CLIMATE SPECIFIC ACCELERATED AGEING TESTS

And outdoor failures observed

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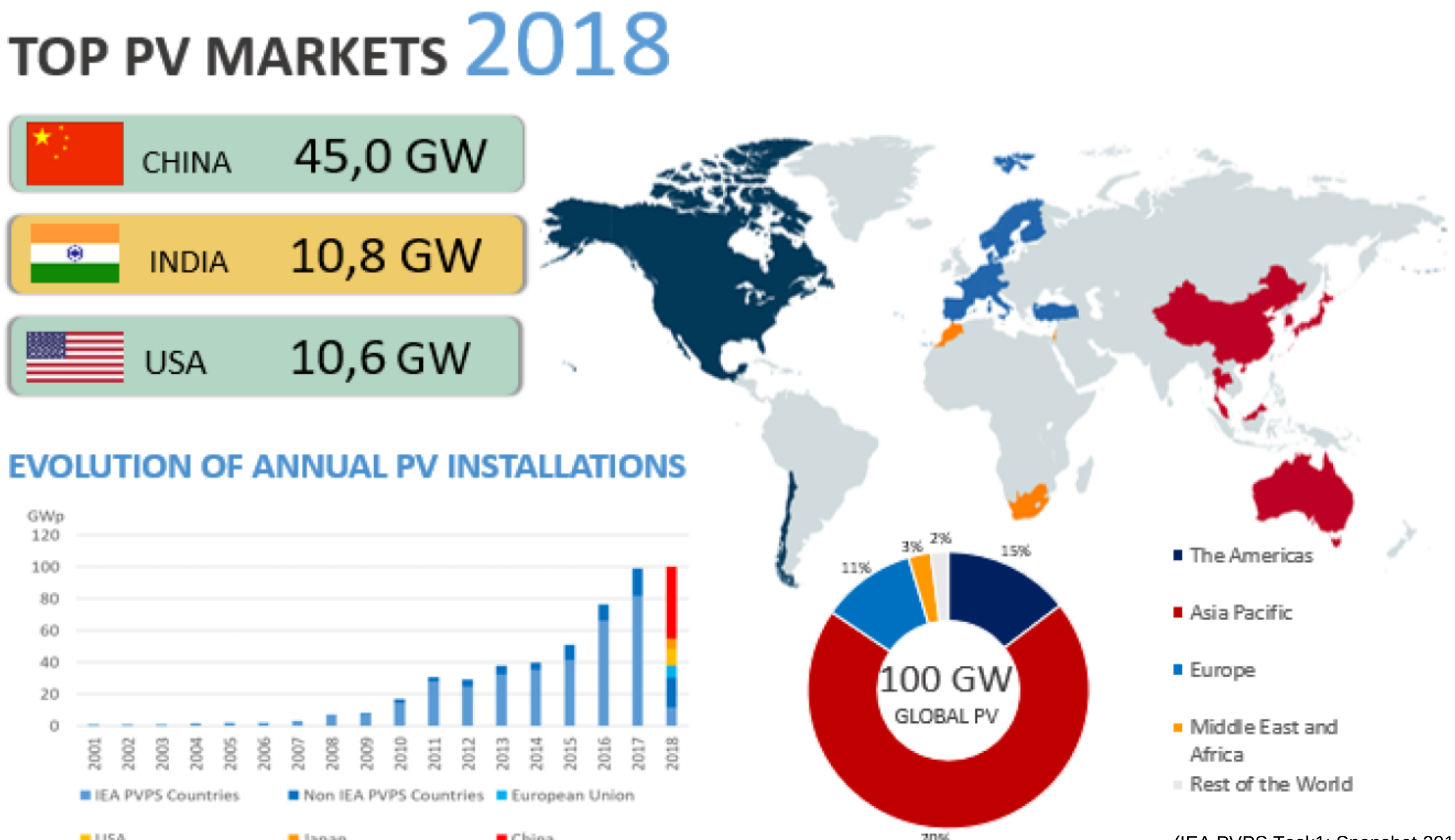
CONTENT

- Motivation: PV installations under challenging climatic conditions
- PV Industry trends in applications
- Outdoor failures observed with respect to Koeppen-Geiger climate zones
- Circular failure tree approach
- Our test results, and the manifold of test procedures and failure modes
- Summary & Outlook

PV MARKETS 2018

ESTIMATED INSTALLATION 2019 ABOVE 100GW AGAIN

Rapid worldwide market grow: mostly young systems, few data about long term performance



(IEA PVPS Task1: Snapshot 2019)

Changing markets

- Early PV installations & markets: mostly in moderate climates
  Large incentives to get started
- NOW: many installations under more challenging environmental conditions
- Extremely competing market conditions: Cost driven
- Fast uptakes of new processes, materials and technologies if promising
- Growing incentives for NON-renewables

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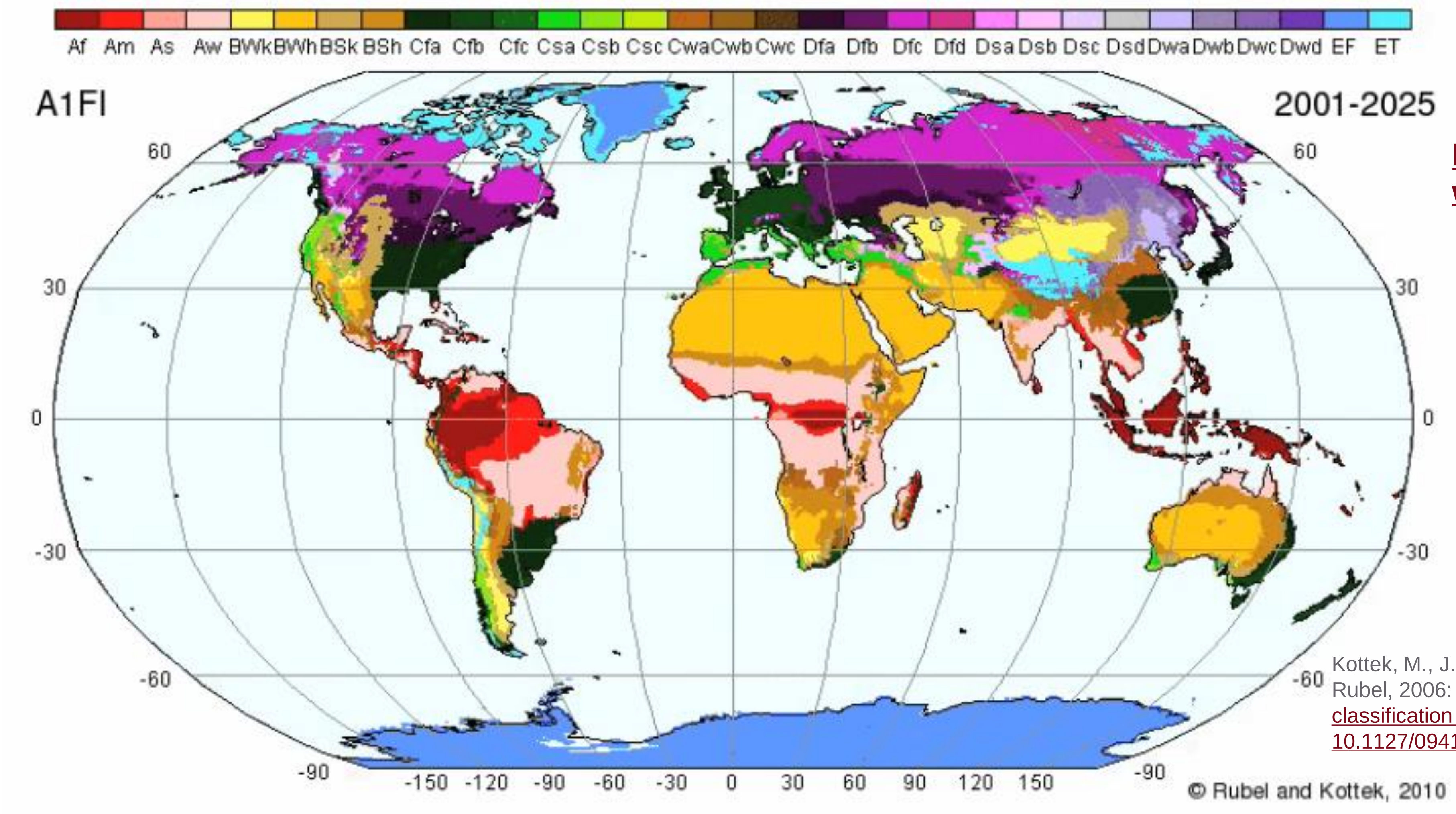
KOEPPEN-GEIGER

Online map, and different scenarios how the climate zones may change in the 21th century,



http://koeppen-geiger.vu-wien.ac.at/shifts.htm

vetmeduni vienna

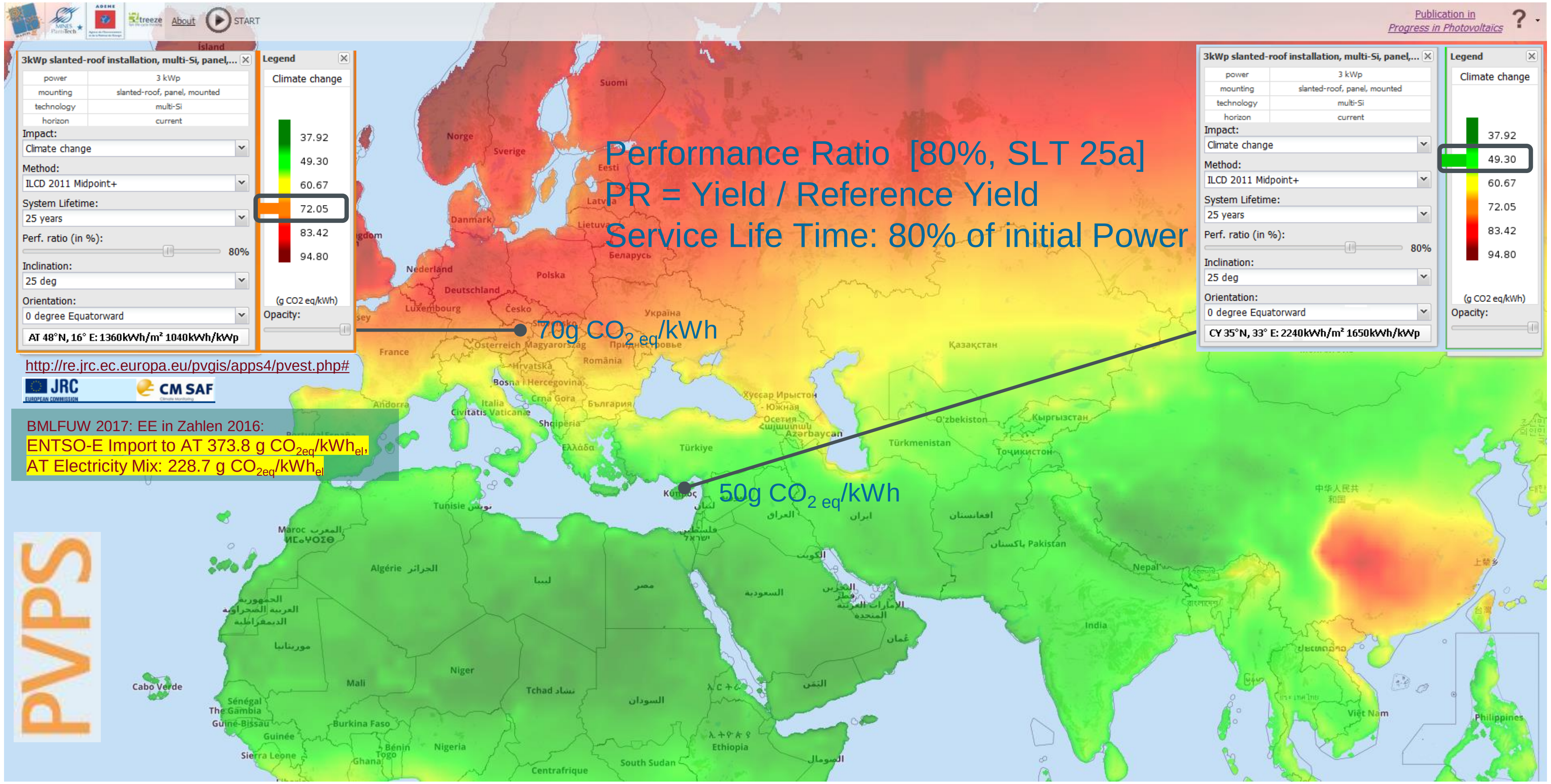
Kottek, M., J. Grieser, C. Beck, B. Rudolf, and F. Rubel, 2006: World Map of the Köppen-Geiger climate classification updated. *Meteorol. Z.*, **15**, 259-263. DOI: 10.1127/0941-2948/2006/0130.

