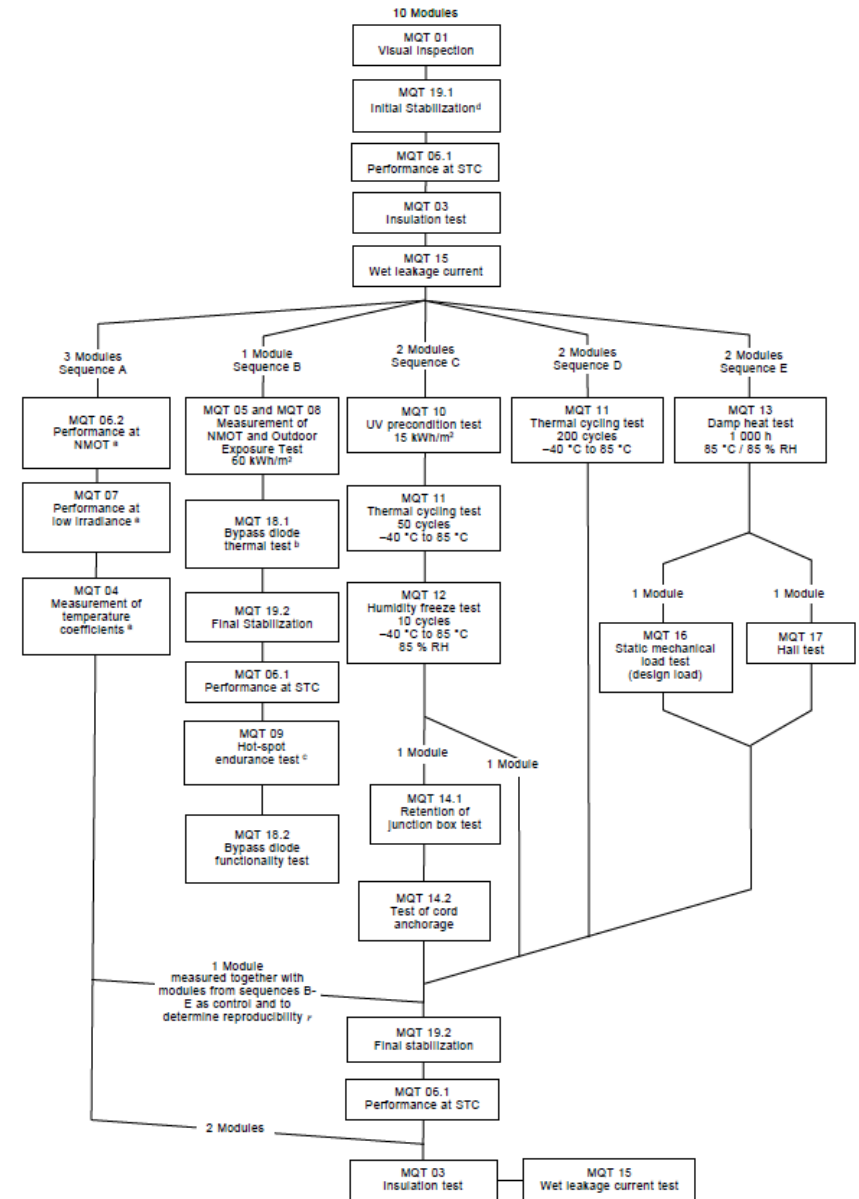
RELIABILITY IN PV: THE NORM IEC61215

Unqualified modules suffered from **45%** filed failure rate, while **qualified** modules suffered from less than **0.1%** filed failure rate.

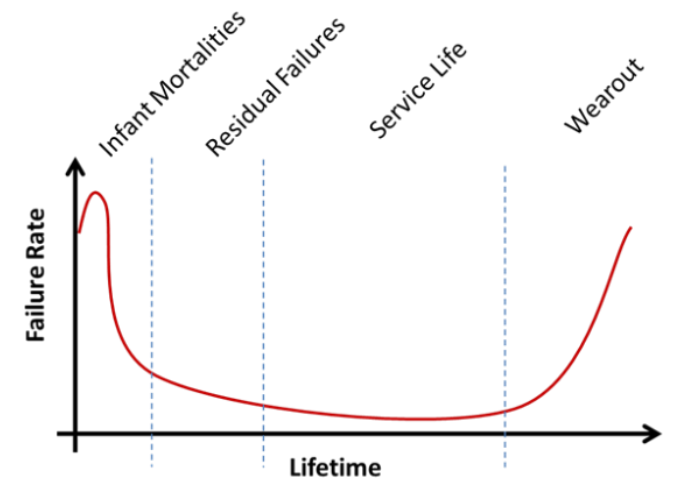
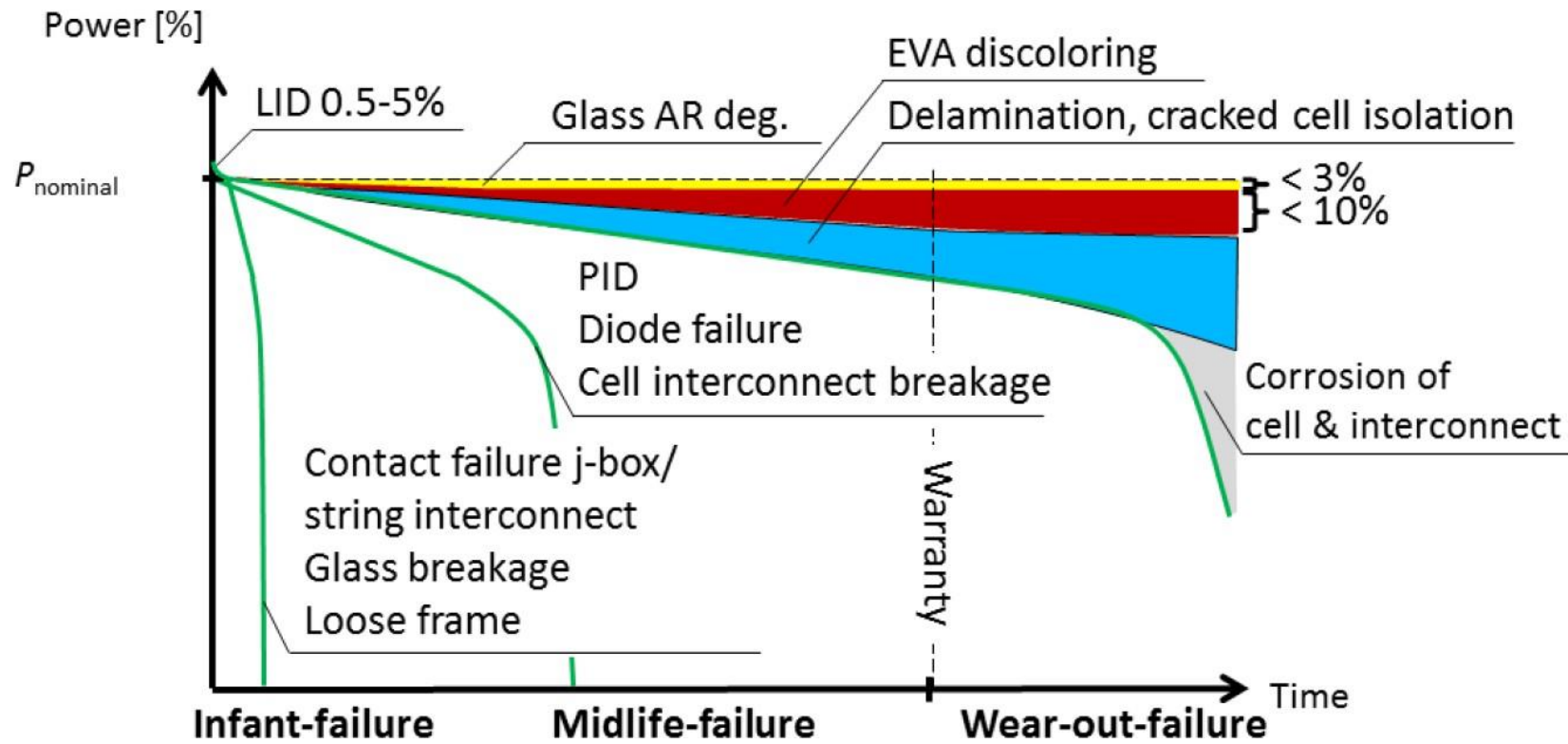
(Wohlgemuth, 2012)

