CLIMATE-SPECIFIC WEATHERING TESTS FOR SERVICE LIFE ESTIMATION OF PV MODULES

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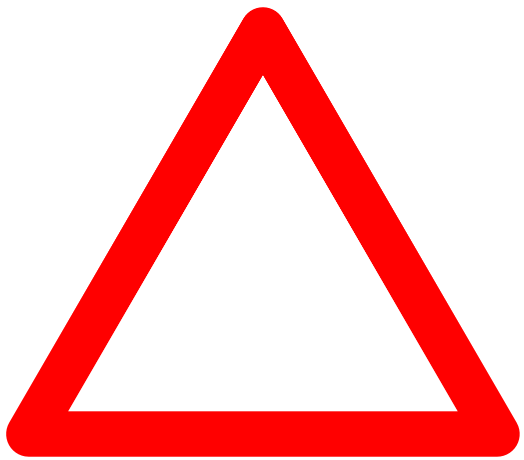
Developing new products => **Cost/performance ratio**

Performance P_0 (t=0)



Durability P (t)　　**Total cost**

$$\frac{\int_0^{t_{lt}} \mathrm{Cost}(t)\, dt}{\int_0^{t_{lt}} P(t)\, dt}$$

Goals:

Decrease costs	
Increase performance	P_0
Decrease degradation	$\Delta P/\Delta t$
Increase lifetime	t_{lt}

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Service lifetime estimation

BORDER CONDITIONS:

- Service lifetime (minimum time-to-failure): **25 years** e.g.
- Performance criteria **$P(t = t_{lt}) = 0.8\ P(0)$** e.g.

STRESS CONDITIONS => INTERACTION WITH SAMPLES:

- Climate-dependent loads
- Micro-climatic stresses

ACCELERATED STRESS CONDITIONS:

- Time-transformation-functions
- Acceleration factors ⇔ Test duration **$a \approx 50 - 100$**

Is it possible to develop generic ALT – procedures without knowing the failure modes?

What are the weathering stresses?

STRESS FACTORS (Climate-dependent loads)

- **Irradiation:** **UV, solar**
- **Temperature:** **maximum, effective, changes (thermomechanical)**
- **Moisture:** **Effective surface humidity**
- Sand: Sand-blasting of the glazing or the back-sheet
- Soiling: Regeneration possible

  Bio-contamination
- Corrosivity: Salt, SO_2, etc
- Voltage (PID): Leakage current, ion migration (infant mortality)

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How to accelerate?

- Constant stress instead of daily cycling
- Enhanced doses (e.g. irradiation intensity, humidity)
- Enhanced temperatures

Process kinetics depend on module temperature :

$t_{test} = \Delta t_i \cdot \exp[-(E_a / R) \cdot (1/T_{test} - 1/T_{mod,i})]$ (Arrhenius relation)

Integration of the outdoor loads yields corresponding indoor test conditions

$t_{test} = \Sigma_i \{\Delta t_i \cdot \exp[-(E_a / R) \cdot (1/T_{test} - 1/T_{mod,i})]\}$

E_a = activation energy for the rate dominating degradation process

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What weathering stresses? => climate monitoring

Urban reference

Freiburg Germany

Arid

Sede Boqer

Israel

Alpine

Zugspitze

Germany

Tropical

Serpong, Indonesia

operated by TÜV

Maritime

Pozo Izquierdo

Gran Canaria

Ambient climate and sample temperatures as 1min averaged time series

corrosivity, salt concentration as yearly or monthly dose

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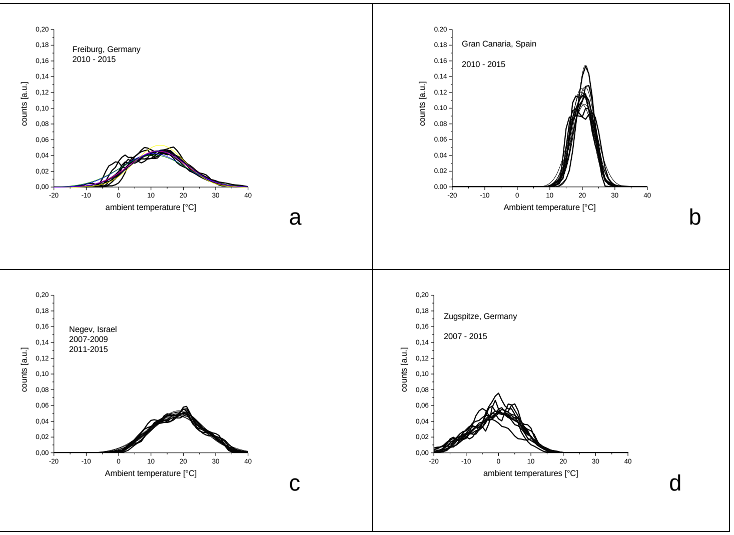
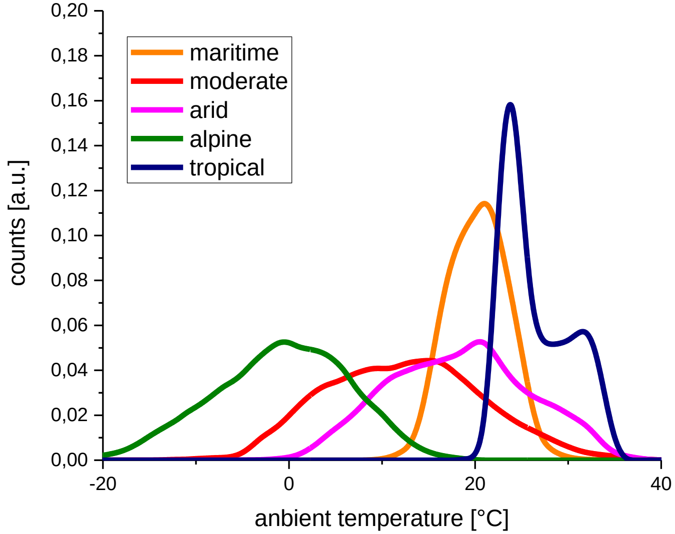
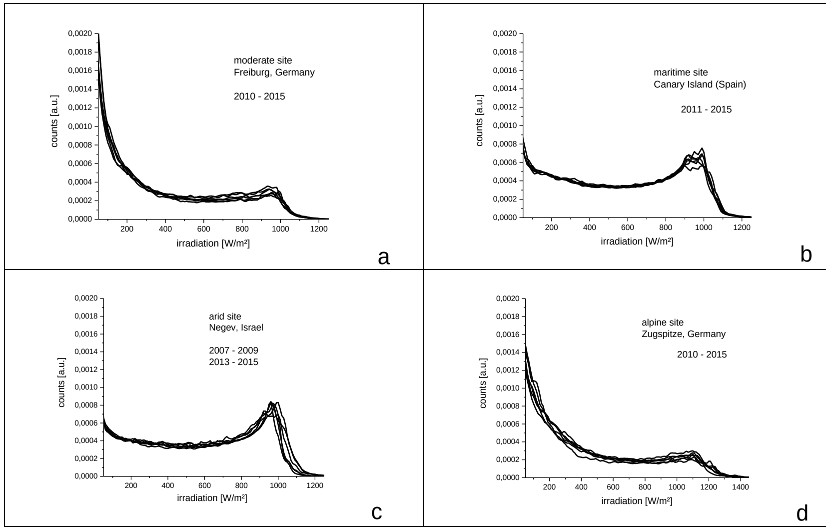
What weathering stresses? => climate monitoring