PV CO_2 FOOTPRINT

IEA PVPS TASK12 IMPACT ASSESSMENT TOOL

PVPS Task 12 Environmental Impact Assessment Service Tool, http://viewer.webservice-energy.org/project_iea/

Vienna, Austria
Moderate Cfb
1360 kWh/m²a



Cyprus
Dry summer subtropical (mediterranean) Csa
2240 kWh/m²a

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PV CO_2 FOOTPRINT

IEA PVPS TASK12 IMPACT ASSESSMENT TOOL

IF PV system is very performant and long-lasting – better … and better the more sun we have

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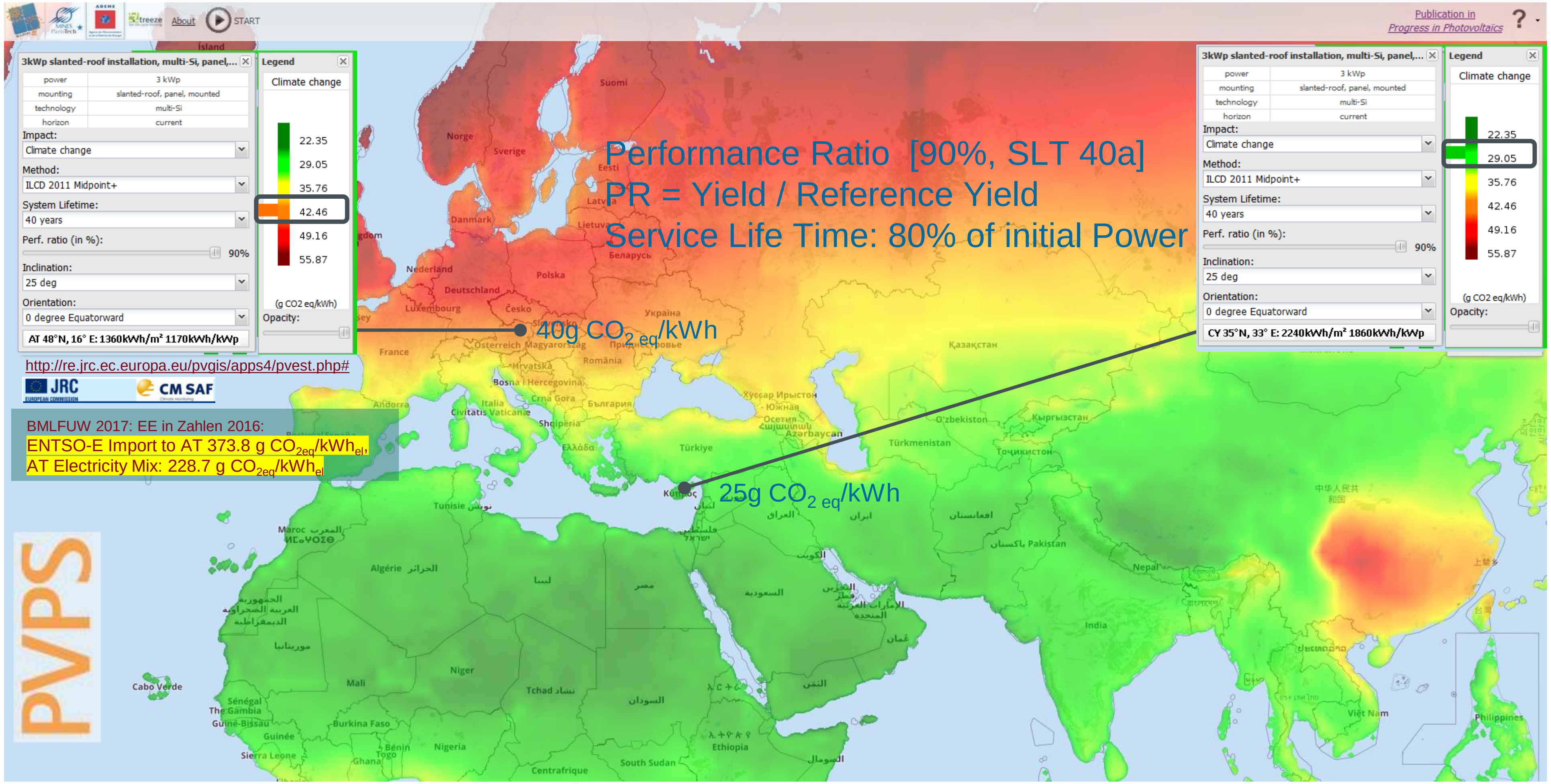

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PV CO_2 FOOTPRINT

IEA PVPS TASK12 IMPACT ASSESSMENT TOOL

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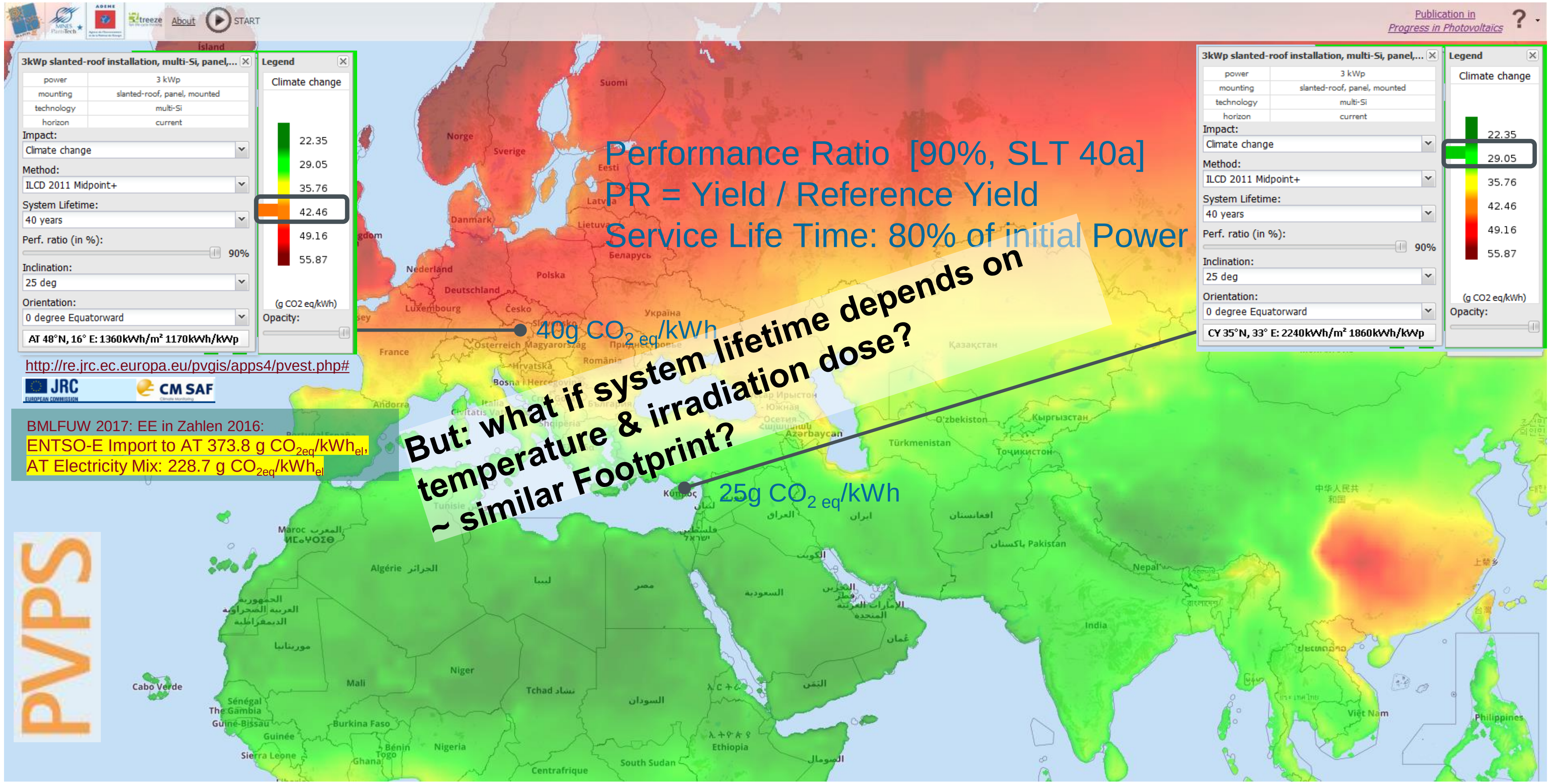

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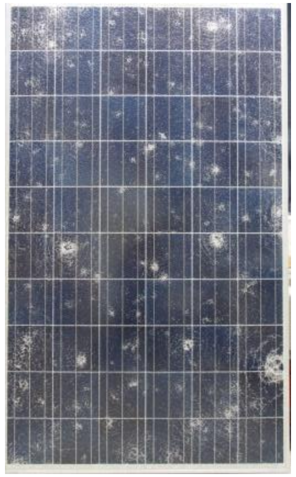
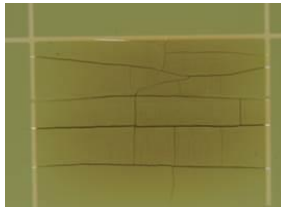
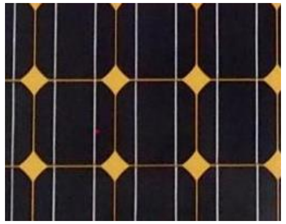
MOTIVATION & OBJECTIVE

- Photovoltaic has enormous potential, and is able to outperform non-renewables by an order of magnitude in CO_2-footprint.
  This gets even better, when industry and its power supply gets more and more environmental friendly
- But this is only true, if PV is performant and long lasting:
  Apart from initial failure modes, performance losses due to continuous ageing and degradation of the materials/components ("midlife failures") are defining the long-term stability and profitability of PV-systems
- To guarantee this, artificial accelerated ageing tests, simulating ageing-induced degradation of PV-modules under given stress conditions, are seen as a key for an efficient and fast product improvements
- As a part of the Austrian "Energy Research Program" project INFINITY field failures were analyzed, and climate related test-procedures applied







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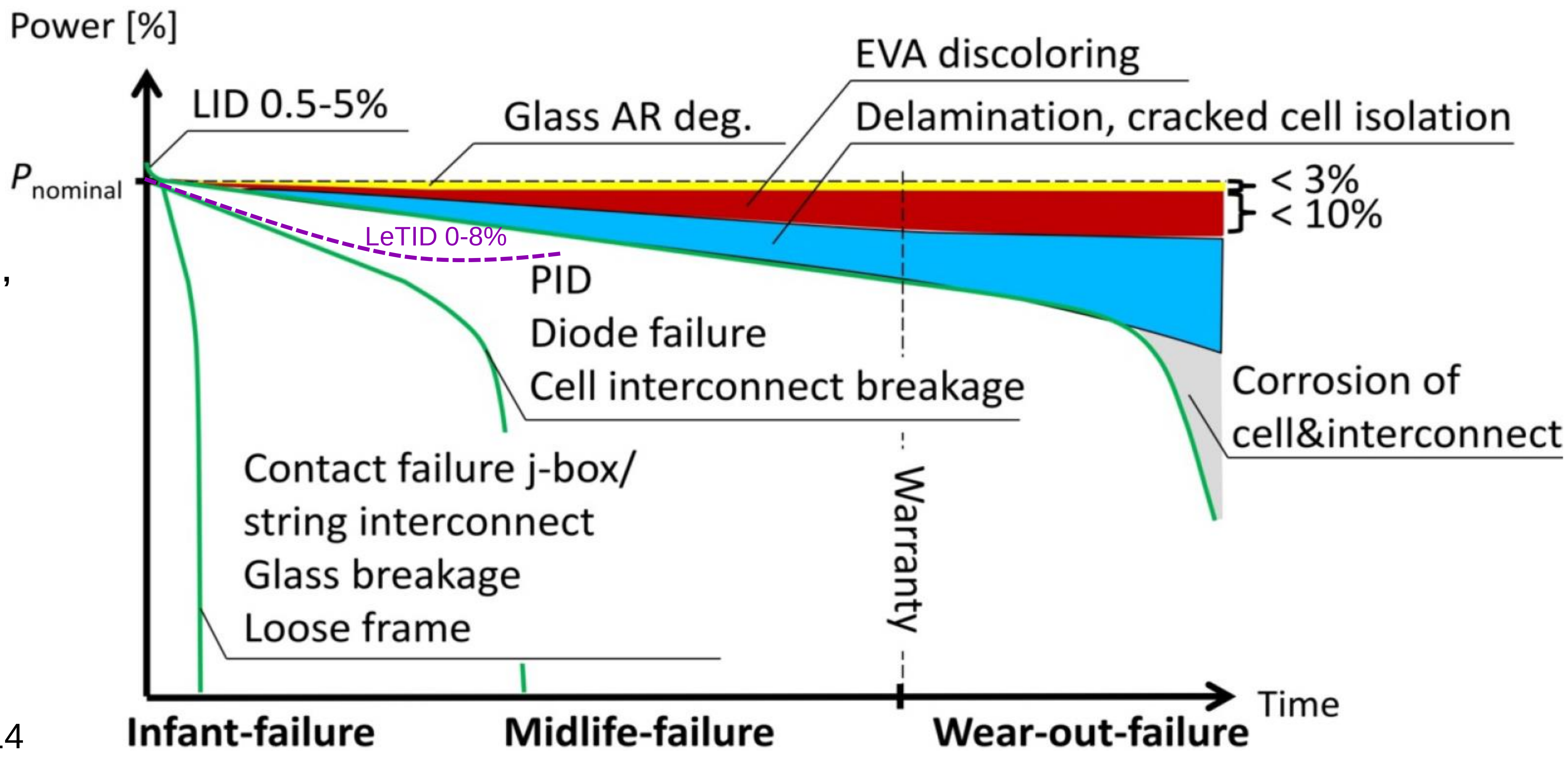
MODULE FAILURE MODES
(OVERVIEW FROM 2014)

- **Different PV-module failure types – the reverted Bathtub Curve**
  - Infant failure
  - Midlife failure
  - Wear-out failure
  -



- **Although very general, failure modes to add?**
  - E.g. LeTID
  - Other?