Environmental stress test

- Thermal cycling
- Humidity freeze
- Damp heat
- UV preconditioning



RELIABILITY IN PV: FAILURE OF C-SI PV MODULES



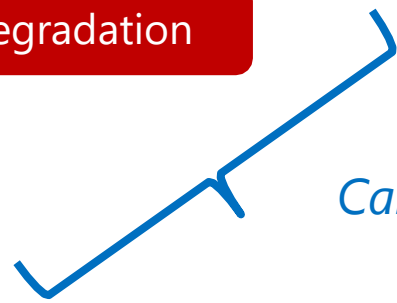
Köntges et al. (2014) IEA-PVPS Task 13 Report on "Review of Failures of Photovoltaic Modules"



Module lamination

Material degradation

Component selection



Can be delayed to some extent with proper stabilization

Mostly avoidable: Extensive R&D, quality and reliability testing needed

RELIABILITY IN PV: UNDER GIVEN CONDITIONS MEANS...

Conditions

Floating **Desert**

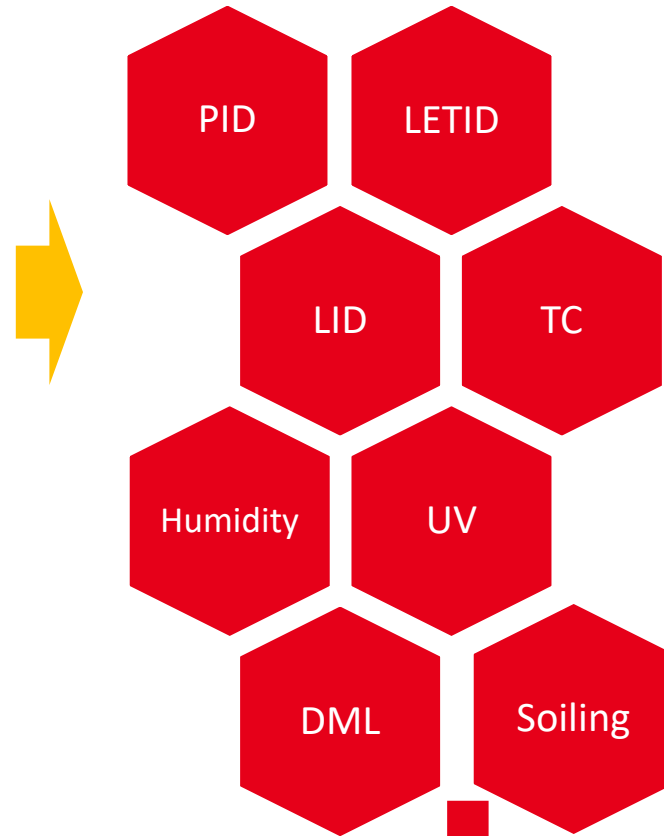


Tropical **Cold & snow**




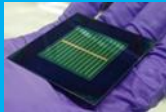
Icons representing: Time (t), Light (I), Wavelength (λ), Temperature (T), and Humidity (H).

extended testing beyond what is prescribed by the standards

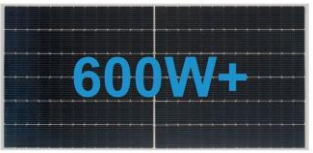
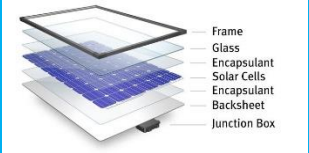


BOM

Tandem **Perovskite**



Bifacial **Big size**



Performance modelling

confidence of the right choice of components

RELIABILITY IS ALSO SUSTAINABILITY

Ecodesign approach for circular economy strategy

Strategies for circularity are encompassed with the “R-ladder” strategy (refuse, rethink, reduce, reuse, repair, remanufacture, repurpose, recycle, energy recovery).

As a circular economy covers the entire lifecycle of a product, it requires a broad and systemic approach to production.

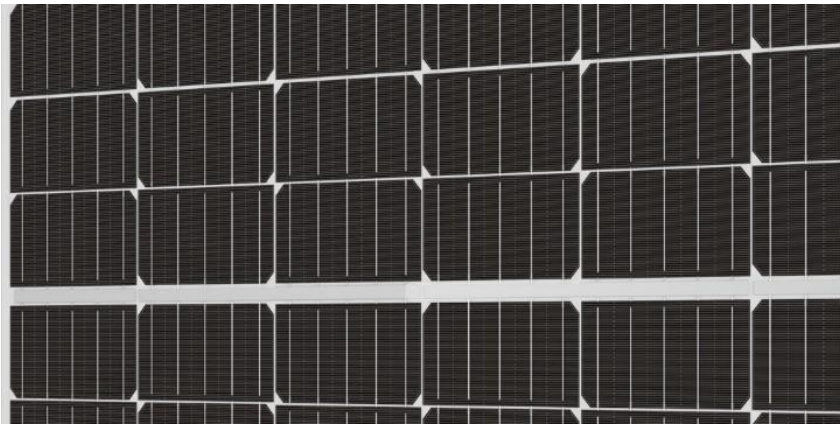
Strategic agenda for PV, ETIP PV 2021



CHALLENGES ON NEW MATERIALS AND MODULE DESIGN

- **New technological requirements**
 - *Wafer technology*
 - *New cell and interconnection technologies*
 - *New module designs*
 - *Less material use (In, Ag)*