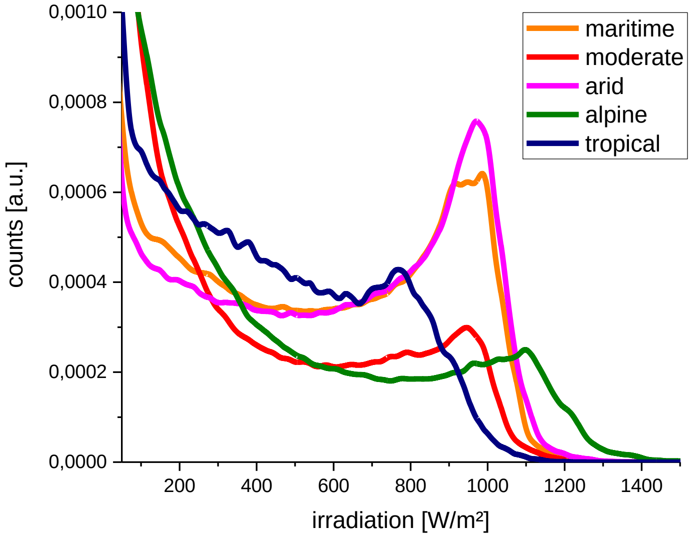
Ambient temperature





Solar irradiation





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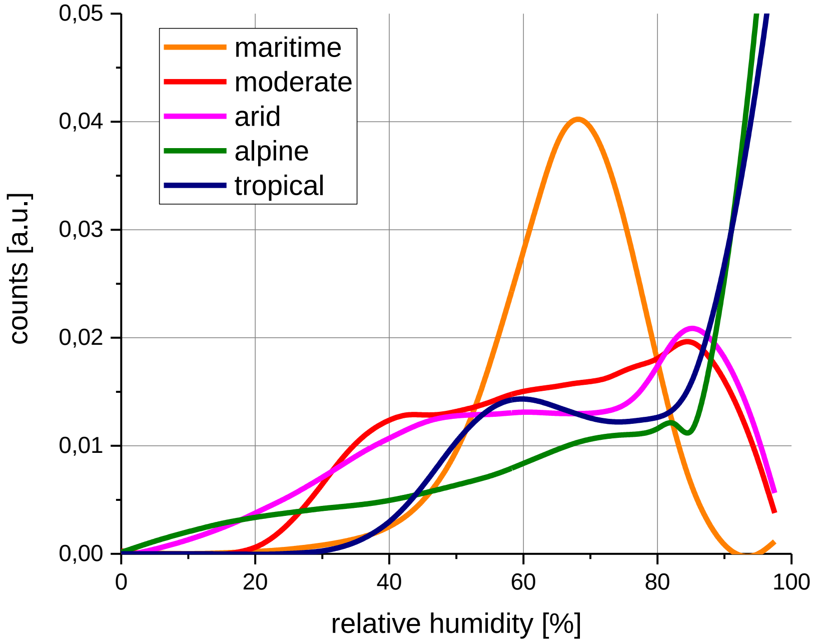
Humidity impact



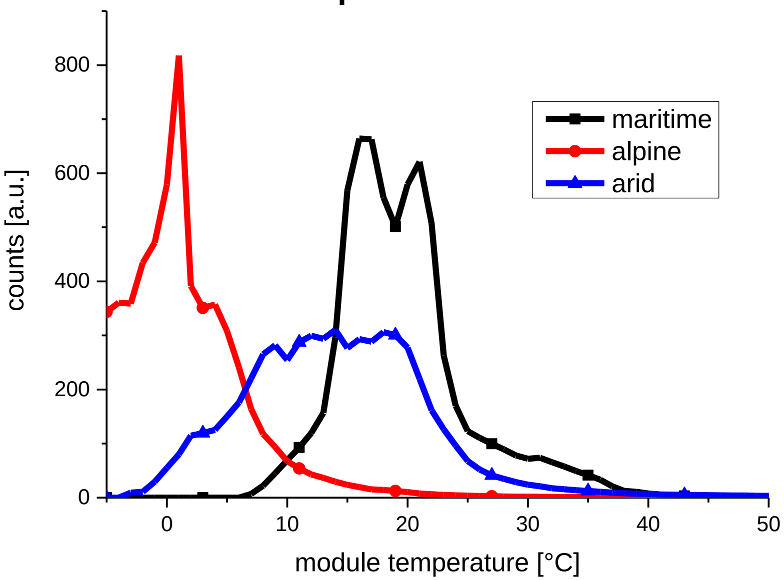
Alpine and tropical site show high relative humidity

Ambient and module temperature have to be taken into account

=> Surface moisture depends on module temperature

Macro-climate

=> micro-climate (stress factors)



Koehl M et al.: Modeling of the nominal operating cell temperature based on outdoor weathering, *Solar Energy Materials & Solar Cells* 95 (2011) 1638–1646.

M. Koehl, S. Hoffmann and S. Wiesmeier, Evaluation of damp-heat testing of photovoltaic modules, Prog. Photovolt: Res. Appl. (2016) DOI: 10.1002/pip