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MANIFOLD OF MODULE FAILURES

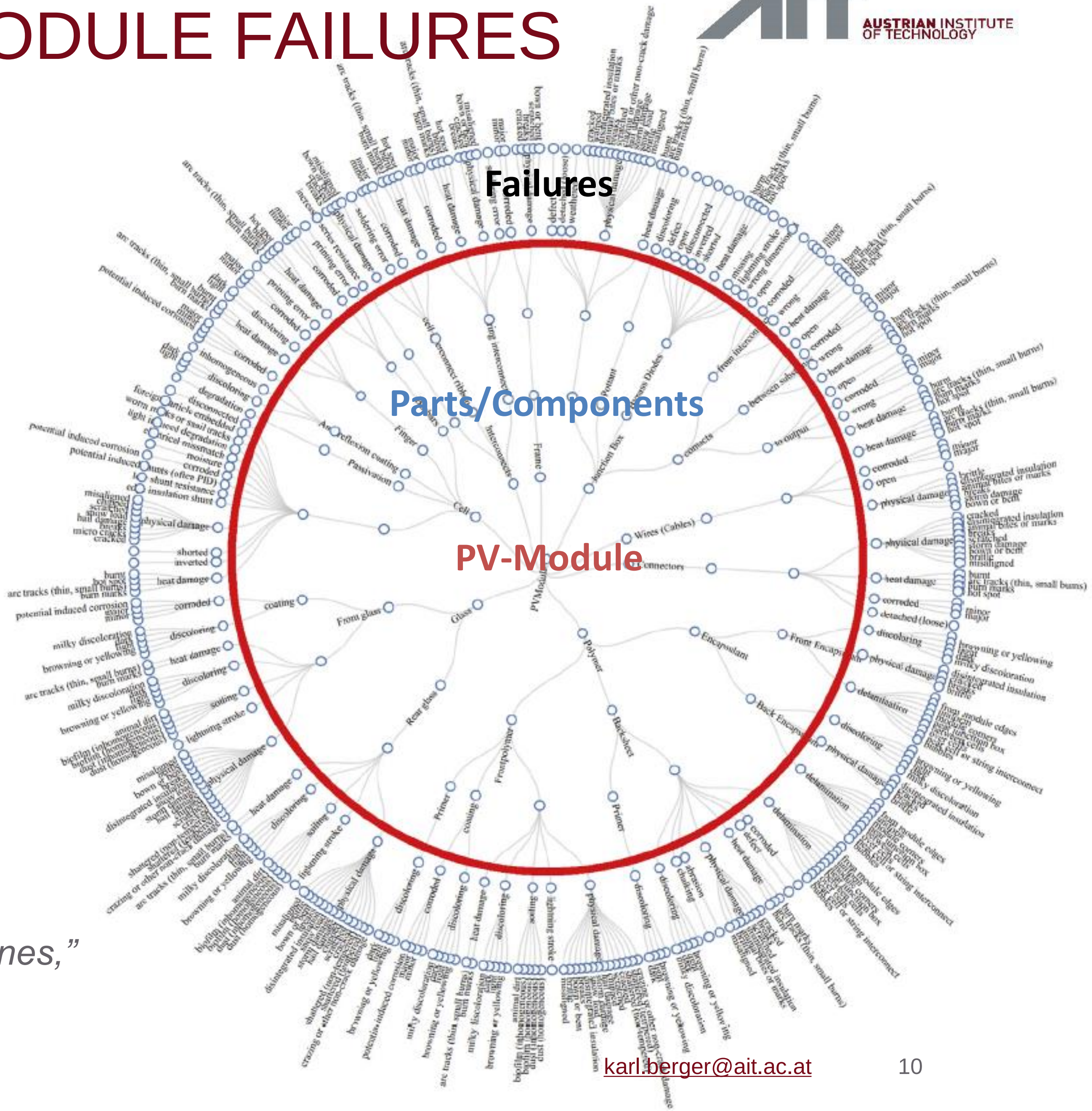
AUSTRIAN INSTITUTE OF TECHNOLOGY

INFINITY Circular failure tree

- 1048 samples
- 340 sub-systems
- 45 countries

✓ Literature
✓ Own data sets from O&M
✓ IEA PVPS Task 13 data collection

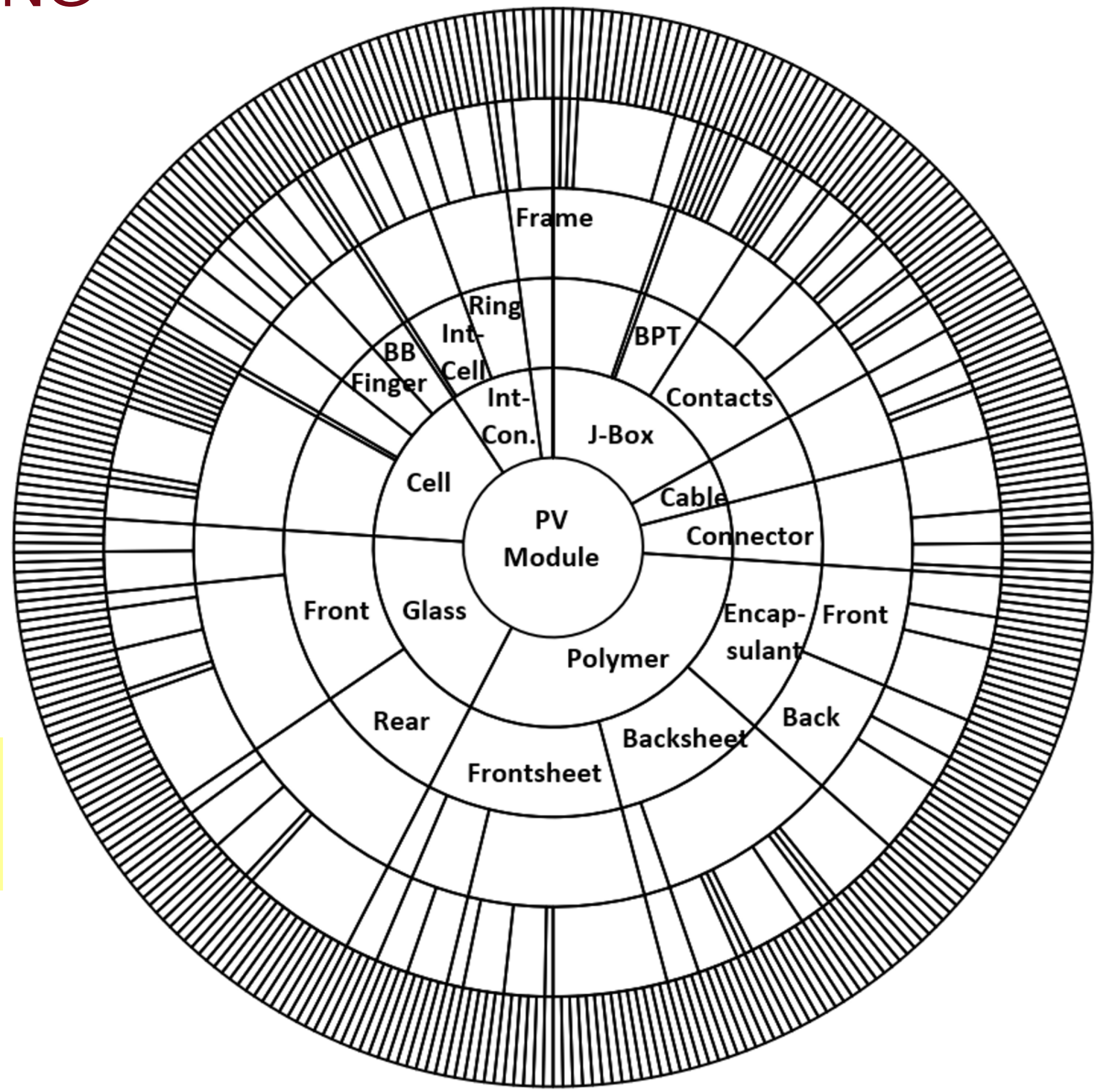
IEA PVPS Task 13 http://www.iea-pvps.org/index.php?id=344



M. Halwachs et al., *“Statistical evaluation of pv system performance and failure data among different climate zones,”* Renew. Energy, vol. 139, pp. 1040–1060, 2019.

IEC TC82 ACTIVITY ON COMBINED AND SEQUENTIAL TESTING

- Circular failure tree
- Center: module
- Outer areas:
  parts and interfaces



P. Hacke & Tadanori Tanahashi: Draft IEC TR:
Combined and Sequential Accelerated Stress Testing for Derisking Photovoltaic Modules (IEC TC82 WG2 Spring meeting @ PTB, 2019)

M. Halwachs et al., *“Statistical evaluation of PV system performance and failure data among different climate zones,”* Renew. Energy, vol. 139, pp. 1040–1060, Aug. 2019.

FAILURE STATISTICS FIELDED PV-MODULES >2000, (303)

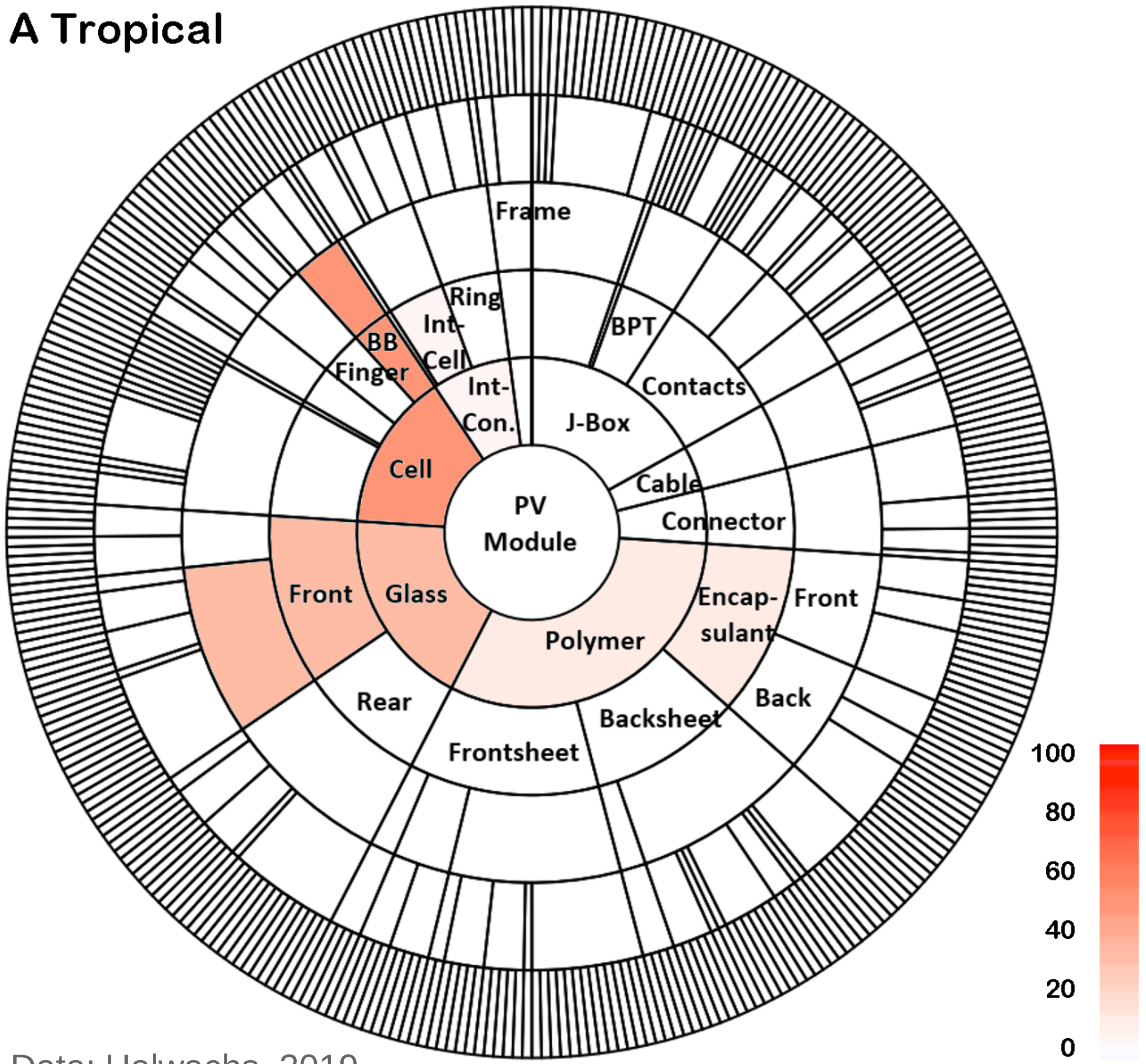
RELATIVE PERCENTAGE OF REPORTED FAILURES PER COMPONENT AND CLIMATE ZONE AS DERIVED FROM THE INFINITY STUDY, M. Halwachs et al., Renewable Energy, vol.139, pp. 1040-1060, 2019.