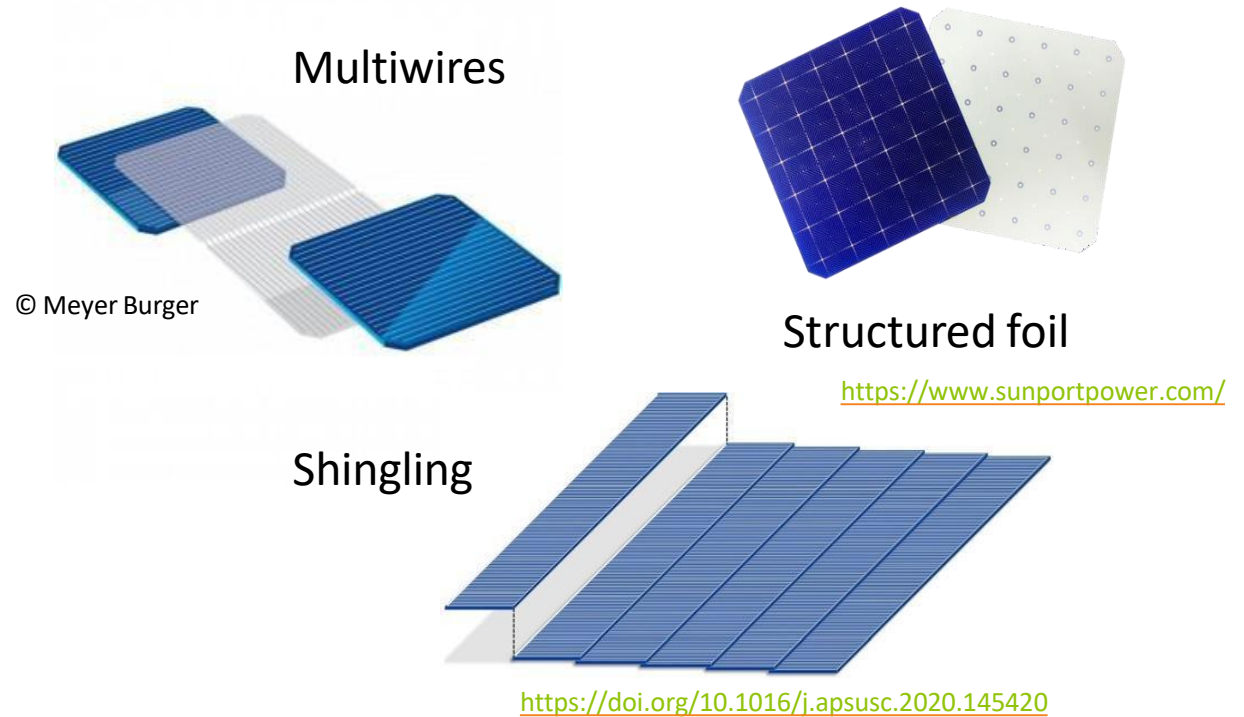
New cell technologies



© Trina Solar

- PERC and HJT will become dominant cell technologies
- Half cells will gain more market share
- Module sizes increase

Interconnection for Ag reduction



Or Ag-free
moving to Copper!

CHALLENGES ON NEW MATERIALS AND MODULE DESIGN

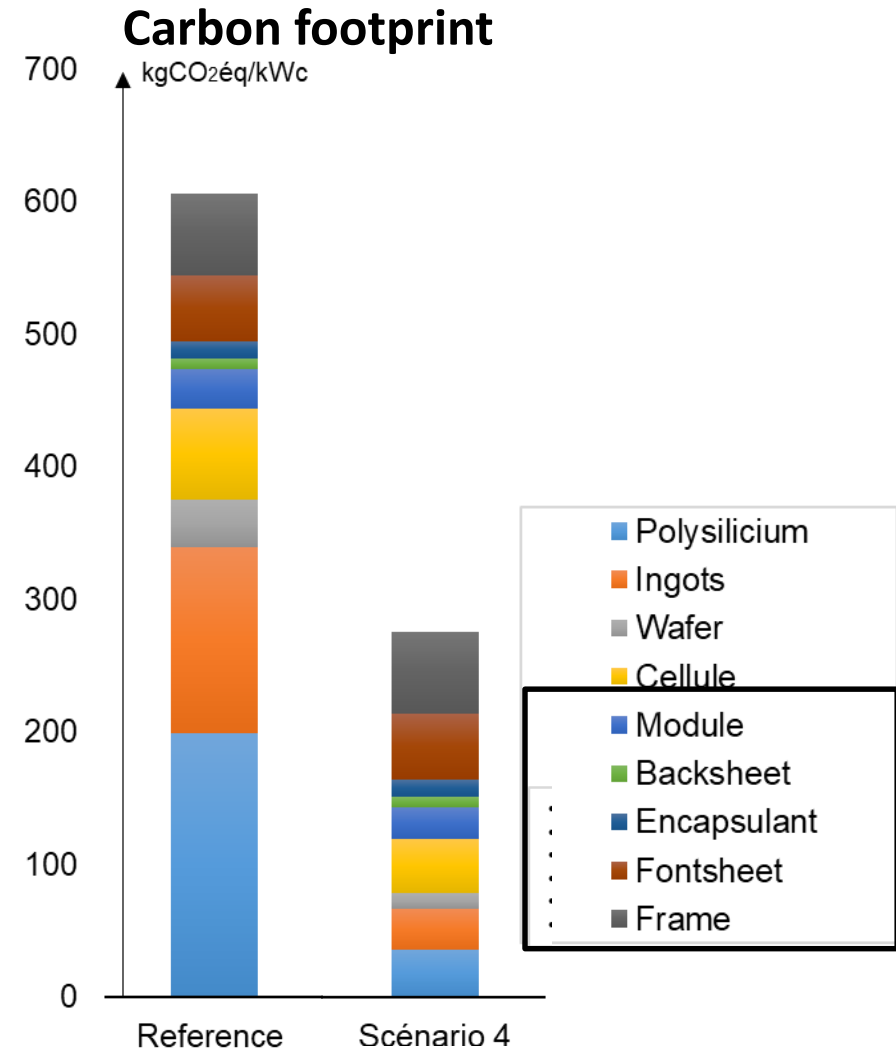
Duality of increasing performance, improve reliability and reducing Ag consumption with novel cell and module interconnexion technologies

1. Safe road of continued optimisation
2. Introduction of novel materials and technologies
1. Tandems

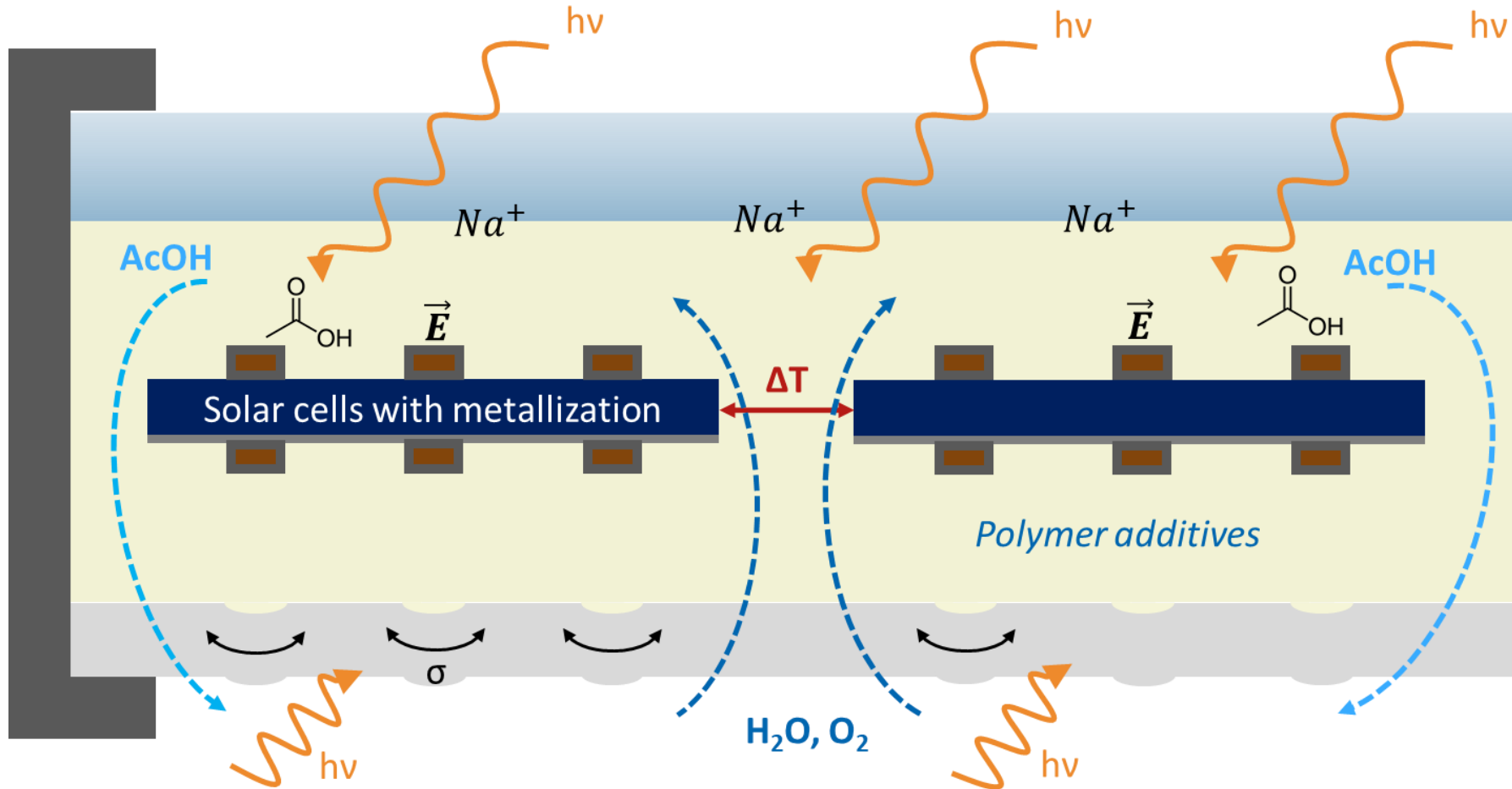
New metric:
mg

Wp (kWp)