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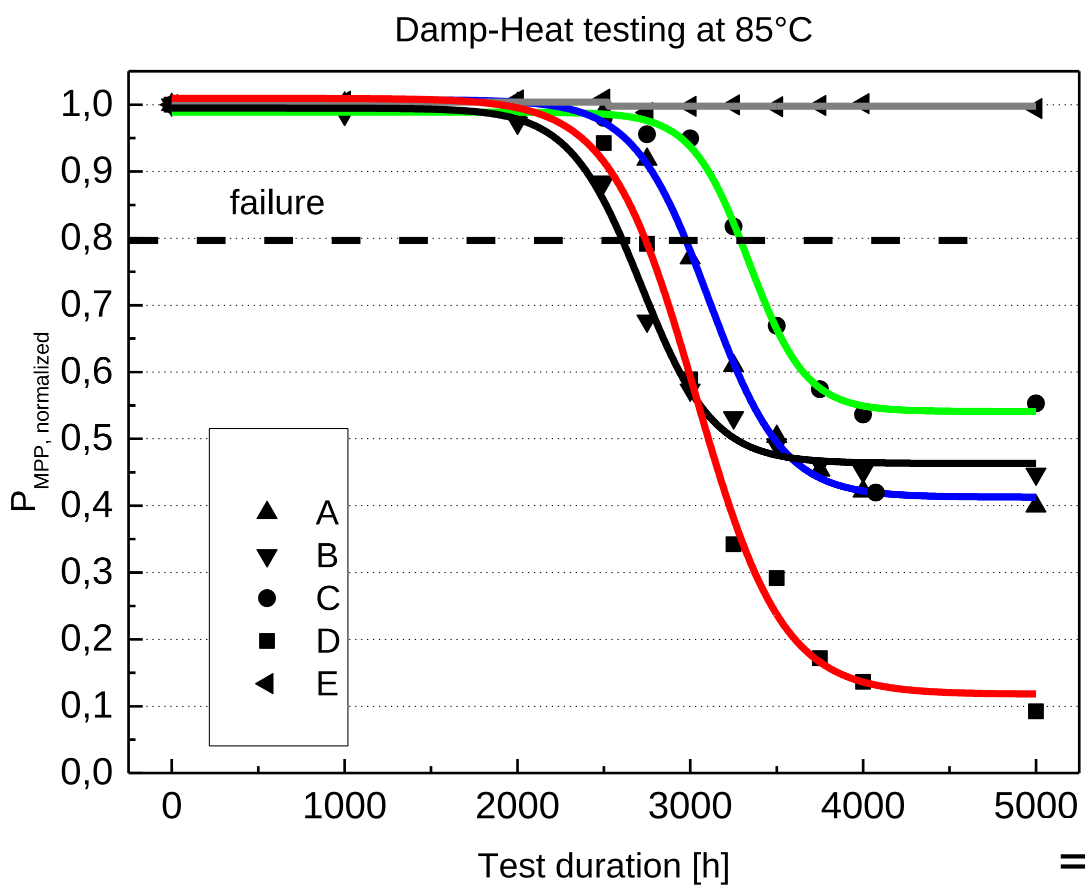
Evaluation of the parameters for time-transformation functions by ALT

t_{test} = Lifetime (years) $\cdot \Sigma_i \{\Delta t_i \cdot (rh_{eff,s,\,i} / rh_{eff,test}) \cdot \exp[-(\mathbf{E_a} / R)\cdot(1/T_{test} - 1/T_{mod,i})]\}$

with $rh_{eff,s} = 1/(1 + 98 \exp(-9.4\, rh_s))$ and $rh_s(T_{mod}) = rh(T_{amb}) * P_{sat}(T_{mod}) / P_{sat}(T_{amb})$



Testing to failure of 5 different commercial c-Si modules

=> different times to failure

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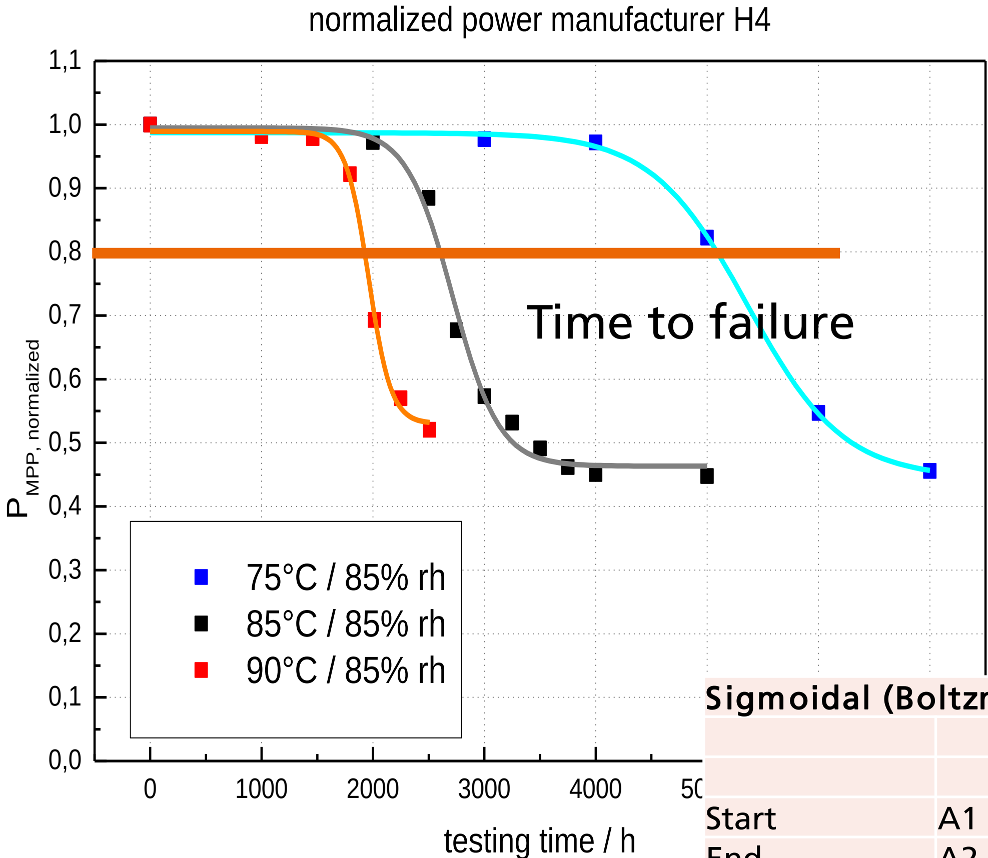
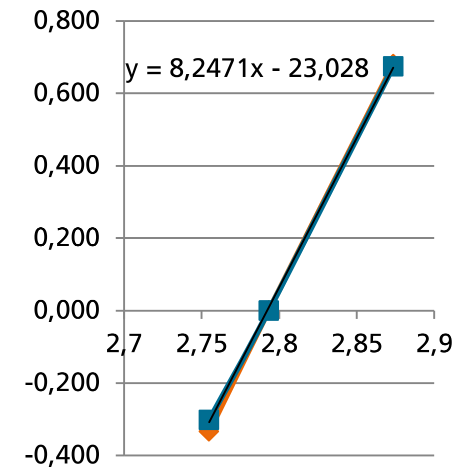
Evaluation of the parameters for time-transformation functions by ALT

Damp-heat testing at 85%rh@ 75°C, 85°C and @90°C





Arrhenius-Plot:
Activation energy = 69 kJ/mol

Sigmoidal (Boltzmann) Fit: $y = A2 + (A1-A2)/(1 + \exp((x-x0)/dx))$							
		75°C		85°C		90°C	
		Value	Error	Value	Error	Value	Error
Start	A1	0,987	0,01	0,995	0,01	0,988	0,01
End	A2	0,445	0,01	0,463	0,01	0,556	0,01
Induction time	x0	5364	51,11	2717	30,84	1946	12,67
Degradation	dx	430	39,55	208	28,99	90	9,86
Time to failure	tlt	5117		2608		1928	
Acceleration a		0,51		1,00		1,35	