	Köppen Geiger main climate zone				
Component	A tropical	B arid	C temperate	D continental	E alpine / polar
Glass	33%	22%	22%	19%	-
Cells/Busbars	46%	29%	38%	62%	15%
Interconnectors	4%	5%	3%	-	15%
Encapsulant	8%	11%	12%	-	8%
Backsheet	-	9%	1%	5%	54%
Junction Box	4%	15%	13%	-	8%
Other	4%	8%	7%	14%	-

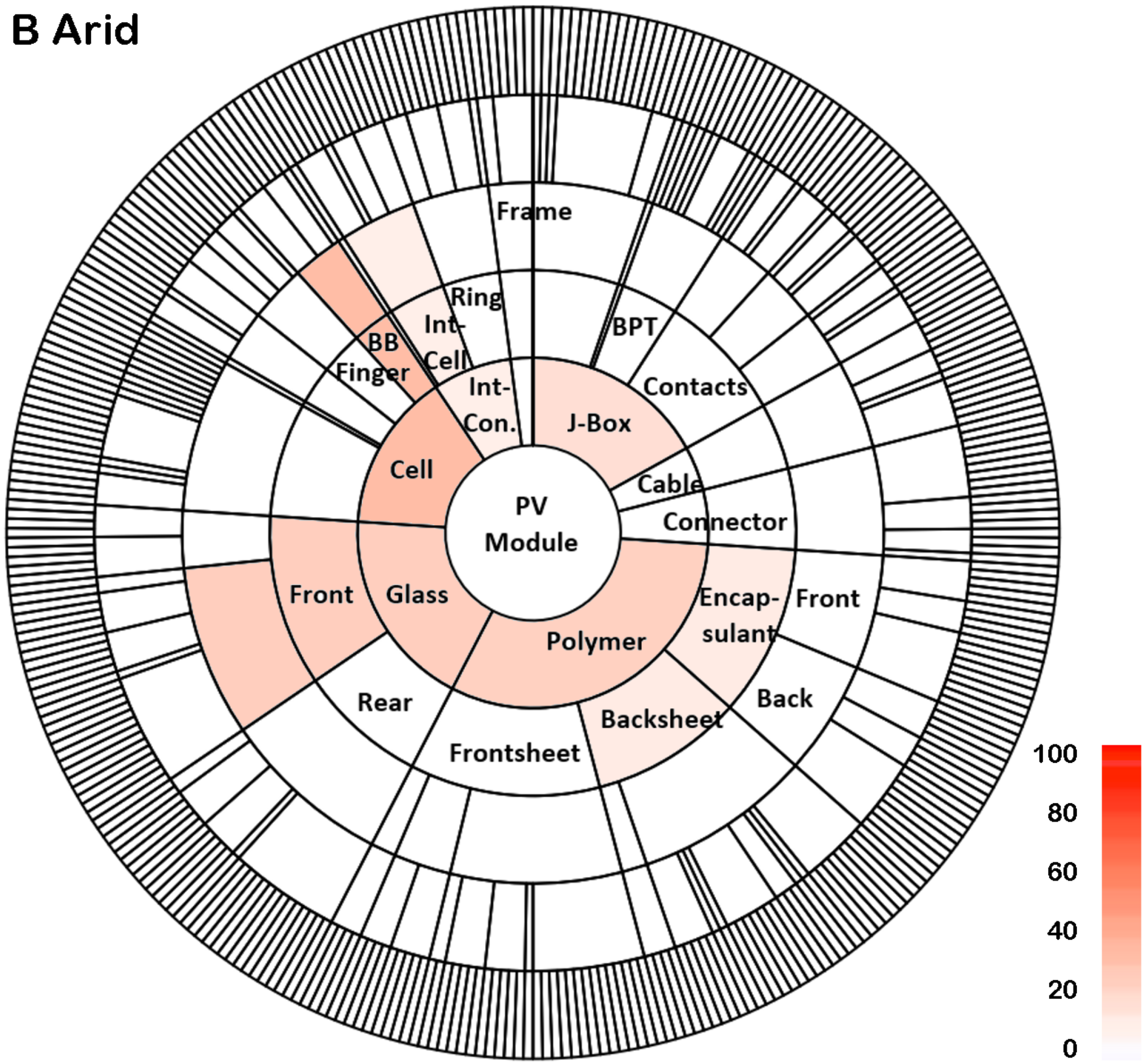
Stress also by application / µ-climate

MODULE FAILURE STATISTICS >2000

A Tropical



B Arid



Data: Halwachs, 2019.

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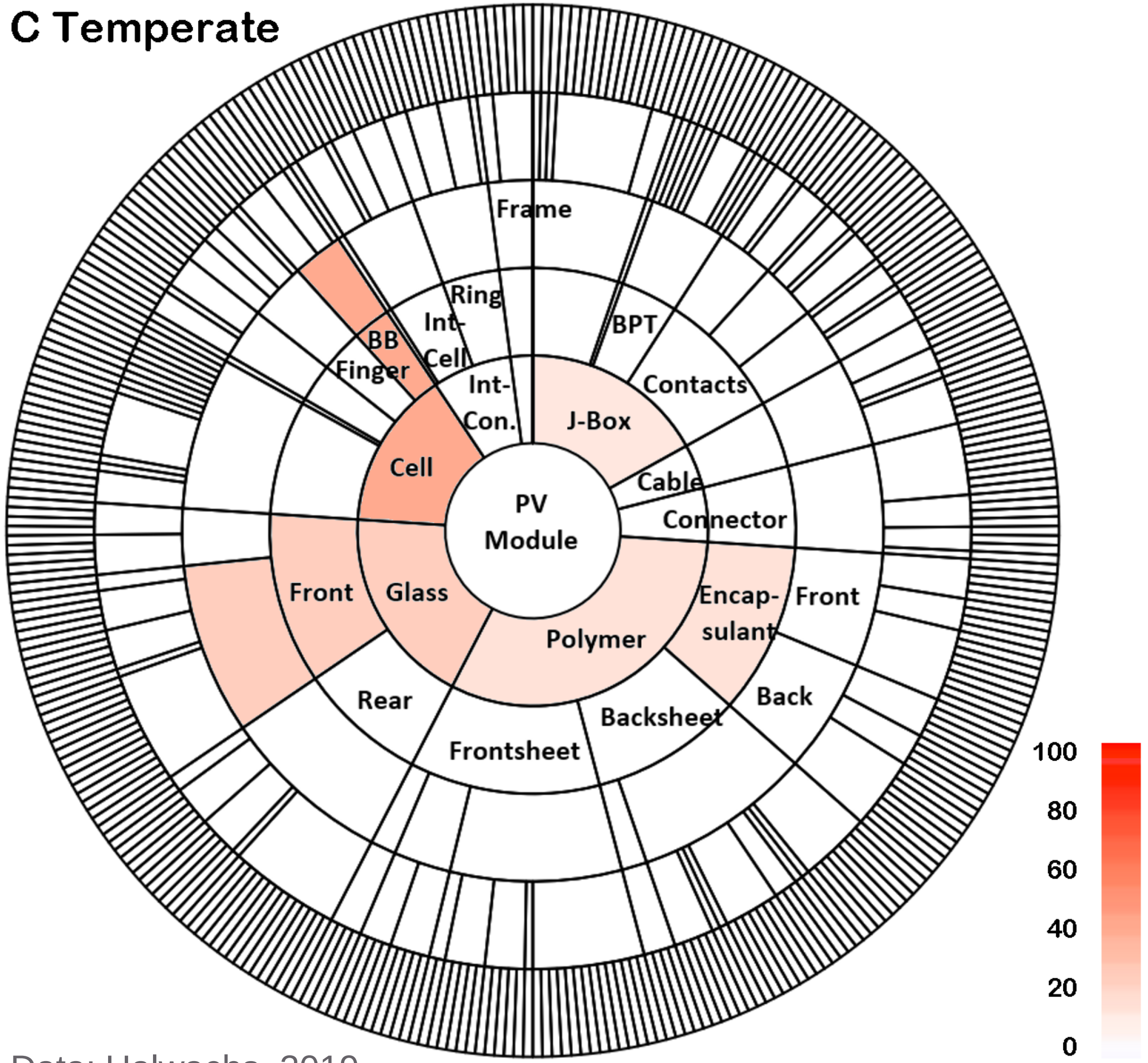
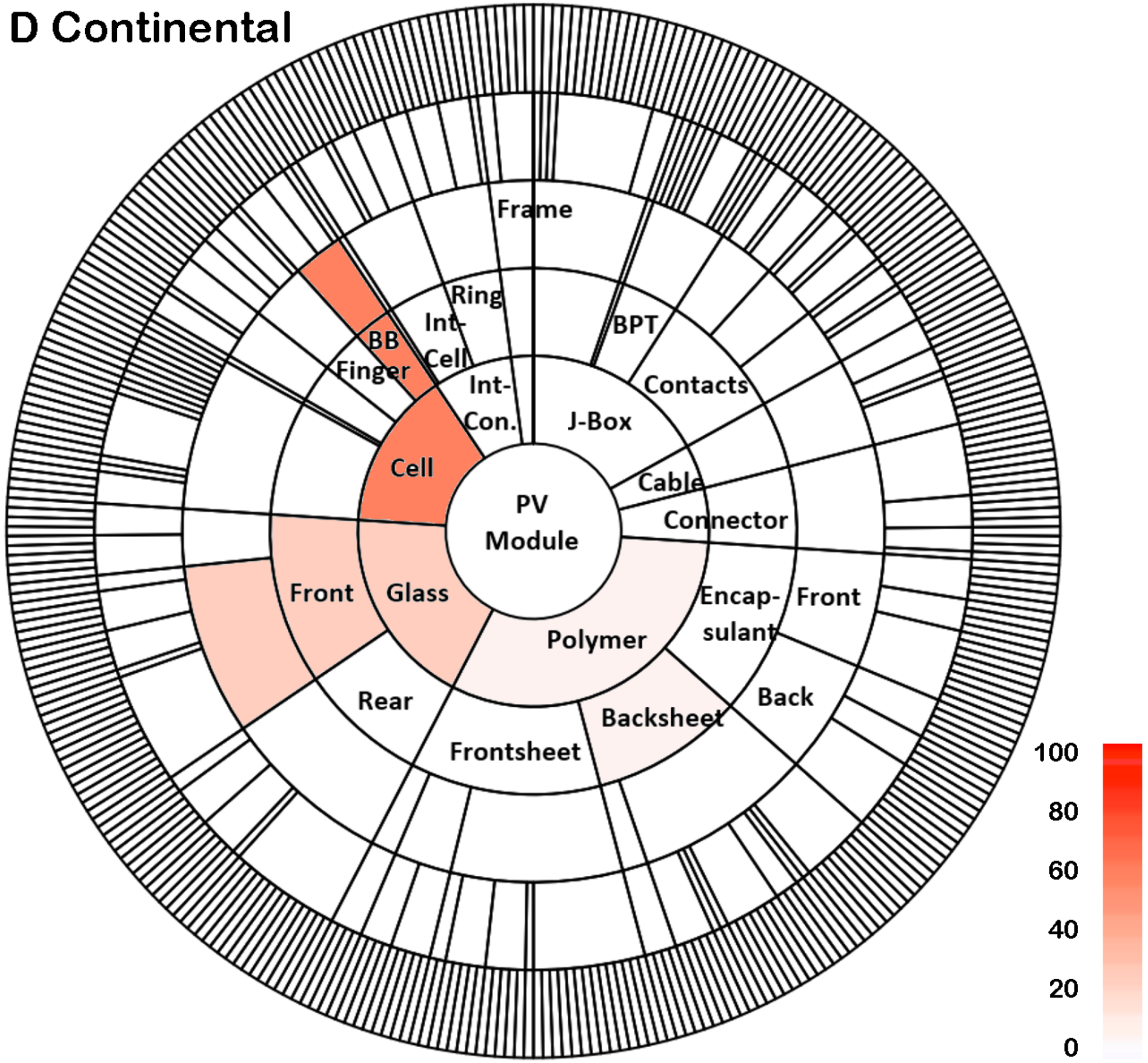
MODULE FAILURE STATISTICS >2000