Reduction of environmental impact by bio-sourced/designed for recycled module packaging materials



CHALLENGES ON NEW MATERIALS AND MODULE DESIGN



External factors

- Irradiation
- Temperature
- Humidity
- Atmospheric gases
- Mechanical loads (Wind, snow)

Internal factors

- Bill of material
- Processing effects
- Interfaces

- External and internal stress factors influence performance and long-term reliability of PV modules
- The materials in PV modules have to withstand extremely challenging micro-climatic conditions.

CHALLENGES FOR NEW MATERIALS AND COMPONENTS

Check of compatibility of PV module components will get more and more important in the future, as the variety on materials and components will grow



Adhesion - delamination:

- *Adhesion to glass and solar cell strongly dependent of lamination parameters*
- *Surface treatment of backsheets usually optimized for adhesion to EVA but not alternative encapsulants*



Backsheet yellowing: *Migration of additives into backsheet -encapsulant interface are main cause for backsheet yellowing*



Corrosion: *Broad variety of new ribbon materials, interconnection technologies and encapsulant films*

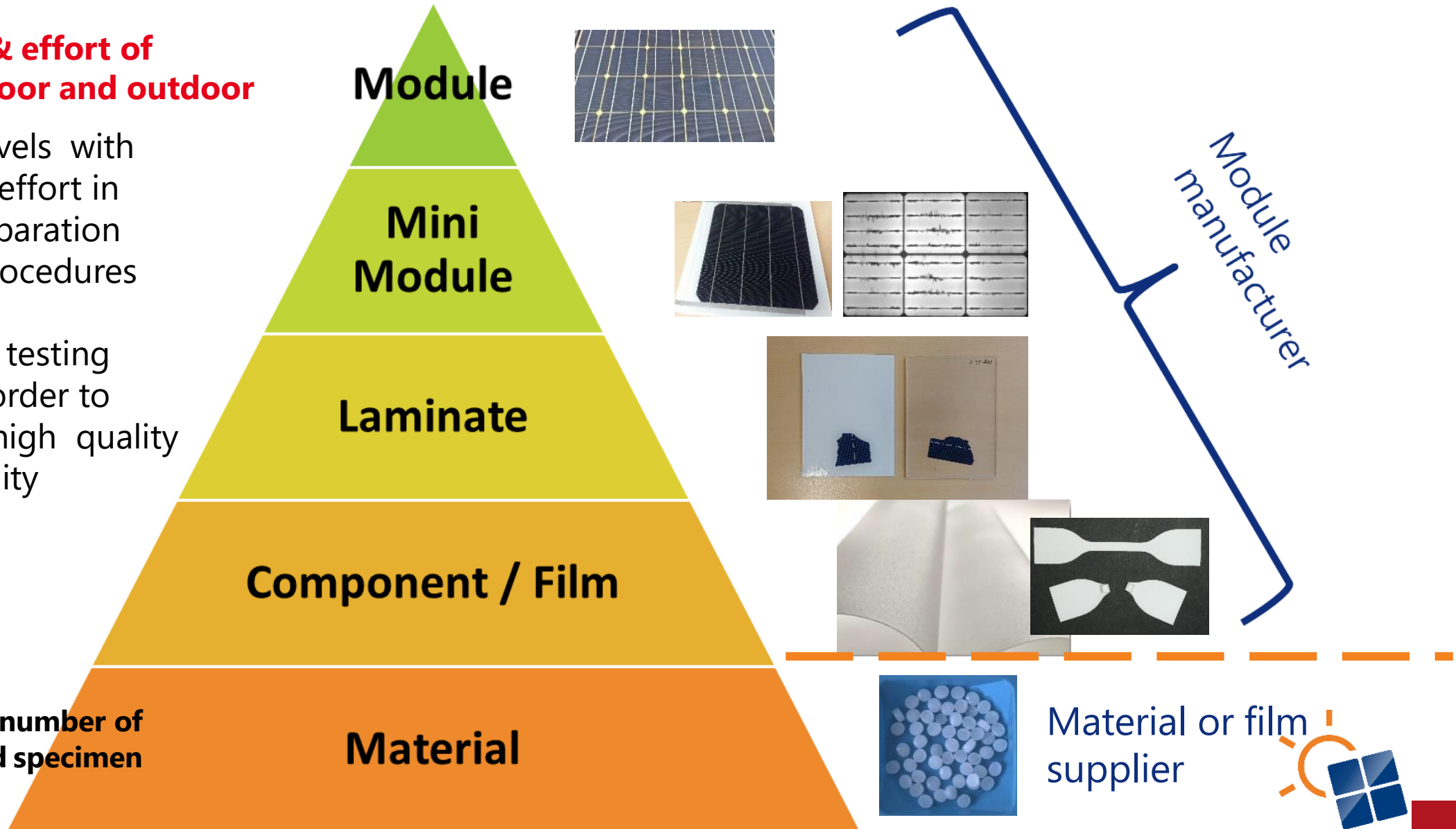
NEED OF TESTING NEW MATERIALS AND COMPONENTS

High cost & effort of testing indoor and outdoor

Different levels with increasing effort in sample preparation and test procedures