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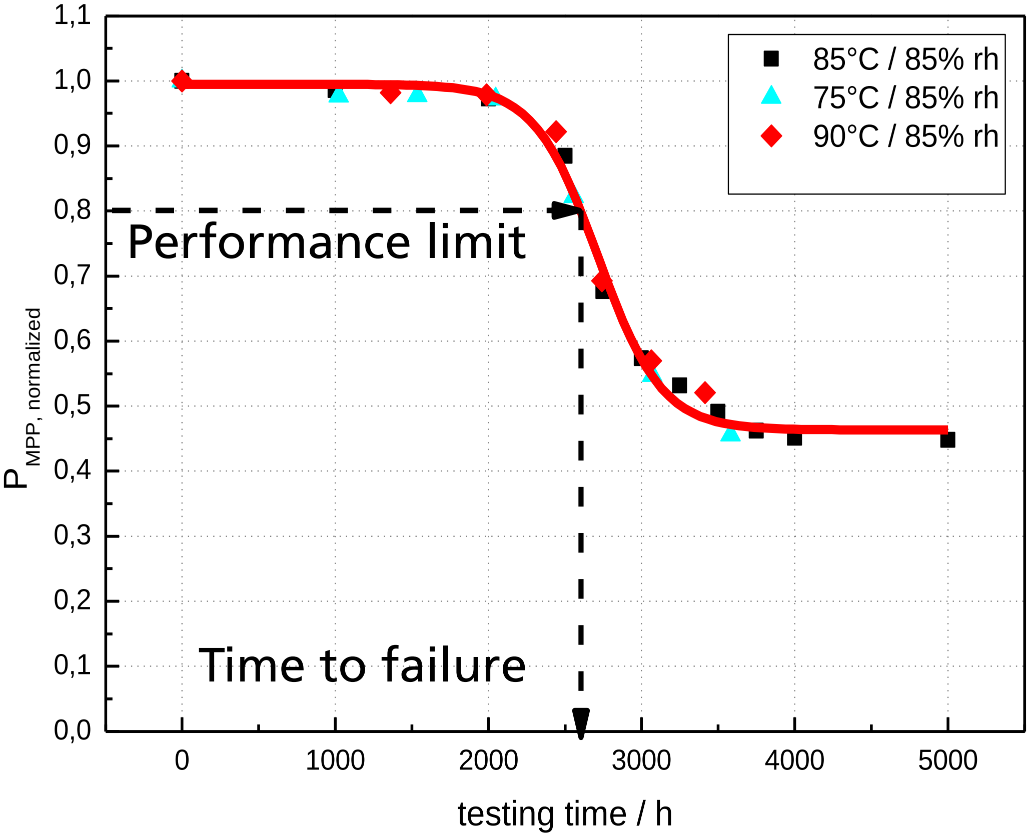
Evaluation of the parameters for time-transformation functions by ALT

Master degradation function

For damp-heat conditions:

Performance over time @ 85°C



Acceleration factor

$a = \exp[-(E_a / R)\cdot(1/T_1 - 1/T_2)]$

Module #	**1**	**5**	**4**	**2**
Lifetime @ 85°C [h]	**3290**	**2750**	**2600**	**2950**
Accelaration 75/85	**1,85**	**1,85**	**1,95**	**1,7**
Activation E [kJ/mol]	**64,5**	**63,7**	**69,2**	**55,0**

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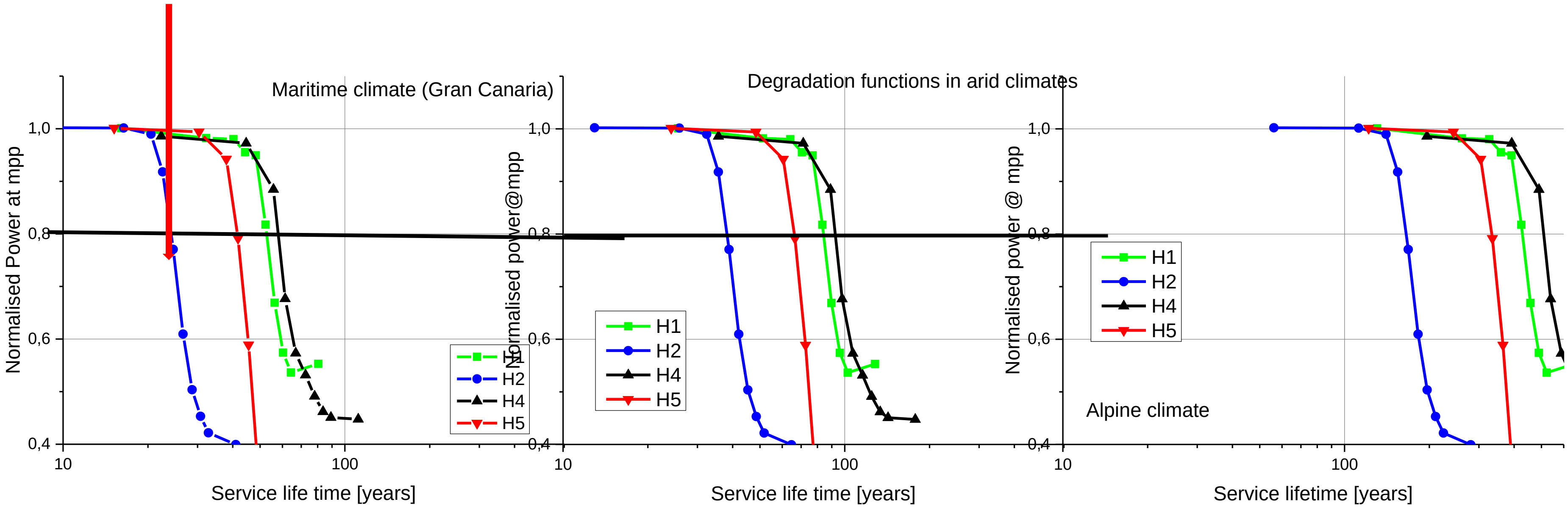
Time-transformation functions for the different modules and climates

Lifetime smaller than 25 years

Energy yield = $\int_0^{t_{lt}} P(t)/P(0)dt$



	Damp heat 85%/85°C		Gran Canaria	maritime	Negev	arid	Zugspitze	alpine
Sample	time to failure [h]	Activation energy [kJ/mol]	lifetime [a]	normalised yield	lifetime [a]	Normalised yield	lifetime [a]	Normalised yield
H2	2950	55	24	23,6	38	37,5	168	165
H5	2750	63,7	41	40,3	66	65	333	327
H1	3290	64,5	53	51,7	84	82	430	420
H4	2600	69,2	58	56	93	90	511	495