C Temperate



D Continental

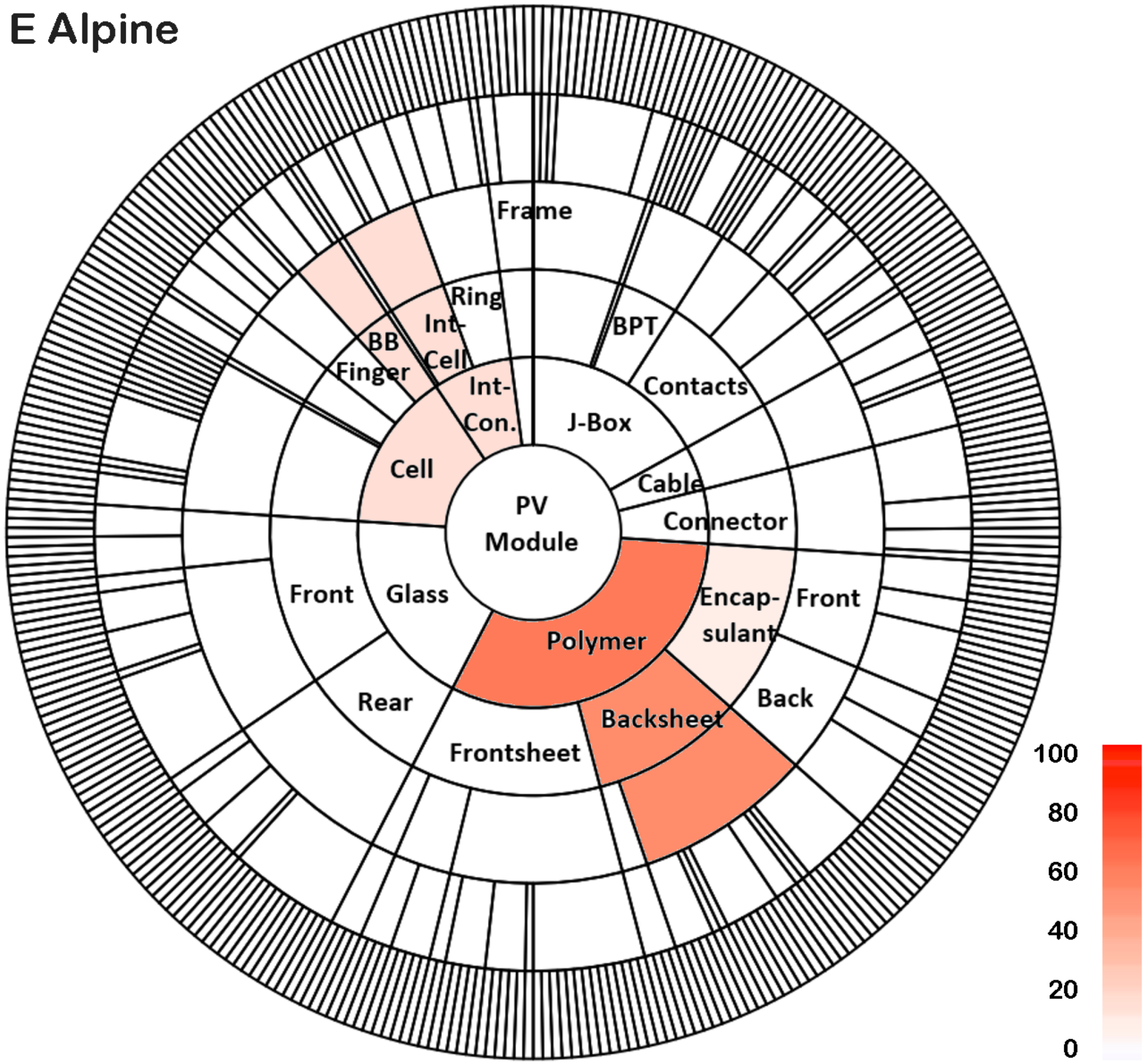


Data: Halwachs, 2019.

MODULE FAILURE STATISTICS >2000

Failure tree patterns

- Many common failures in A – D
  but clearly visible differences
- E (Alpine) clearly differs from the others
  (with having no broken frames or glass in our sample)
- >300 observed failures in systems
  built after 2000 is still a (too) small sample
- Update with more data would be nice …



Data: Halwachs, 2019.

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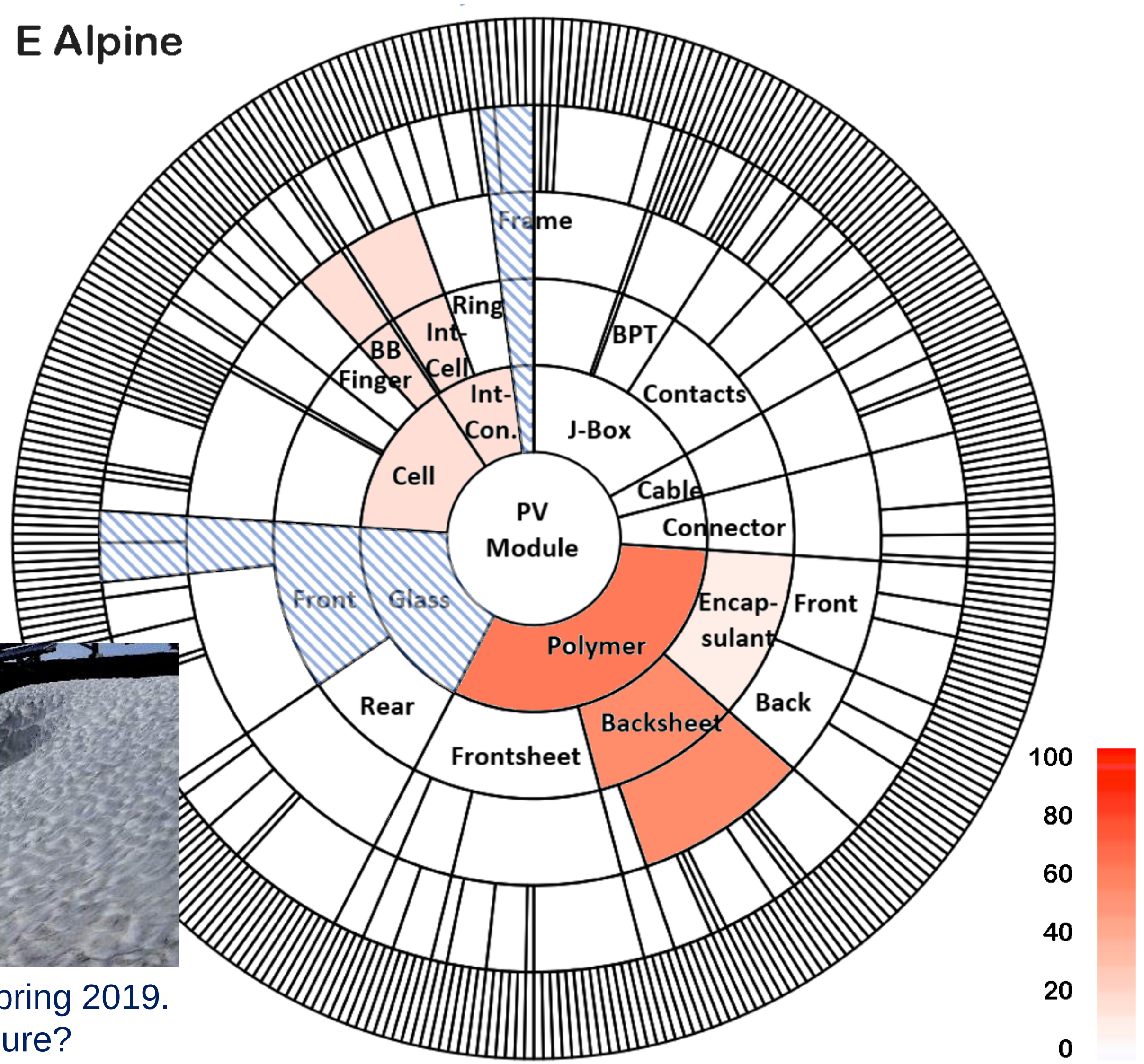

MW system +2000 m a.s.l. buried under several meters of snow in early Spring 2019.
Pics from mid May & June 2019. Module top bent backwards – System failure?

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SUMMARY: FIELD FAILURES – IV PARAM.

	Cause	Trigger / Accelerator	Climate zone
Degradation I_{SC}	– Soiling – Encapsulant discolouration – Delaminations	+ high UV-irradiation (at high temperature) + sand/dust	• Arid (B) • Alpin (E)
Degradation FF/R_S	– Cell corrosion – Breakage connectors – Corroding ribbons/grid lines – PID	+ high humidity and T + large T-changes (TC) + mechanical loads (snow load, wind) + Corrosive environment (salt)	• Tropical (A) • Arid (B) • Continental (D) • Alpin (E)
Degradation U_{OC}	– Bypass diode defect – Inactive cells – Increased cell temperature (partial over heating)	+ Partial shading + Inhomogeneous Surface coverage (snow, soiling ..)	Not very climate sensitive • Arid (B) • Alpin/polar (E)

M. Halwachs et al., *"Statistical evaluation of PV system performance and failure data among different climate zones,"* Renew. Energy, vol. 139, pp. 1040–1060, Aug. 2019. https://doi.org/10.1016/j.renene.2019.02.135

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CLIMATE ZONES ↔ ACCELERATED AGEING TESTS

Ageing tests applied, named like the climate zones, and hopefully provoking some similar failures …

- **A humid and hot** → tropical/equatorial
- **B dry and hot** → arid
- **C warm moderate** → temperate
- **D cold moderate/snow** → continental
- **E high irradiation/snow** → alpin/polar

Additional stress factors like salt-mist and wind, mechanical-load (DML)

→ **test program of 10 climate specific stress combinations**

Objectives:

a) Development of climate specific accelerated ageing test procedures for PV-modules (optimized for the installation in different climates)

b) Comparison of the climate specific failures and degradation effects observed in real PV-plants to those detected using the climate specific accelerated ageing test procedures

Identical test-modules composed of poly c-Si cells, soldered (2 × 3) strings, EVA-encapsulation, PET-based backsheet, and front glass, framed.
3 (or more) such mini-modules per test sequence, add. single cell "modules" for destructive testing

Details see:

- Gabriele C. Eder, Karl Knöbl, et.al.: ***Climate specific accelerated ageing tests***, 2019 IEEE PVSC-46 | Chicago, IL.
- G.C. Eder, et.al: ***Climate specific accelerated ageing tests and evaluation of ageing induced electrical, physical, and chemical changes***, Prog Photovolt Res Appl. 2018;1–16., DOI: 10.1002/pip.3090

ACCELERATED AGEING TEST SEQUENCES

	Duration		Temperature		Relative Humidity	Irradiance	DML	Salt	TC	Intervalls
			Module	Chamber						
Trop1	3000h	1		85°C	85%	-		-	-	simultaneous
Trop2	3000h	1		90°C	90%	-		-	-	simultaneous
Arid	1000h	1	129°C	95°C	50%	1200 W/m²		-	-	simultaneous
Mod1	1000h	1	113°C	85°C	85%	1000 W/m²	-	-	-	simultaneous
Mod2	1000h = 7 cycles	1	78 °C	60°C	40%	1000 W/m²	-	-	-	48h
		2		85°C	85%	-	-	-	-	96h
Mod3	1000h = 7 cycles	1	78°C	60°C	40%	1000 W/m²	-	-	-	48h
		2		85°C	85%	-	-	-	-	96h
		3		-	-	-	1000 c	-	-	24h
Mod4	1000h = 7 cycles	1	78°C	60°C	40%	1000 W/m²	-	-	-	48h
		2		85°C	85%	-	-	-	-	96h
		3		60°C	-	-	-	Salt-mist	-	24h
Mod5	1000h = 7 cycles	1	78°C	60°C	40%	1000 W/m²	-	-	-	48h
		2		85°C	85%	-	-	-	-	96h
		3		-40/+85°	-	-	-	-	50 c	300h
Alpine	2000h = 4 cycles	1		85°C	85%	-	-	-	-	250h
		2	119°C	85°C	85%	1200 W/m²	-	-	-	250h
		3		-	-	-	1000 c	-	-	24h

EXPERIMENTAL APPROACH

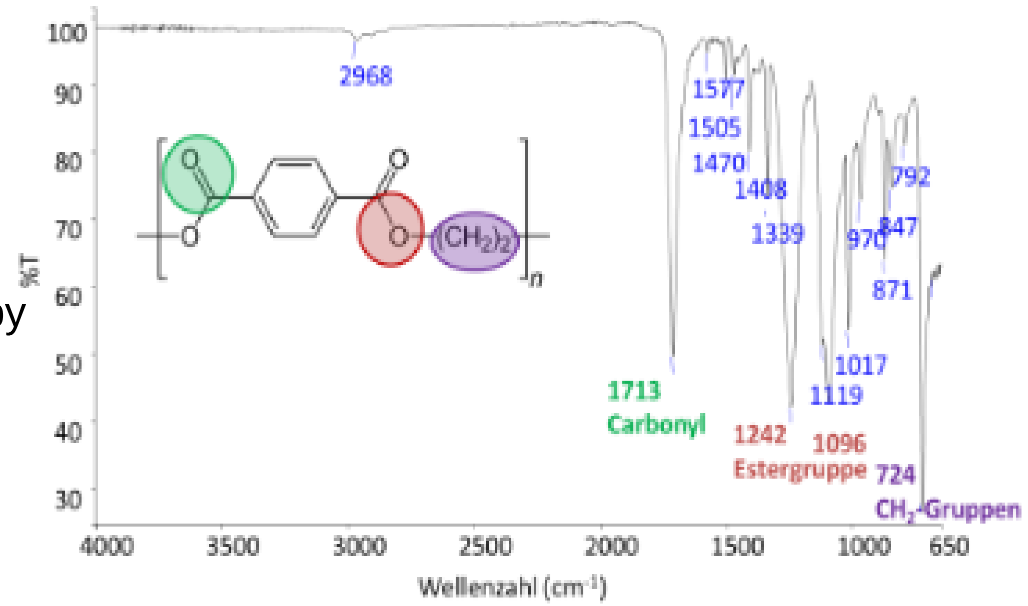
Test procedures:

- adaptation/advancement of existing standard procedures like e.g. PV module design qualification and type approval (IEC 61215-2), safety requirements (IEC 61730) or salt mist corrosion testing (IEC 61701)
  - reliable testing for use in certain climatic conditions needs to induce climate specific material degradation, performance losses and failure modes

Characterization:

- NON-destructive
  - Electrical characterization: I-V curves and ele. parameters, electroluminescence imaging
  - Encapsulation analysis: UV-fluorescence (UV-F) imaging and UV-spectroscopy
  - Backsheet characterization: colour (ΔE) and FTIR spectroscopy
- DESTRUCTIVE material analysis of encapsulant:
  - FTIR-analysis and/or
  - thermodesorption GC/MS (additives and degradation products)

FTIR of backsheet air side B1 PPF



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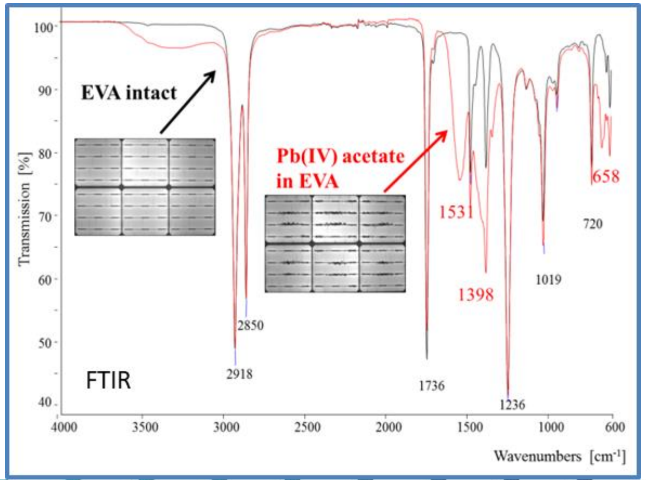
TEST RESULTS: A - TROPICAL

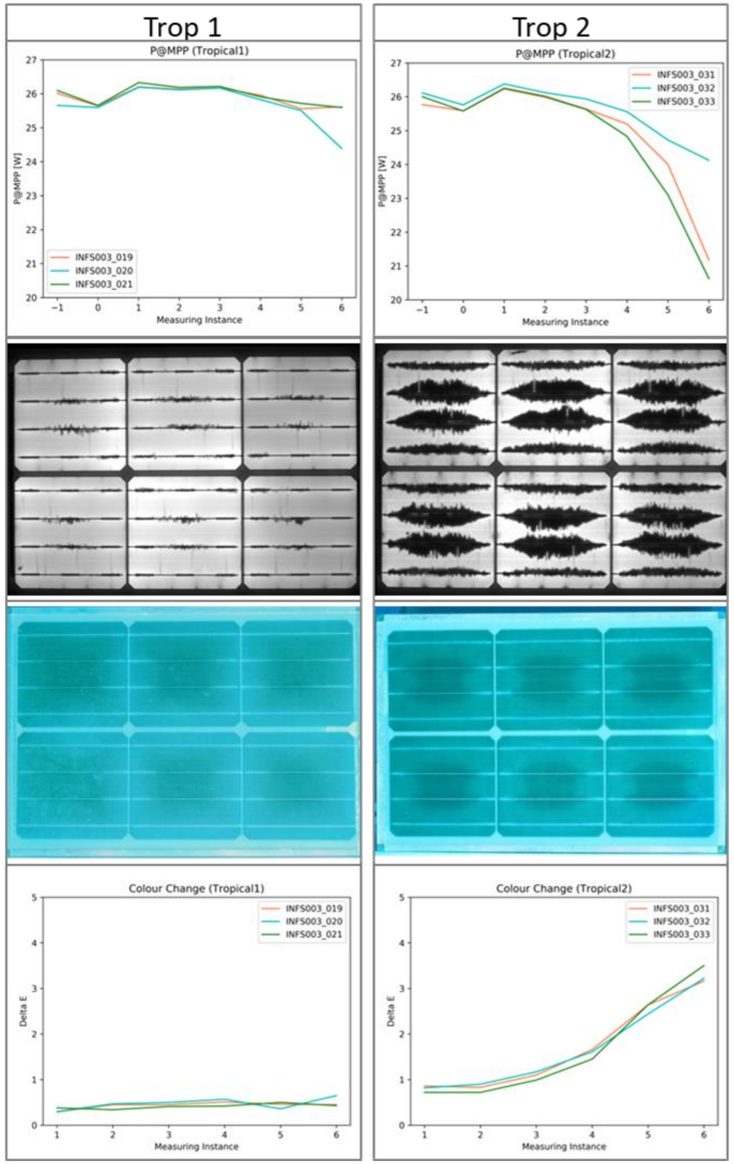
	real failures (24)	INFINITY accelerated ageing tests	
	A tropical	**Trop1**	**Trop2**
		T & H 85°C/85%	High T & H 90°C/90%
Glass	**33%**	-	-
Cell	**46%**	x	xxx
Inter-connectors	4%	-	-
Encapsulant	8%	x	x
Backsheet	-	-	xxx
Junction Box	4%	-	-
Other	4%	-	-

3000h T+, H+

Encapsulant (EVA) degradation
Formation of acedic acid, acetates
@ribbon/solder ↔ EVA

Cell corrosion → FF, R_S +





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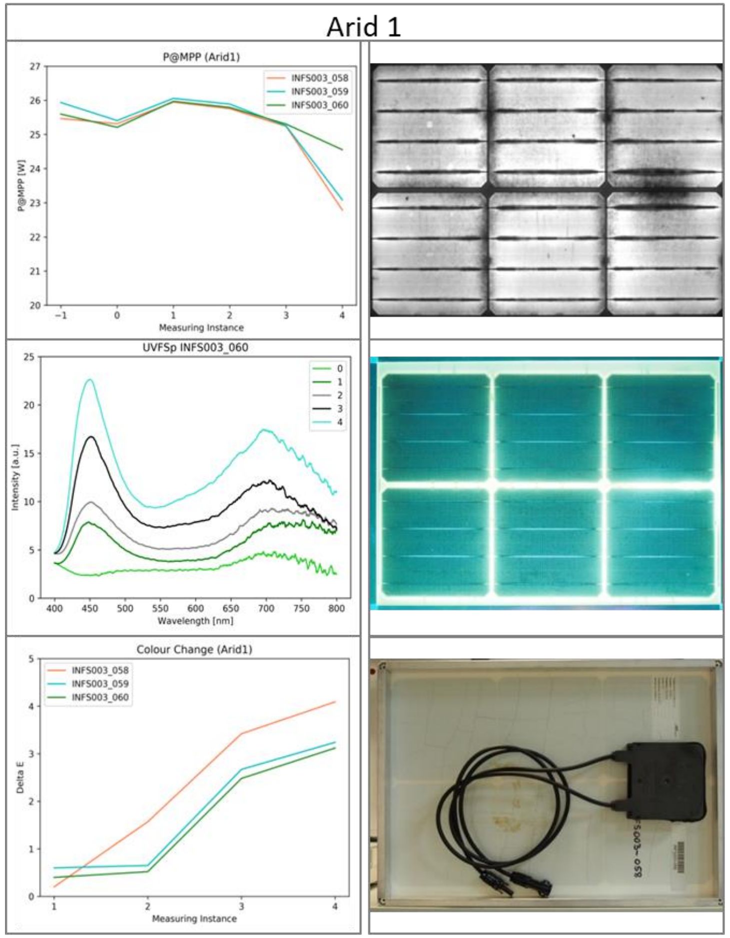
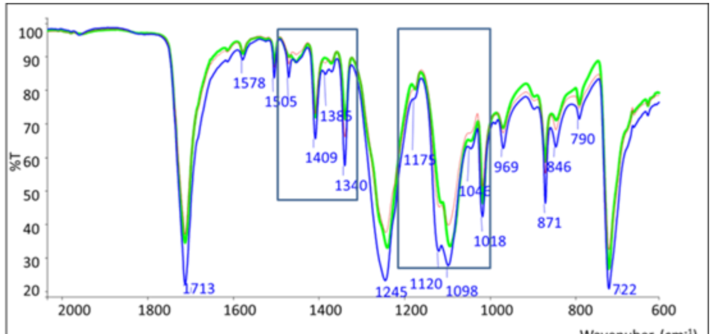
TEST RESULTS: B - ARID

	real failures (138)	INFINITY accelerated ageing tests
	B arid	**Arid**
		High T & I
		T_{Module} 129 °C
Glass	**22%**	-
Cell	**29%**	x
Inter-connectors	5%	x
Encapsulant	11%	xx (JB)
Backsheet	9%	xxx
Junction Box	**15%**	-
Other	8%	-

High Irradiation (1200 W/m²)

- High module temperatures (129° C)
  - Encapsulant (EVA) degradation formation of acedic acid
    - Cell corrosion → FF, R_S+
  - Backsheet (PET) degradation ΔE, embrittlement, cracking





FTIR of inner layer of PET

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TEST RESULTS: C – TEMPERATE / WARM MODERATE

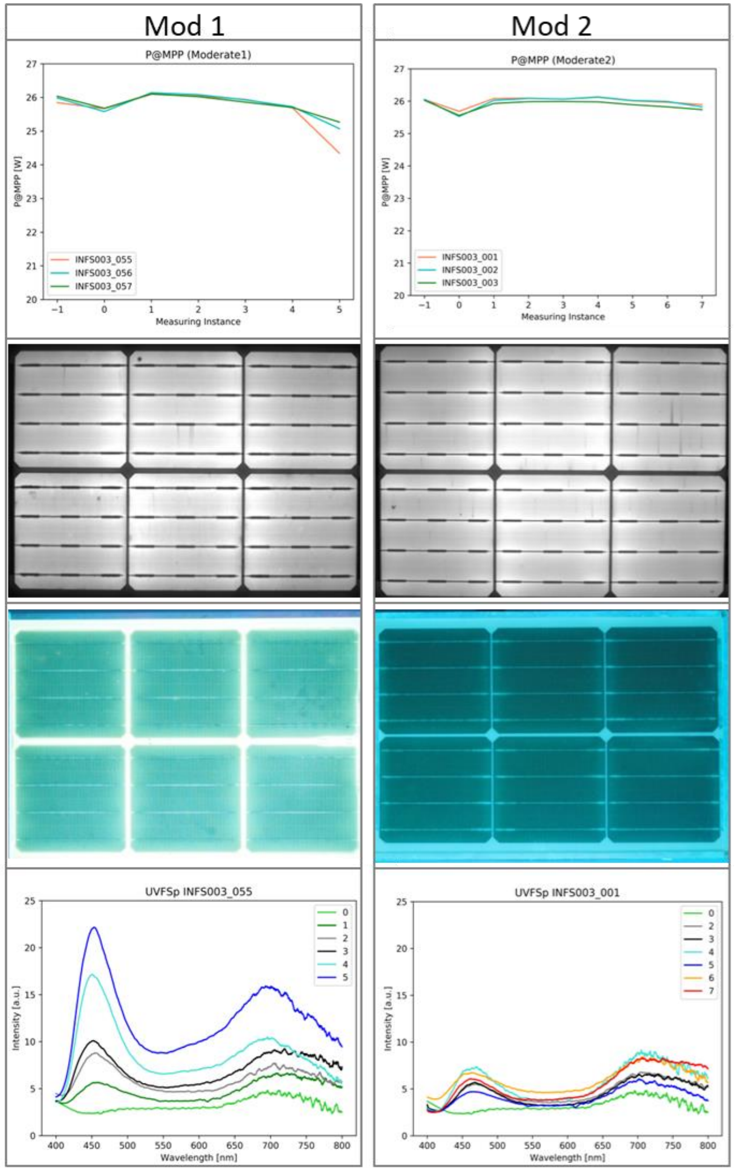
	real failures (107)	INFINITY accelerated ageing tests		
	C temperate	**Mod1**	**Mod2**	**Mod4**
		T,H & I	1) I 2)T & H	1) I 2) T & H 3) Salt
		T_{Module} **113°C**	78/85°C	78/85°C
Glass	**22%**	-	-	-
Cell	**38%**	x	-	-
Inter-connectors	3%	-	-	-
Encapsulant	12%	x	-	-
Backsheet	1%	xx	-	-
Junction Box	13%	-	-	-
Other	7%	-	-	-

Nearly no degradation!