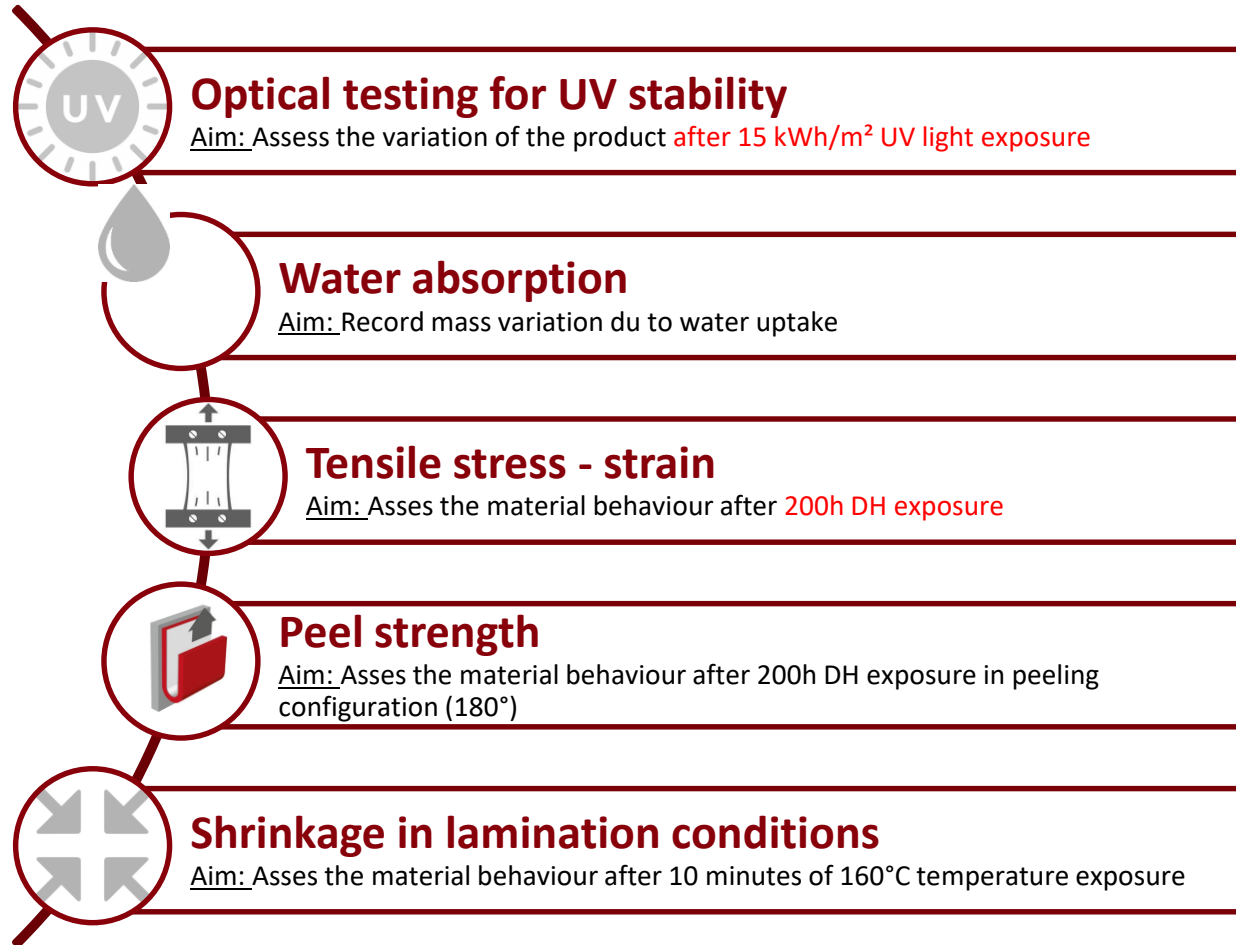
All levels of testing needed in order to guarantee high quality and reliability

High number of tested specimen



TESTING AND QUALIFICATION OF NEW MATERIALS AND COMPONENTS

Material qualification protocol – backsheet and encapsulants



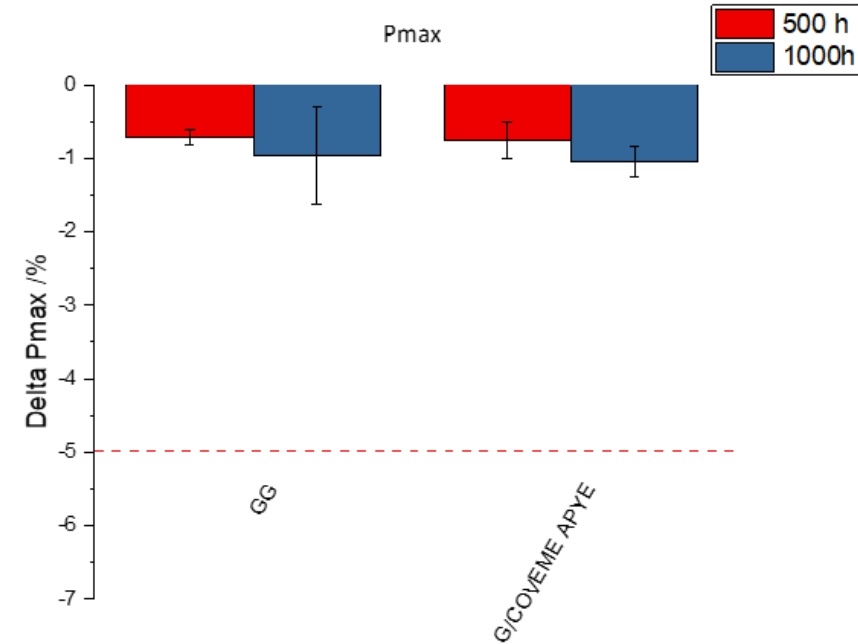
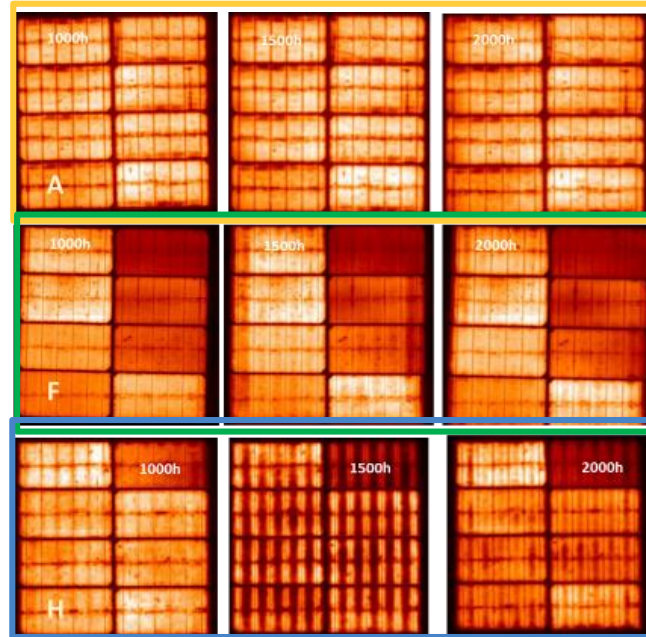
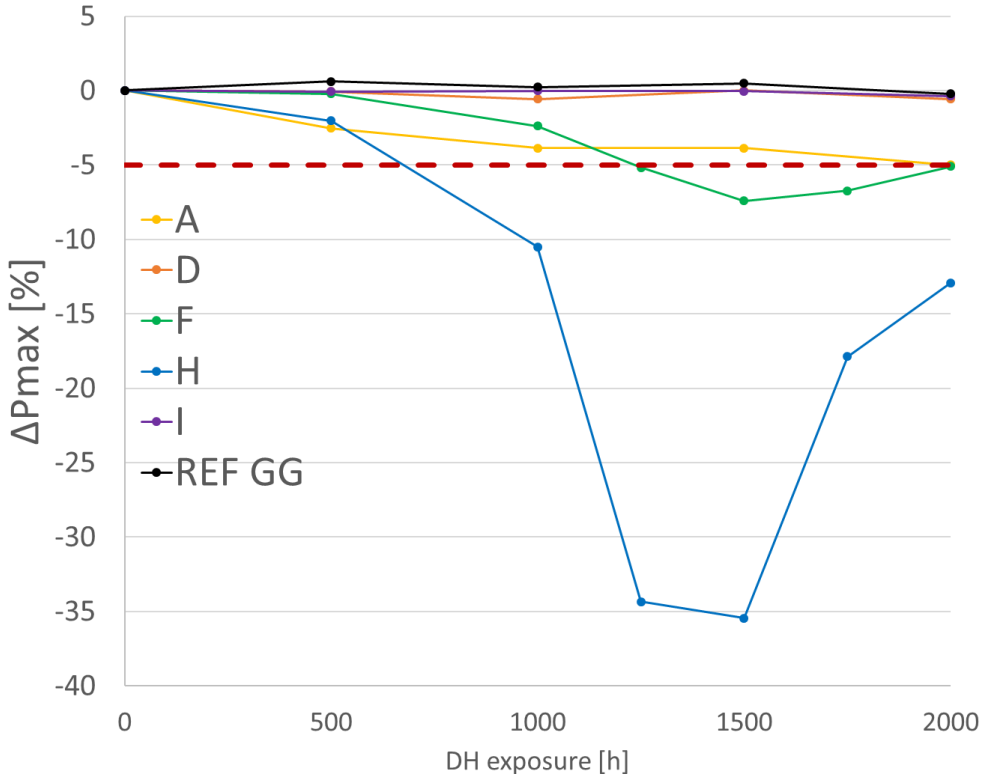
A	B	C	D	E	F	G	H	I
PP	Kynar(PVDF)/ PET/P	Tedlar(PVF)/P ET/P	PET/Al/PET/P P	coating/PET/Si Ox-PET/P	ETFE/PET+/PE T/P	ETFE/SiOx- PET/PET/P	coating/PET/PE T+/PET/P	PET/Al/PET/P OE
+	+	+	+	+	+/-	+	+	+
-	+	+	+	+	+	+	+	+
+	+	-	+	-	+/-	-	+/-	+
-	+	+	+	+	+	+	+	+
-	+	+	+	+	+	+	+	+