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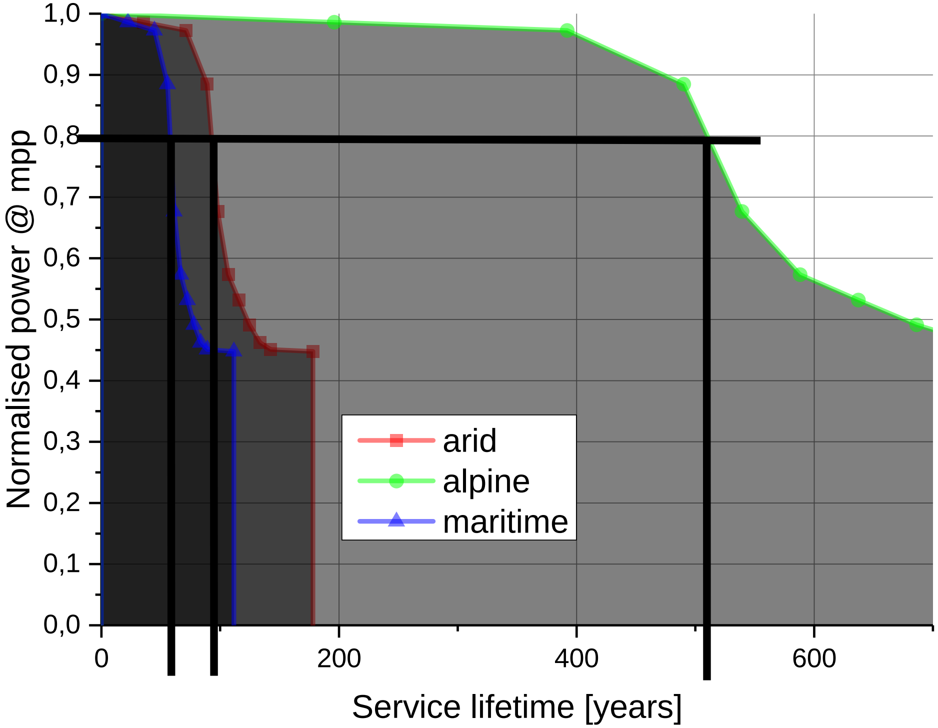
Evaluation of the service life time and energy yield in different climates

H4



$$\frac{\int_0^{t_{lt}} P(t)\,dt}{\int_0^{t_{lt}} P(0)\,dt}$$

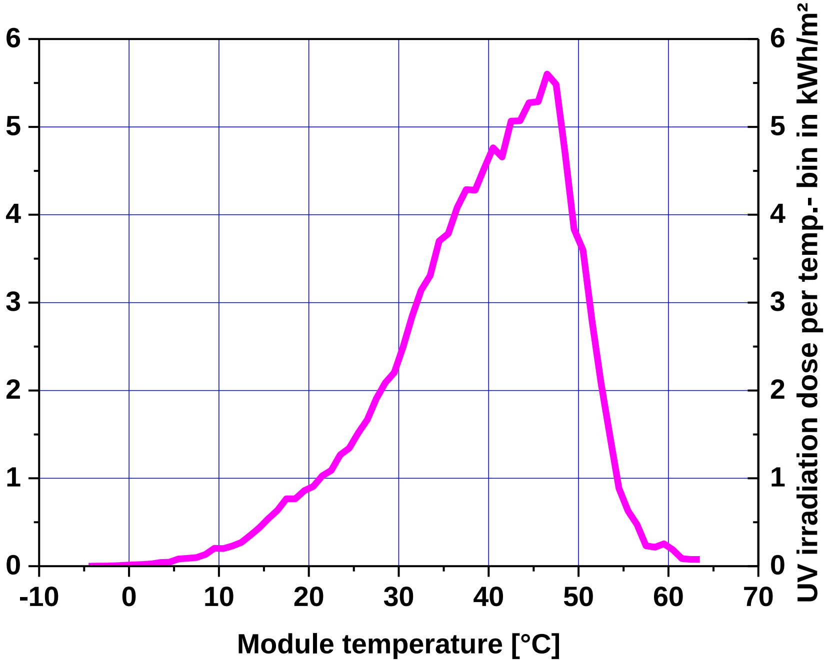
	Gran Canaria	maritime		Negev	arid		Zugspitze	alpine	
Sample	lifetime [a]	normalised yield	relative yield	lifetime [a]	normalised yield	relative yield	lifetime [a]	normalised yield	relative yield
H2	24	23,6	98,3	38	37,5	98,7	168	165	98,2
H5	41	40,3	98,3	66	65	98,5	333	327	98,2
H1	53	51,7	97,5	84	82	97,6	430	420	97,7
H4	58	56	96,6	93	90	96,8	511	495	96,9

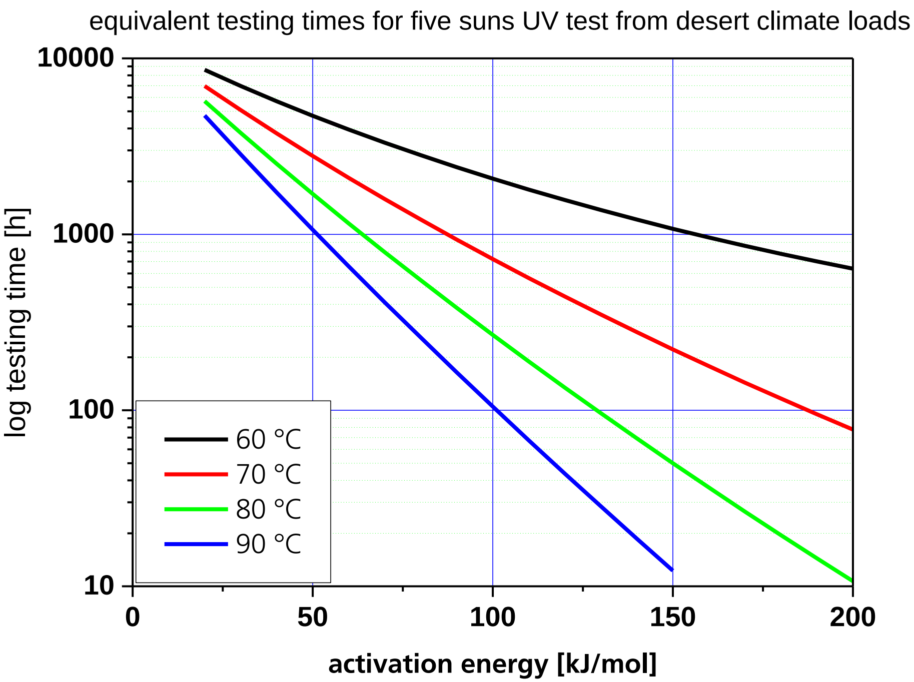
Time-transformation functions for UV degradation processes