Saltmist without effect

Only @Mod1: Higher module temperatures (113° C)

- Beginning EVA degra-dation
- Beginning Backsheet cracking



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TEST RESULTS: D – CONTINENTAL / COLD MODERATE

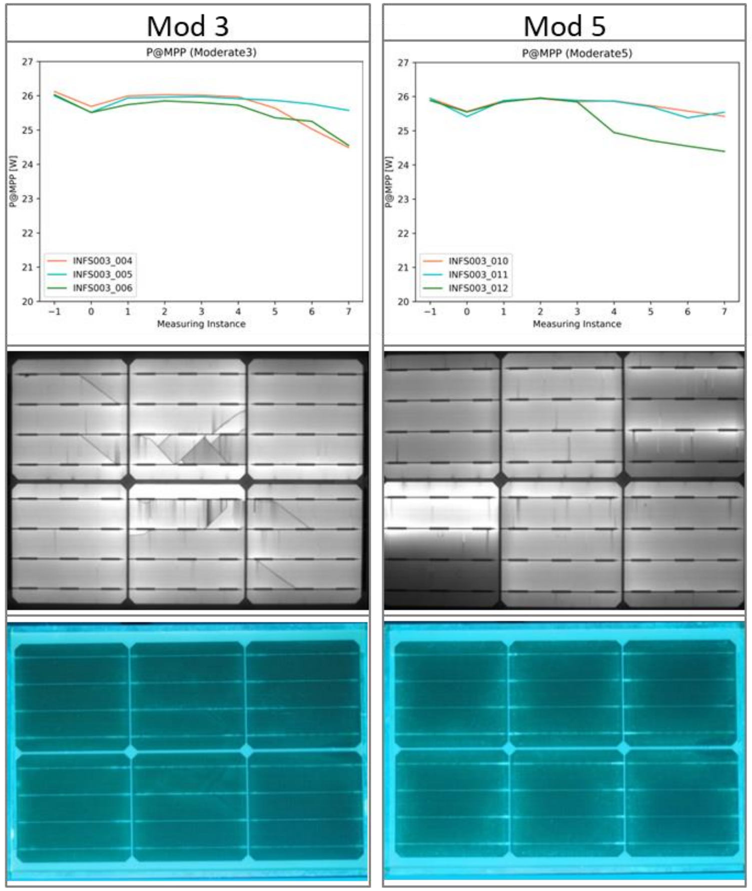
	real failures (21)	INFINITY accelerated ageing tests	
	D continental	**Mod3**	**Mod5**
		1) I 2) T & H 3) DML	1) I 2) T & H 3) TC
Glass	**19%**	-	-
Cell	**62%**	x	-
Inter-connectors	-	-	x
Encapsulant	-	-	-
Backsheet	5%	-	-
Junction Box	-	-	-
Other	14%	-	-

DML @1000 Pa

↳ Cell cracks

TC @-40/+85°

↳ Interconnector breakage → FF



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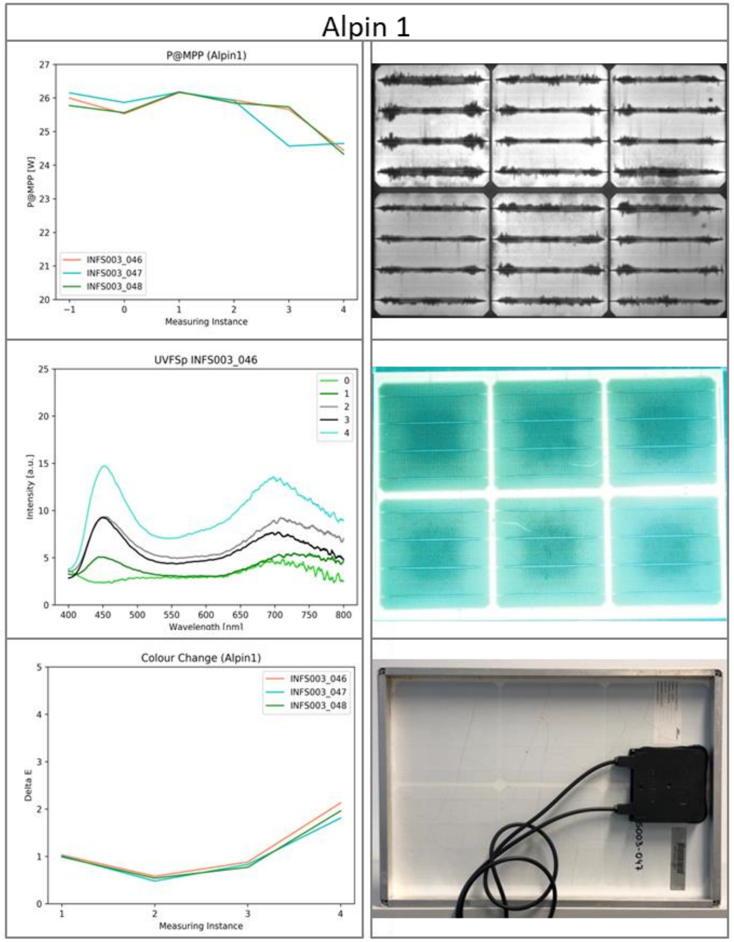
TEST RESULTS: E – ALPINE / POLAR

	real failures (13)	INFINITY accelerated ageing tests
	E alpin/polar	**Alpin** 1) T & H 2) T, H & high I 3) DML T_{Module} 119 °C
Glass	-	-
Cell	**15%**	x
Inter-connectors	**15%**	x
Encapsulant	8%	xx (JB)
Backsheet	**54%**	xxx
Junction Box	8%	-
Other	-	-

High Irradiation (1200 W/m²)
- High module temperatures (119° C)
  - EVA degradation, AA
    - Cell corrosion
  - Backsheet (PET) degradation, ΔE, embrittlement, cracking



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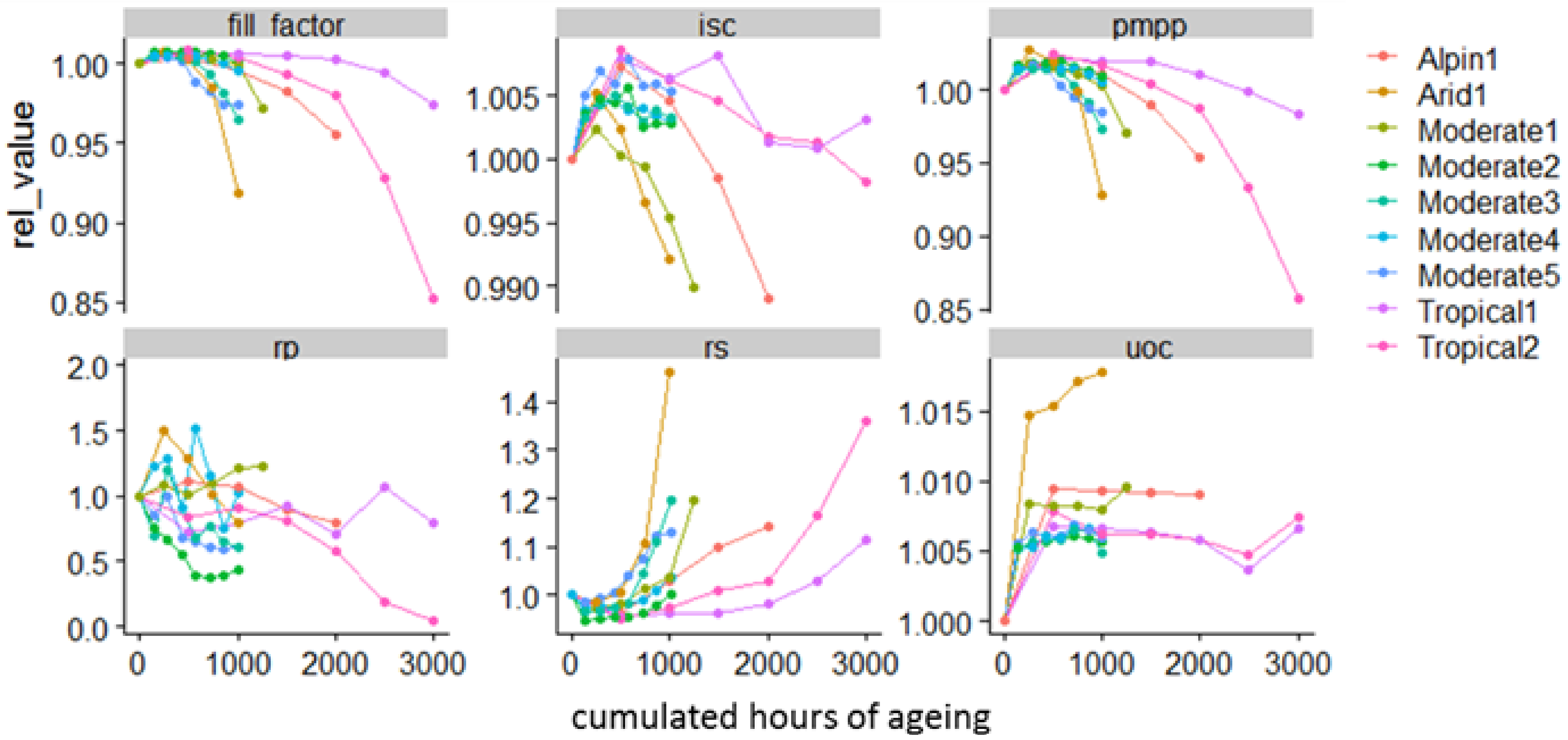
TEST RESULTS: IV-CURVE PARAM'S



- For better comparison, the x-axis is set to “cumulated time of ageing” = time in the climate chamber
- **BUT: in the climate chamber stress conditions differing in T, r.H., I, were applied**
- Starting point (1.0) of all parameters are the values measured after light stabilisation (BO-degr.)

TESTING SUMMARY & CONCLUSION

	INFINITY accelerated ageing tests								
Test protocol	A tropical		B arid	C temperate			D continental		E alpine / polar
Component	1	2	1	1	2	4	3	5	1
Glass	-	-	-	-	-	-	-	-	-
Cells/Busbars	x	xxx	x	x	-	-	x	-	x
Interconnectors	-	-	x	-	-	-	-	x	x
Encapsulant	x	x	xx (JB)	x	-	-	-	-	xx (JB)
Backsheet	-	xxx	xxx	xx	-	-	-	-	xxx
Junction Box	-	-	-	-	-	-	-	-	-
Other	-	-	-	-	-	-	-	-	-

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TESTING SUMMARY & CONCLUSION

Analysis of the performance and material characterization data **able to discover degradation pathways**, dependent on type and combination, duration and mode (sequential vs. constant) of the stresses applied

Most of the characteristic failure modes of each climate zone could be reproduced by the accelerated ageing tests under investigation. Some tests definitely added too much temperature stress

- With the **PET backsheet type** chosen for the test modules, increased temperature **> 90°C** seem to lead to **drastically increased degradation** rates, and sometimes to the onset of new degradation paths
- **Glass breakage**, often found in nearly all climate zones, in our accelerated tests **never occurred**. *Possible reasons:*
  - small test modules (6 cells) with 3.2 mm glass compact and very stable
  - the absence of singular environmental stress events like mounting on uneven substructure and rough handling, hail storms or tempests

Other test protocols closer to reality, provoking more similar failures than outdoors observed?

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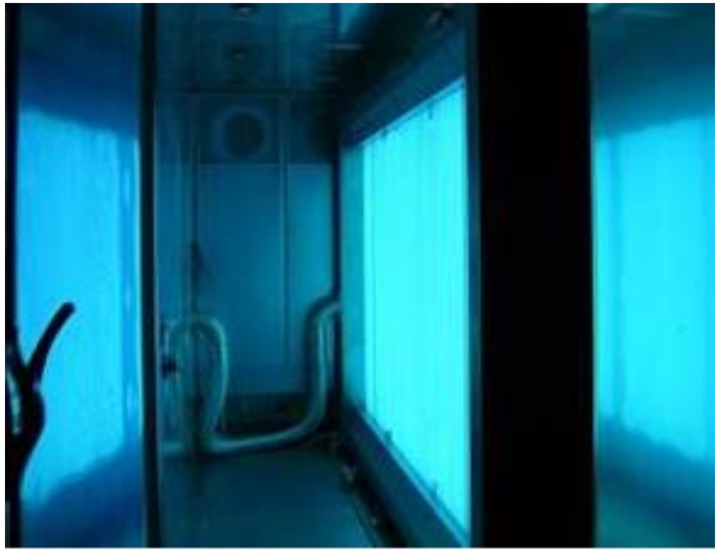
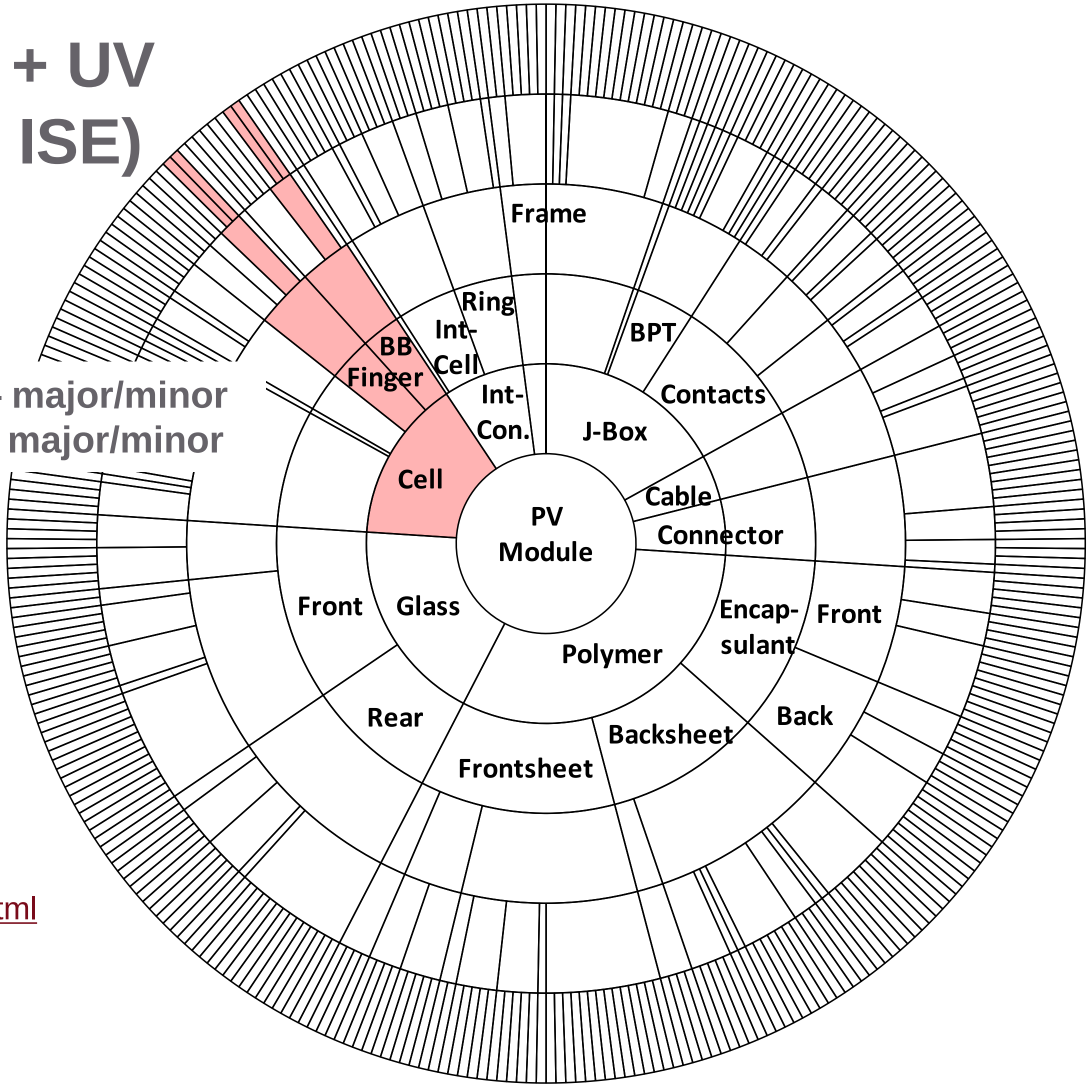
TEST PROTOCOLS & FAILURES