TESTING AND QUALIFICATION OF NEW MATERIALS AND COMPONENTS

Qualification of POE/ backsheet in DH - mini-module



Final validation in full size



- Qualification of encapsulant/backsheet pairs in mini-module
- Best performing backsheets: Al-based (D, I) and PP (A)
- **Two key properties to ensure stability in DH : WVTR & peel strength**

SHJ modules (144 ½ cell) for selection of final encapsulant/ white and transparent backsheet pairs

TESTING ON DEDICATED DESERT CONDITIONS: ATACAMA DESERT

Atacama Desert Solar Platform (PSDA)



International standards

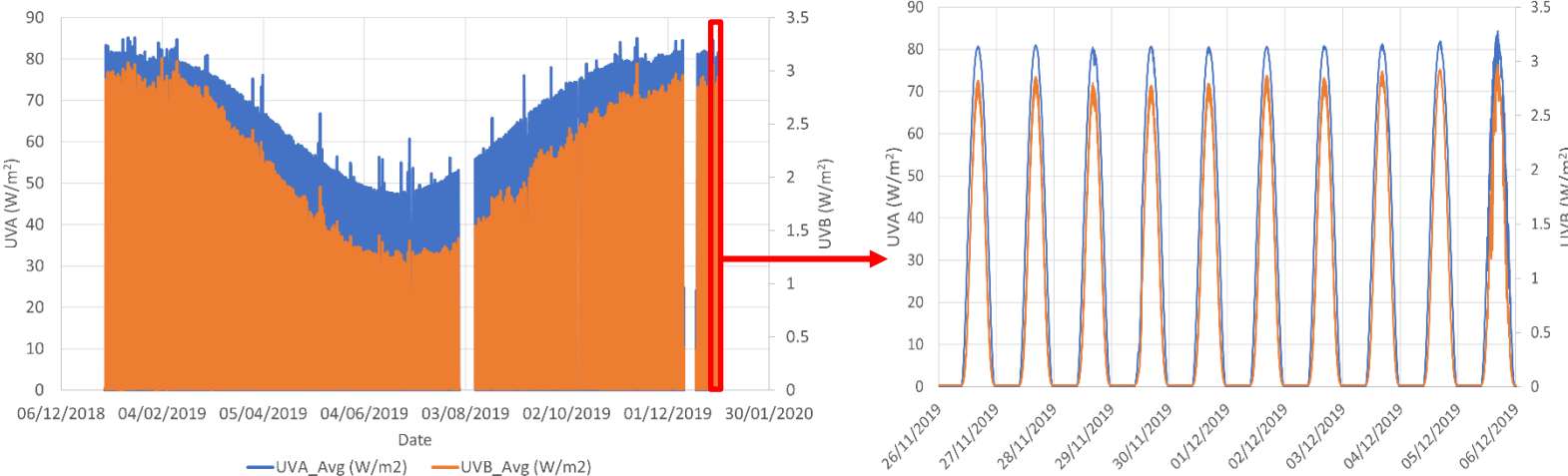
Accelerated ageing Standards applied in PV industry largely underestimate PV module degradation due to ultraviolet (UV)

- ⇒ IEC61215-2016 = UV pre-conditioning sequence of **15kWh/m²** = *slightly more than 1 summer month !*
- ⇒ UV photodegradations are largely underestimated regarding field data (**I_{sc} losses**)



UVA+B irradiance level measured at PSDA

UVA = [320;400nm]
UVB = [280;320nm]



Measurement at:	PSDA	Cadarache (France)
Max UVA+B irradiance level (W/m ²)	80	50
1 year cumulative UVA+B radiant dosage (kWh/m ²)	175	100
including UVB (kWh/m ²)	4.6	2,7
25 years of outdoor UV exposure (kWh/m ²)	4375	2500

UV radiant dosage is 75% higher in Atacama than reference climate

TESTING ON DEDICATED DESERT CONDITIONS: ATACAMA DESERT

Novel combined/sequential ageing tests simulating desert conditions: desert label

Need for adapted (to application and climat) accelerated testing supporting module innovations

- Variety and number of innovations in interconnections and materials are on the rise
- Increasing warranty durations by manufacturer
- Current practices impose technology and material qualification by 2-3x IEC61215 testing
- BUT too long and little relevant to detect failure modes
- Introduction of sequential, combined stress testing

STROKE sequence by CEA

Test	Conditions	Duration
DML	1kPa	1000 cycles
xDH	95°C/85%RH	500 h
xUV	60kWh/60°C	
xCT	-60/105°C	50 cycles
xHF	-60/95 °C and 85 %RH	10 cycles

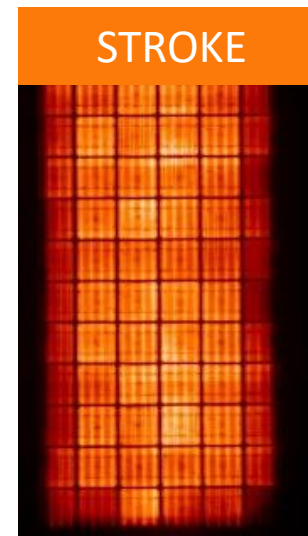
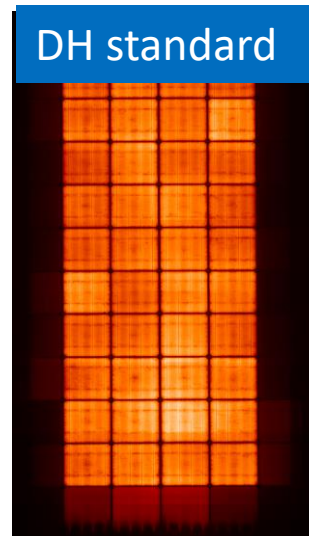
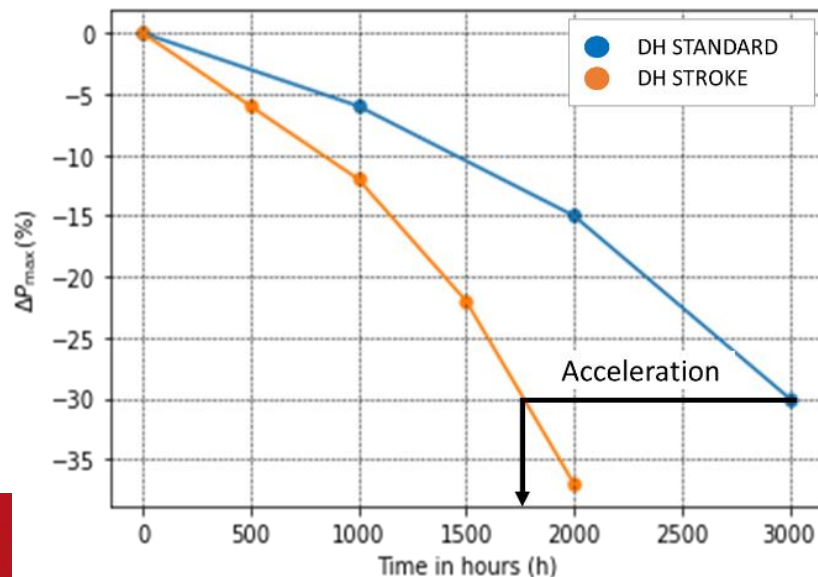
J. F. Lelievre et al.; , Solar Energy Materials and Solar Cells Vol. 236, 2022, Koehl et al. Prog. Photovolt: Res. Appl. 2017; 25:175–183