UV impact:

t_{test} = Lifetime (years) $\cdot\ \Sigma_i\ \{\Delta t_i \cdot (I_{uv,i}/I_{uv,test})^n \cdot \exp[-(E_a / R)\cdot(1/T_{test} - 1/T_{mod,i})]\}$

n ≈ 1, when a linear dose function





UV dose for one year in the Negev

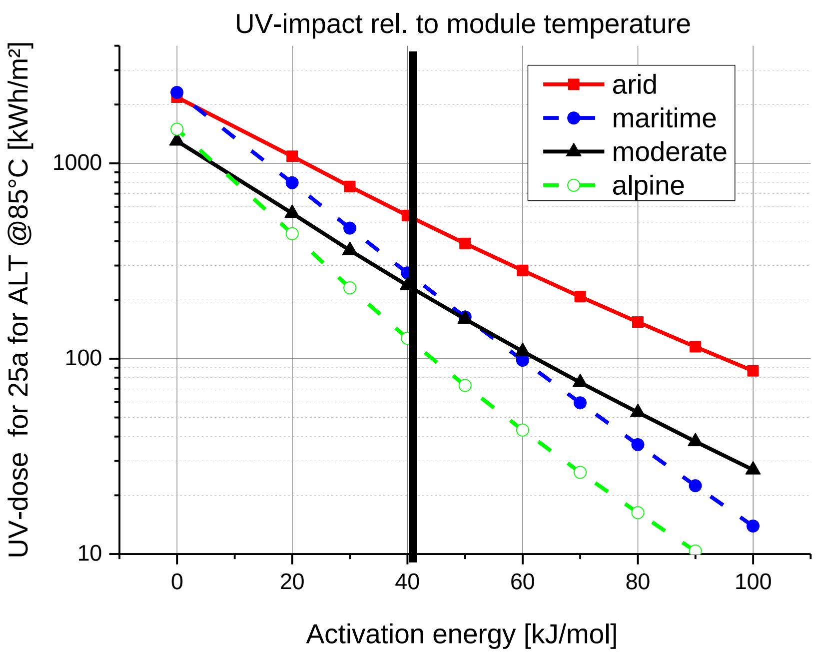
Acceleration by temperature needed !

Take 5 % of the global irradiation (more accurate than most UV measurements)

UV testing for different climates

Factor 2 – 4 for different climates is possible

But about a factor of 10 for testing times compared to IEC 61215 (15kWh/m² @ 60°C)



ALT at **85°C** sample temperature

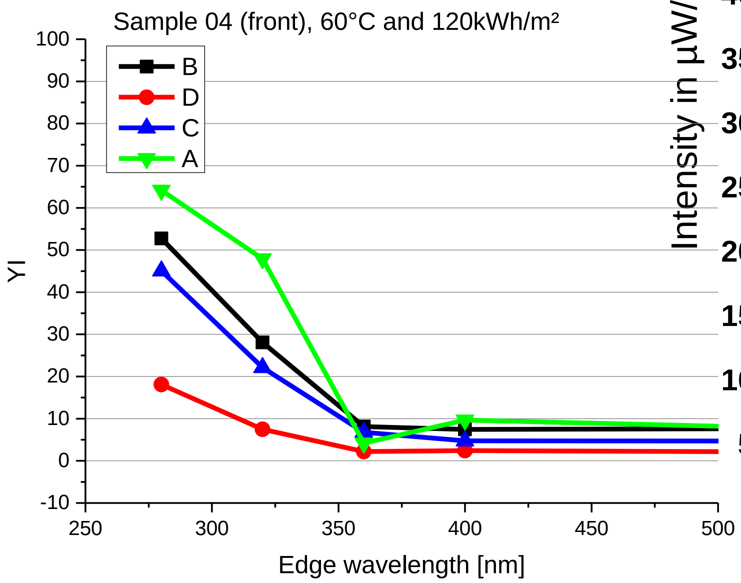
	Ea (kJ/mol)	arid	maritime	moderate	alpine	for 25a
	0	2261	2368	1388	1294	kWh/m²
Tamb	40	154	135	77	34	kWh/m²
Tmod	40	541	275	237	127	kWh/m²