DH + UV (Fh ISE)



Busbars – corroded – major/minor
Finger – corroded – major/minor



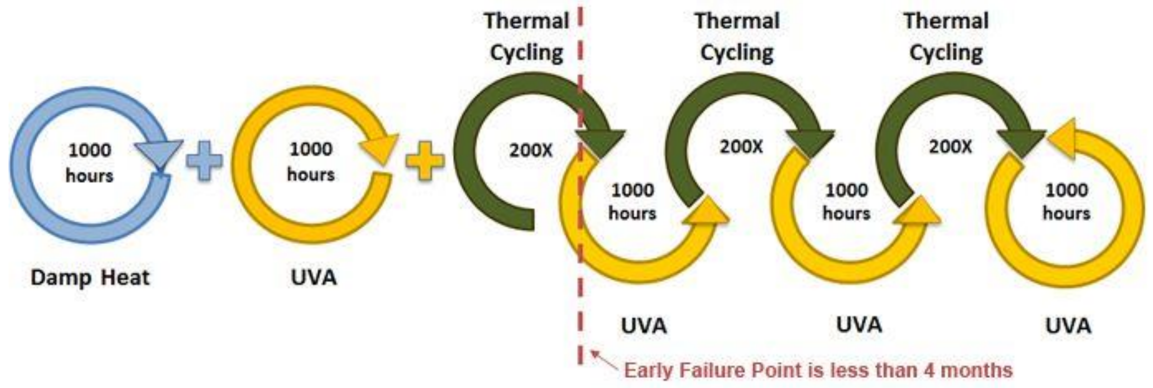
D. Philipp, K.-A. Weiss, and M. Koehl, "Inter-laboratory comparison of UV-light sources for accelerated durability testing of PV modules," in Proc. SPIE 8112, Reliability of Photovoltaic Cells, Modules, Components, and Systems IV, 81120G, 2011, vol. 8112, p. 81120G–81120G–5.

https://cordis.europa.eu/project/rcn/108132/reporting/en
https://www.ise.fraunhofer.de/en/rd-infrastructure/accredited-labs/testlab-pv-modules.html

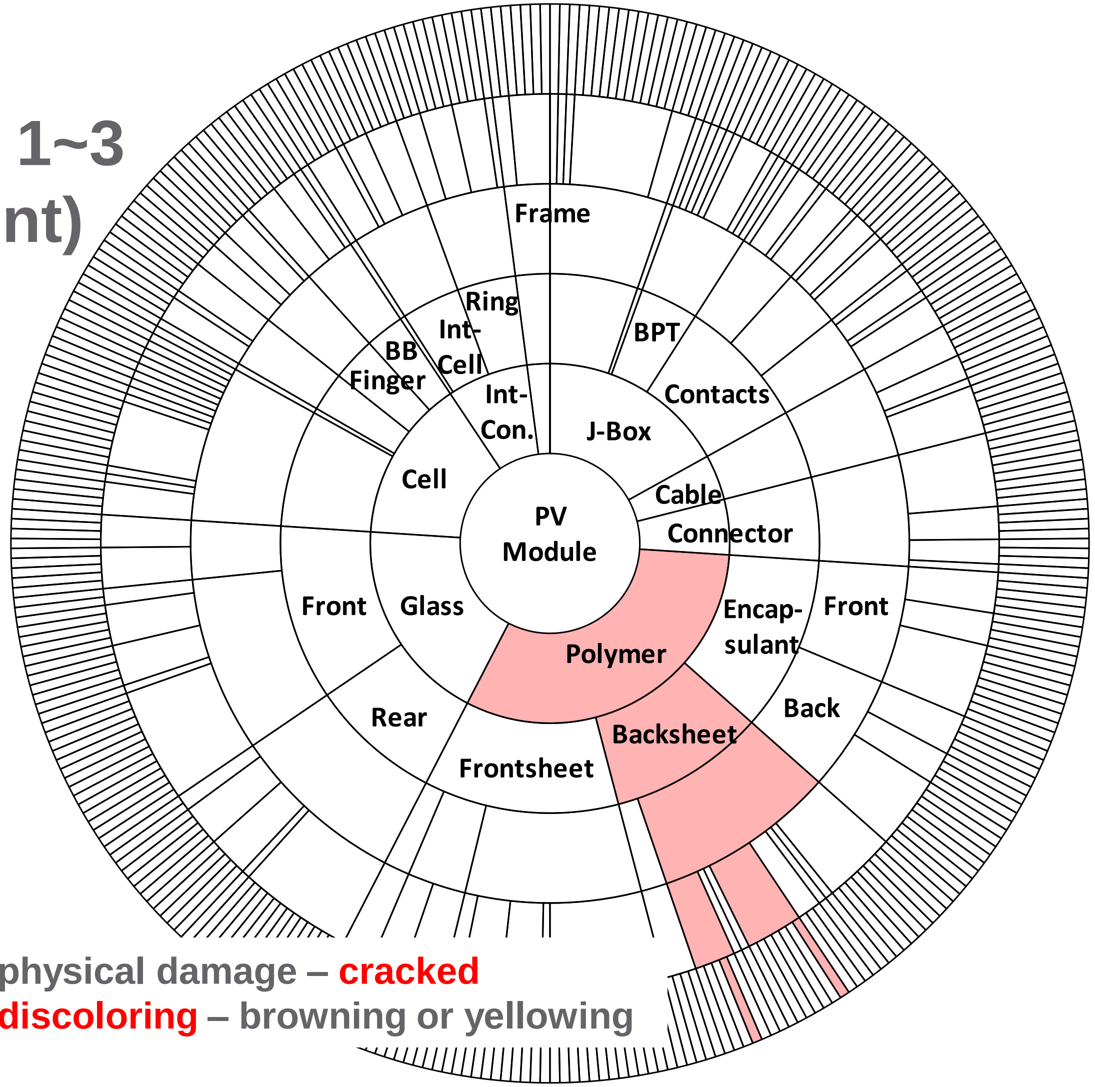
P. Hacke & Tadanori Tanahashi:
IEC TR: Combined and Sequential Accelerated Stress Testing
for Derisking Photovoltaic Modules (IEC Spring meeting @ PTB, 2019)

TEST PROTOCOLS & FAILURES

MAST 1~3 (Dupont)



https://www.dupont.com/products-and-services/solar-photovoltaic-materials/mast_linked_content/Introducing-the-new-solar-panel-testing-standard.html



physical damage – **cracked**
discoloring – browning or yellowing

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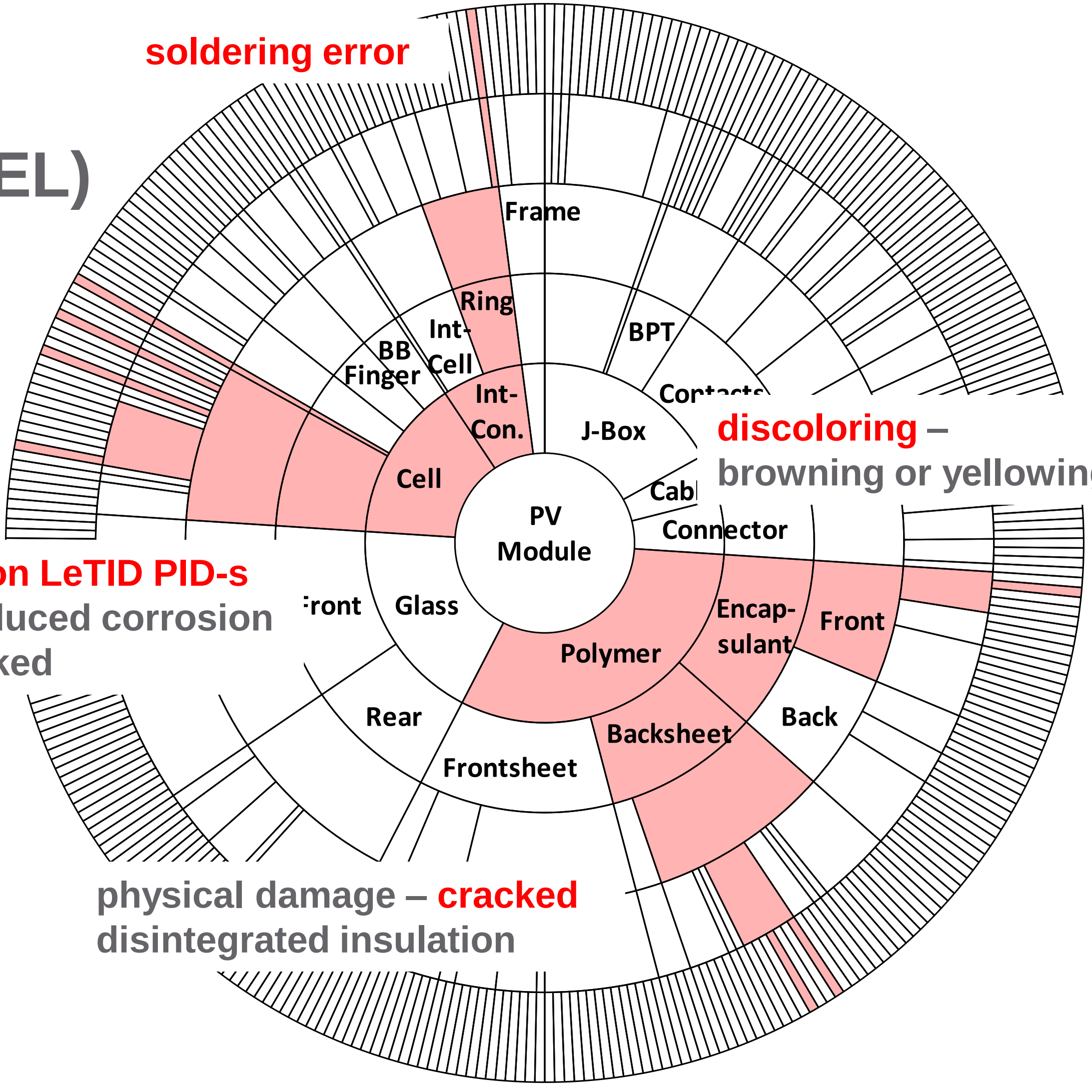
IEC TR: Combined and Sequential Accelerated Stress Testing for Derisking Photovoltaic Modules (IEC Spring meeting @ PTB, 2019)

TEST PROTOCOLS & FAILURES

C-AST (NREL)

Combined-accelerated stress testing
https://www.nrel.gov/docs/fy19osti/73984.pdf



soldering error

discoloring – browning or yellowing

passivation – degradation LeTID PID-s
corroded – potential induced corrosion
physical damage – cracked

physical damage – **cracked**
disintegrated insulation

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CONCLUSION & OUTLOOK

For PV modules

- **Analysis able to discover degradation pathways**
- **Most characteristic known failure modes can be reproduced by accelerated ageing**
- **Balance of applying not too weak and not to hard stresses not an easy task**
- **Proposed combined stress tests provoke known outdoor failures, but (still) miss service life prediction because of often unknown accelerating factors**
- **Ideas, how to find climatic schemes reflecting better the real world µ-climate of different applications, as rack-mount, bifacial over highly reflective ground, floating, rooftop or building integrated?** – for the temperature issues *IEC TS 63126 Module Qualification for High(er) Temperature* as a good start
- **Service life prediction by use of multi-level & combined stresses – how to?**
- **In IEC 61215 & 61730, 63092 drafts, "representative samples" will be allowed for testing – to extrapolate from a set of tested modules to another cluster of modules OD applied, needs tested, certified models & an update of the retesting guideline**

PV-system (BOS) parts – situation at present not better …

- **Electronic components used in inverters don't come with climate & lifetime related data**
- **Field conditions of inverter ambient often less linked to outdoor climate than for modules**

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MANY THANKS TO ALL THE PEOPLE INVOLVED, AND …

AUSTRIAN INSTITUTE OF TECHNOLOGY
TOMORROW TODAY

THANK YOU!

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klima+ energie fonds

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