TESTING ON DEDICATED DESERT CONDITIONS: ATACAMA DESERT

Accelerated ageing sequential ageing

- Acceleration of temperature carefully selected
 - Based on Arrhenius relation
 - Below Polymer fusion/elastic behaviour limit
 - Adapted commercial testing chambers
- **Validation with a selection of industrial benchmark modules**
 - ✓ Same failure modes are triggered at higher T
 - ✓ Significant acceleration

STROKE sequence by CEA		
Test	Conditions	Duration
DML	1kPa	1000 cycles
xDH	95°C/85%RH	500 h
xUV	60kWh/60°C	
xCT	-60/105°C	50 cycles
xHF	-60/95 °C and 85 %RH	10 cycles



FIRST CONCLUSION

■ Motivation for new materials and module designs

- *Decrease of LCOE: Cost reduction and performance improvement*
- *New technological requirements*
- *Sustainability and legal regulations. Lower LCA, Carbon footprint, local production*

PV systems designed for specific application and environmental conditions

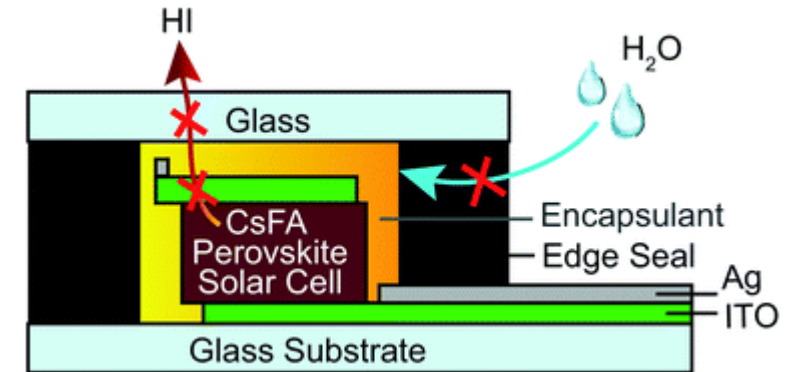
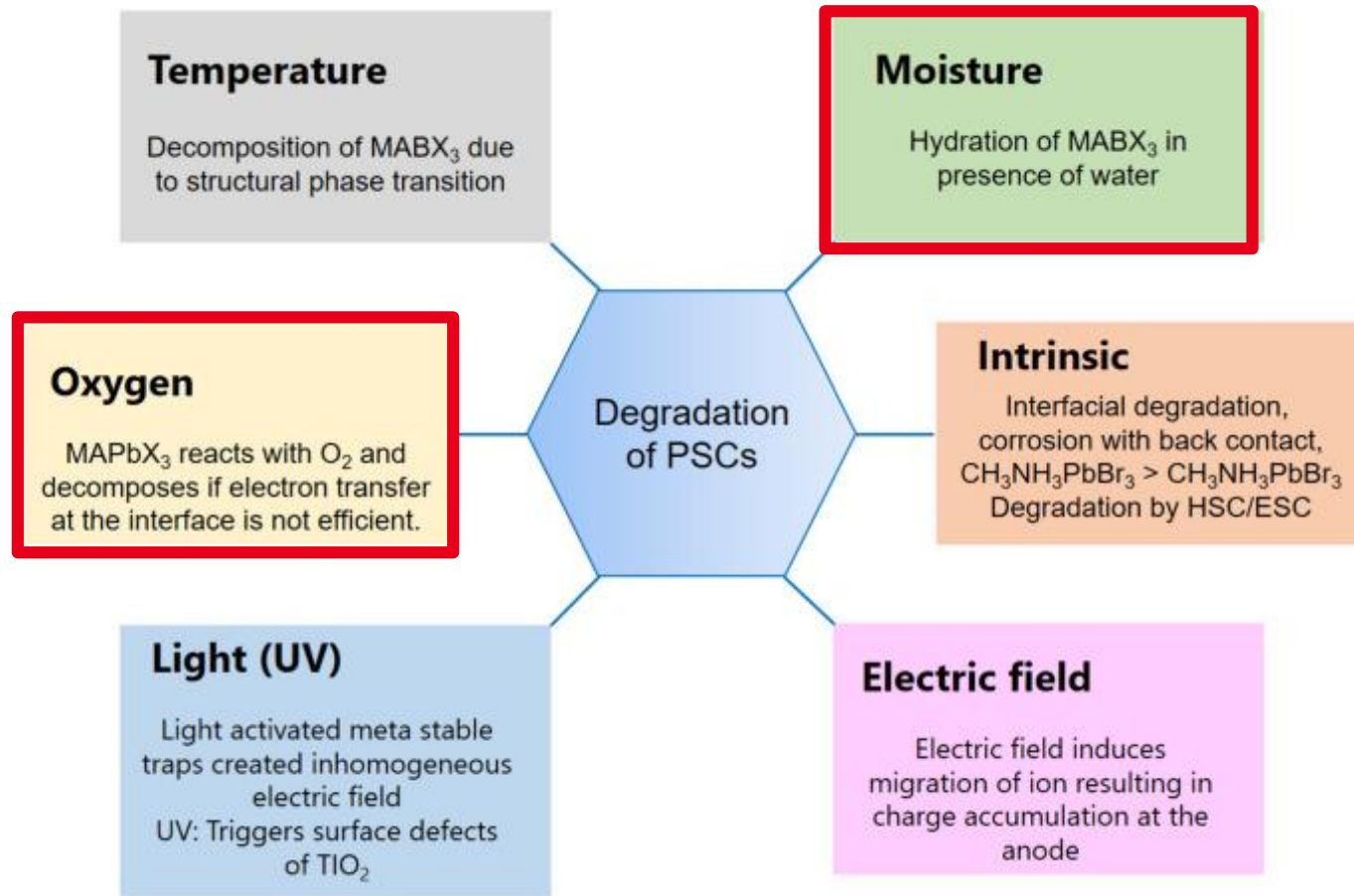
■ Challenges

- *Long term stability is determined by bill of materials and their material interactions*
- *Each material combination should be tested thoroughly before introduction into the market*
- *Single stress testing often does not reveal certain degradation modes observed in the field*

Combined or sequential stress testing necessary, new standards

Better understanding of PV module and material degradation processes is a precondition for a successful development of new components and RELIABLE and SUSTAINABLE PV module designs

CHALLENGES FOR TANDEM: STABILITY ISSUES & ENCAPSULATION STRATEGIES



Rongrong Cheacharoen & al. *Sustainable Energy & Fuels*, 11, 2018
<https://doi.org/10.1039/C8SE00250A>

Does PK tandem need extra encapsulation for strong encapsulation against H_2O and O_2 to prevent or to slow several degradation mechanisms ?