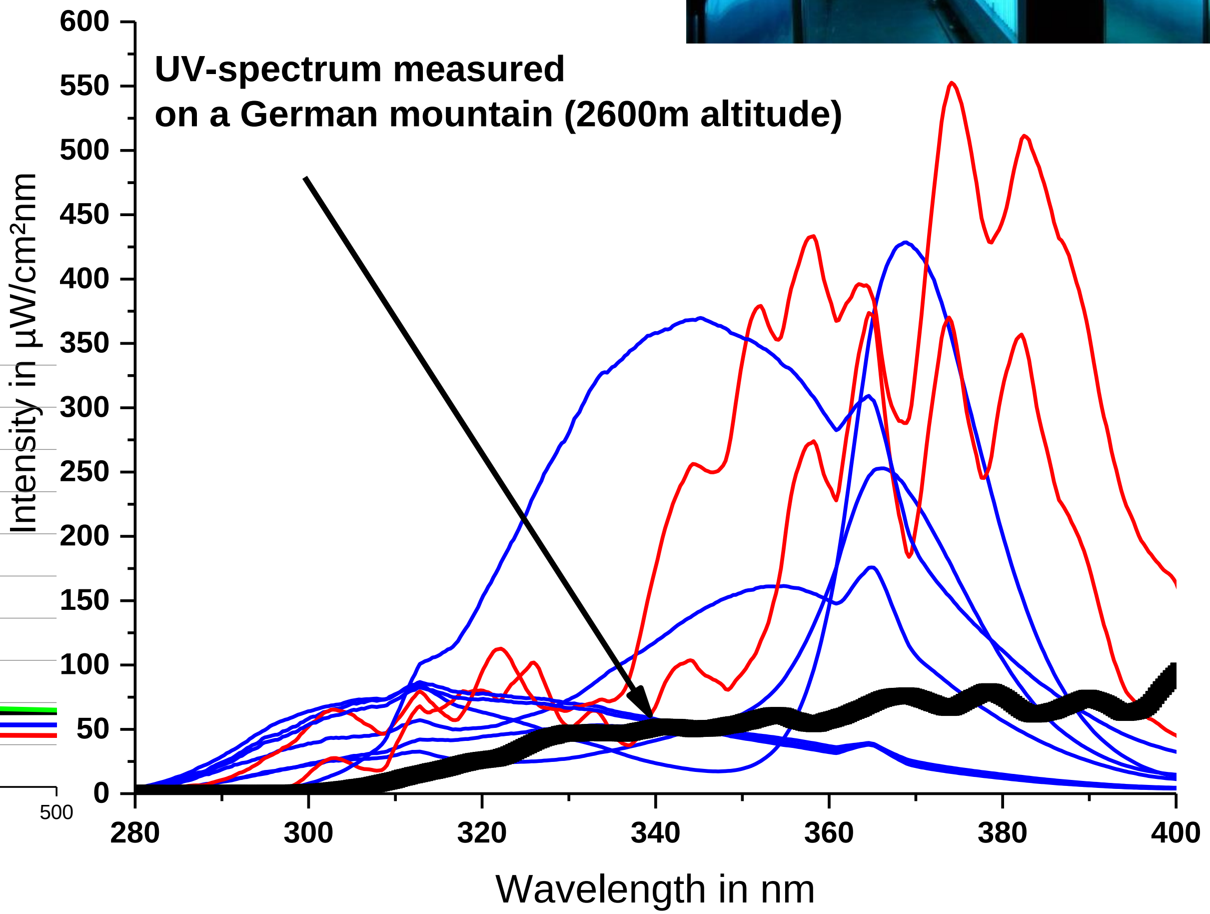
Cooling

UV testing: challenge of irradiation sources

Activation spectra = Irradiation * spectral sensitivity

Back sheet testing





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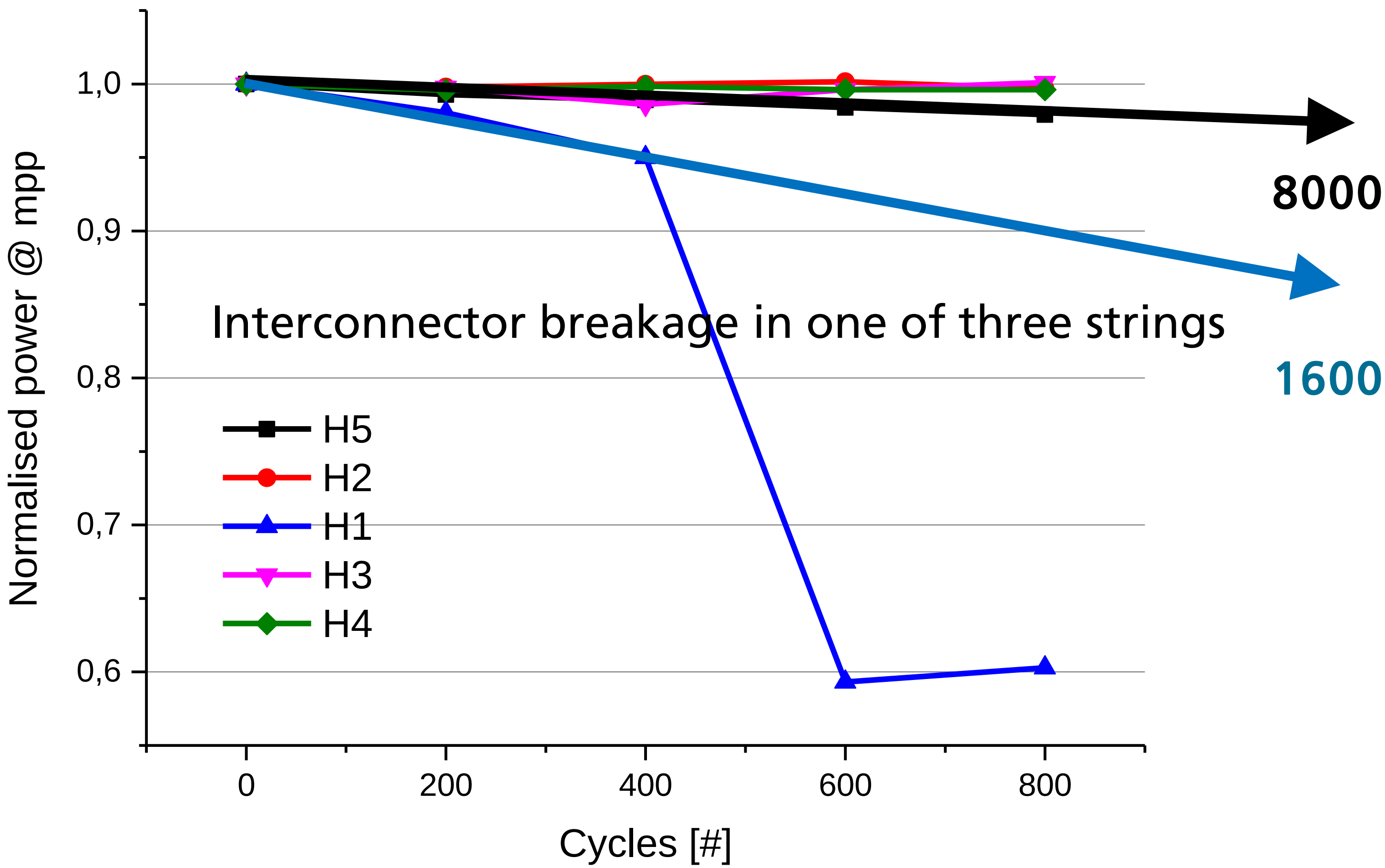
Thermo-mechanical stress by temperature cycling

Tc – testing according to IEC 61215 from -40°C to 85°C



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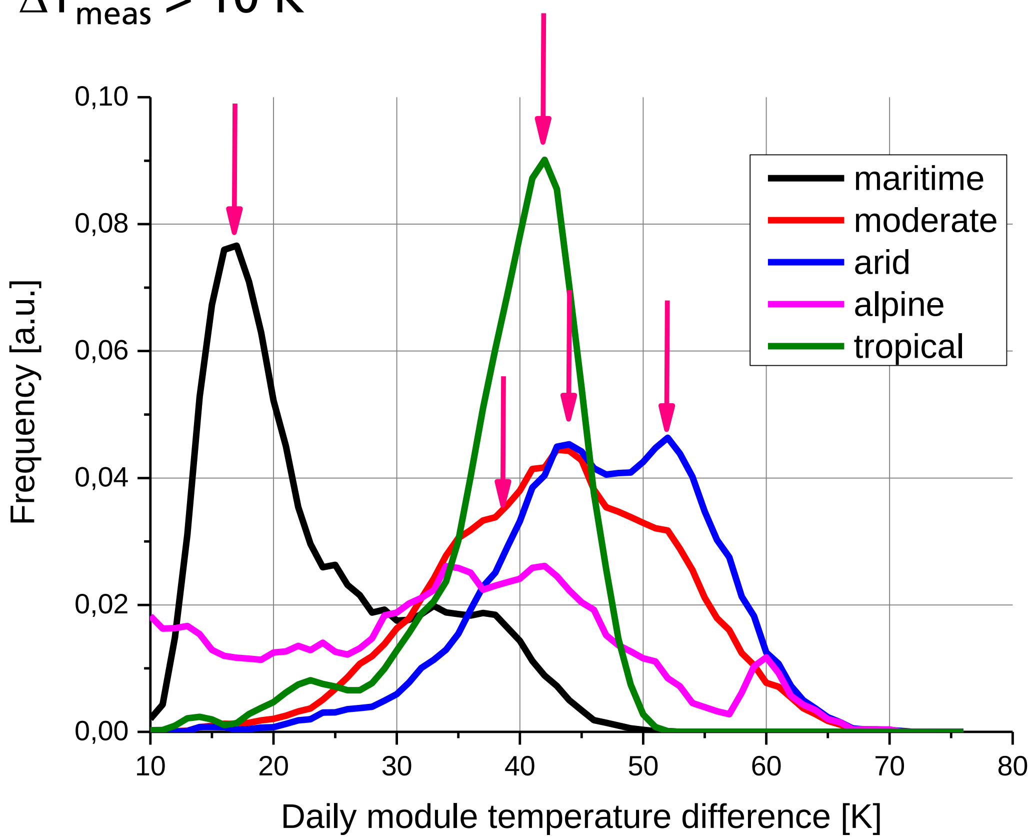
Thermo-mechanical stress by temperature cycling

	maritime	moderate	arid	alpine	tropical	
Maximum D T	17	44	48	40	42	K
Acceleration (c=1)	7,4	2,8	2,6	3,1	3,0	K

$\Delta T_{meas} > 10$ K



Δ **T_{test} = 125K**

Acceleration factor:

$a = (\Delta T_{test} / \Delta T_{meas})^C$

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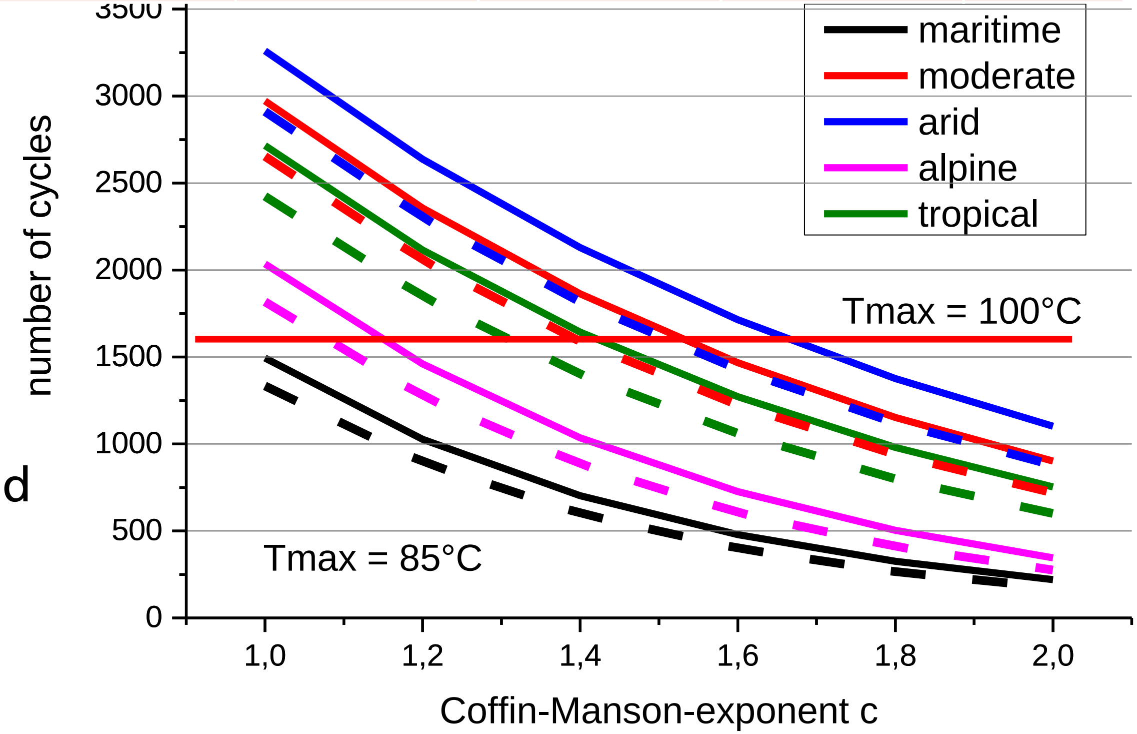
Coffin-Manson Modell for Temperature cycling

	maritime	moderate	Arid	alpine	tropical	
Maximum Δ T	17	44	48	40	42	K
acceleration	7,4	2,8	2,6	3,1	3,0	K
lifetime 1600 cycles	32,2	12,5	11,4	13,7	13,0	a
lifetime 8000 cycles	161,2	62,3	57,1	68,5	65,2	a

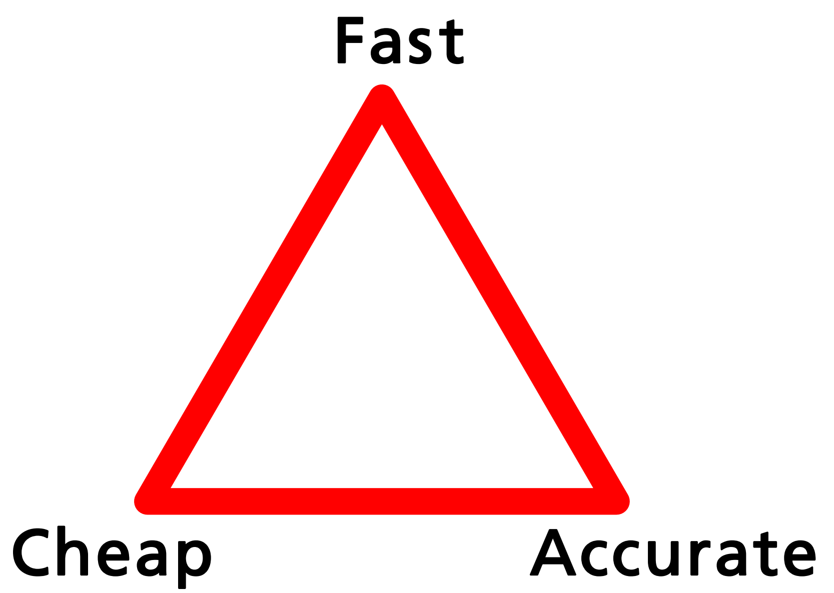
25 years := 9125 cycles

C ist material-dependend parameter, to be determined

Climate-Impact: Factor 2 - 4



Accelerated life testing



Select two of them !!!

Conclusions – how to perform accelerated service life tests

1. Find climatic data as time series with sufficient time-resolution from monitoring or modelling for your desired location

2. Simulate module temperature, effective surface humidity, UV-irradiation, daily temperature differences by suitable models

3. Define end-of-life criteria: design service life time, performance property (power or yield…), performance limit,

4. Perform AL tests at maximum load conditions till the failure criterium is reached and the time to failure is determined or terminate the tests at a maximum duration in case of very durable modules

5. Perform ALT at one or more different stress level (mostly temperature) until the degradation of the performance property is clearly measureable in order to determine the material specific parameters of the time transformation models (e.g. the activation energy, Coffin-Mansion coefficent, UV-dose reciprodity) based on the acceleration factors

Conclusions contd.

6. Integrate the monitored or modeled outdoor data by applying the time transformation models and calculate the corresponding ALT conditions for the design life-time

7. The module is not suitable for the planned location, if the time to failure at ALT is smaller than the evaluated life-time test duration.

Next steps:

Apply all stress factors to the same modules, as in operation. Combined test cycles show a different degradation behaviour than single stress testing.

How to accelerate all in the same way?

The possibility for using them as ALT has to be investigated.

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