CHALLENGES FOR TANDEM: STABILITY ISSUES & ENCAPSULATION STRATEGIES

1. Is standard c-Si technology **Hot Vacuum lamination** enough?

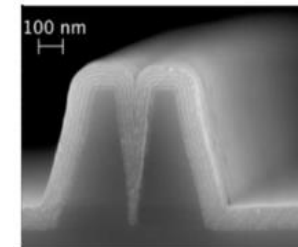
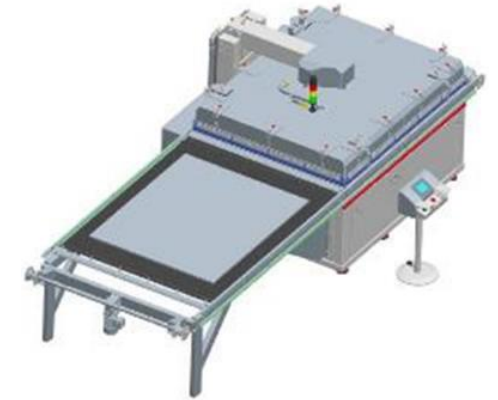
- Relatively slow process
- Low cost materials available but with poor gas barrier properties
- Use of additional edge sealing
- Limit of processing T°

2. Should we add **UV liquid adhesives (like OPV)**?

- Rapid process
- Low T° process
- Cost of gas barrier grade considering the thickness

3. Or go to extra **Thin film deposition layer**?

- No side permeation
- Need further encapsulation but can relax the constraints
- Need effective & pretty slow deposition process (ALD, PECVD)
- Cost?



CHALLENGES FOR TANDEM INTERCONNECTION

		PERC	HJT	TANDEM
Temperature range		High (800°C)	Low (200-250°C)	Very low (< 160°C)
Interconnection Process	Soldering		Metallization paste has to be solderable Tf > 220°C for Pb free alloy	T > 200°C
	LT Soldering (< 160°C)			To be assessed
	ECA			To be assessed
	Shingle		High silver consumption (metallization) High reliability (<1% loss after 800TC)	To be assessed

CHALLENGES FOR TANDEM INTERCONNECTION

Temperature < 160°C

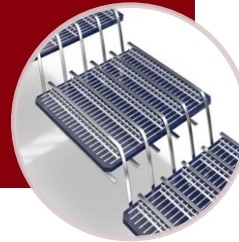
- Bi or In alloy ($120^{\circ}\text{C} < T_f < 140^{\circ}\text{C}$)
- Compatibility with tandem metallization unknown
- T_{process} critical (usually an overshoot $+20^{\circ}\text{C}$ above T_f is necessary)

Low
temperature
soldering



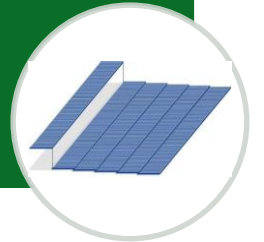
- Current process around 180°C **BUT** ECA curable at 120°C already assessed
- Silver consumption in ECA but less BB required for tandem (lower J_{sc})

ECA ribbons



- ECA compatible as for BB
- Silver metallization less critical because of lower J_{sc}
- Laser cutting ?

Shingle

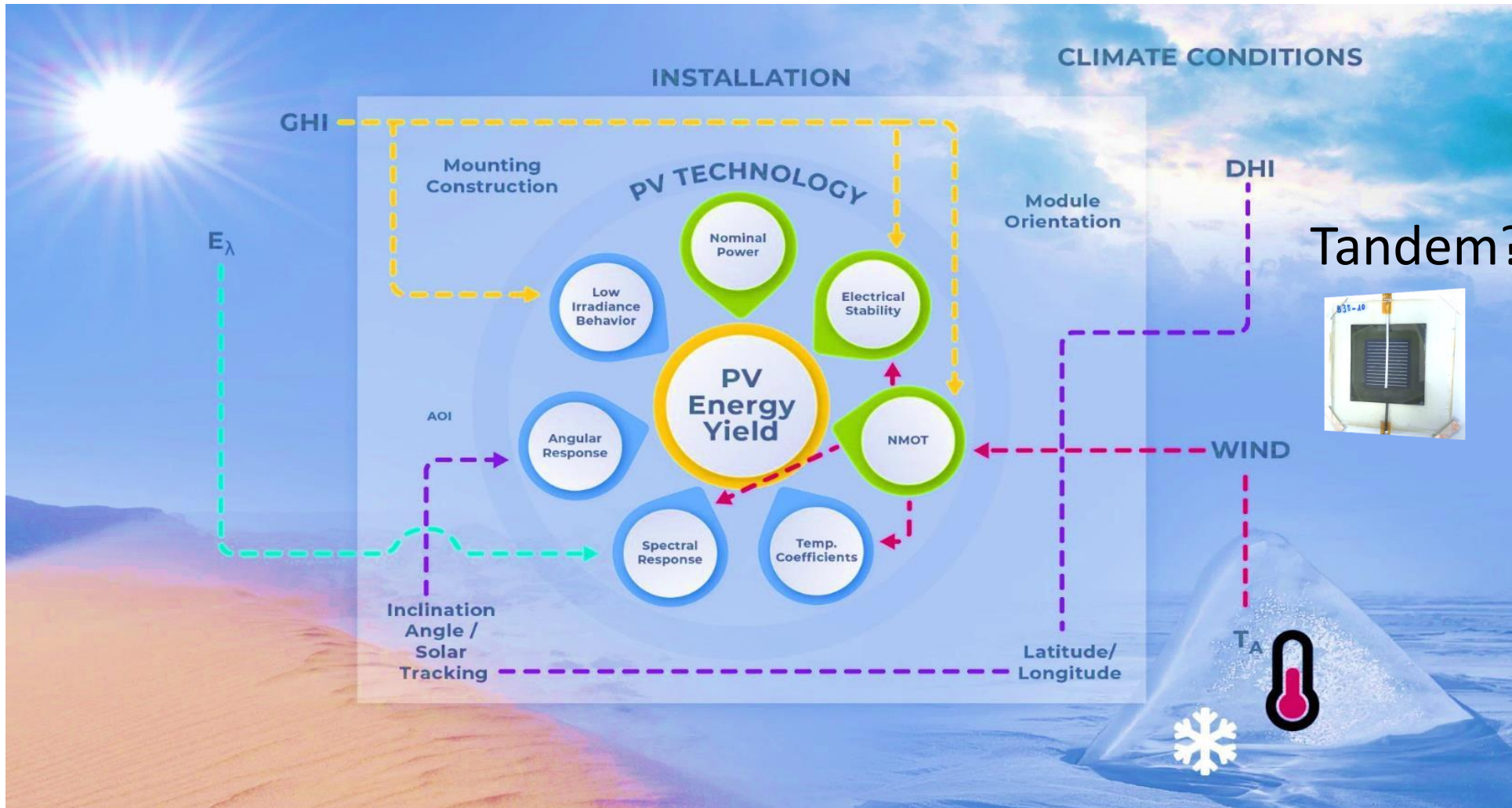


CONCLUSION

- Lessons learned, methodologies and protocols from cSi technology (and others) are the baseline for new PV technologies development.
- BOM has to be adapted for tandem and perovskite development taking into account all boundary conditions for > 30 y reliability with a sustainable approach.
- The Terawatt PV era is a multi-technology ERA. We need all technologies in the market to be able to integrate PV everywhere with a sustainable manufacturing.

NEXT STEP: SMART INTEGRATION OF PV

Different PV module technologies for various operating conditions



J. Bonilla Castro, M. Schweiger, D. Moser, T. Tanahashi, B.H. King, G. Friesen, L. Haitao, R.H. French, B. Müller, C. Reise, G. Eder, W. van Sark, Y. Sangprongsanon, F. Valencia and J.S. Stein. "Climatic Rating of Photovoltaic Modules: Different Technologies for Various Operating Conditions". Report IEA-PVPS T13-20:2020. ISBN 978-3-907281-08-6.

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