Is it possible to design accelerated service life tests for PV modules?

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Presented at the EMPA Workshop

Durability of Thin Film Solar Cells

April 2011

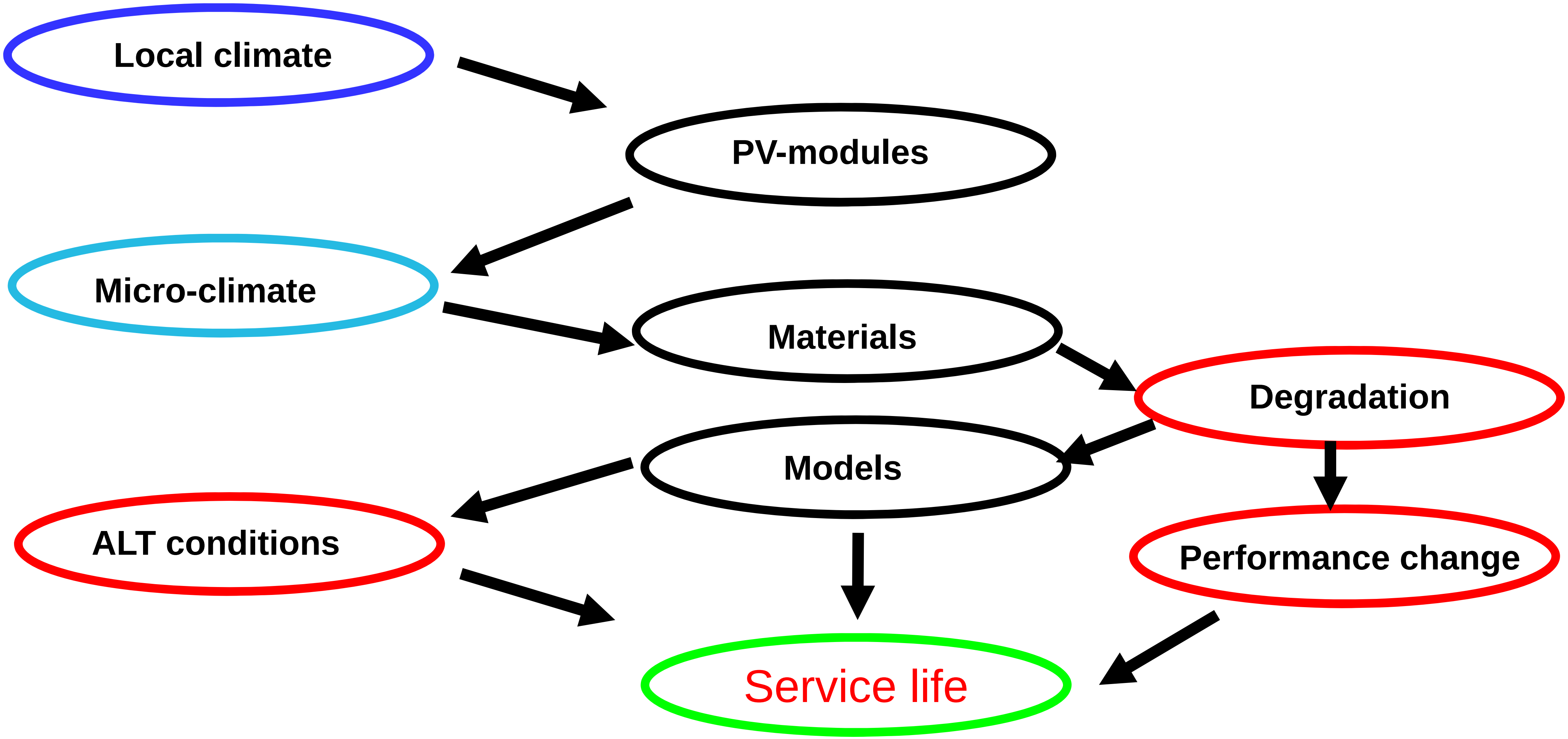
General methodology for service life assessment

Assumptions

1. Only long-term wear out degradation is considered
2. The primary degradation factors are due to weathering
3. The stress-levels depend on local climate and installation
4. The stress-levels depend on the micro-climate at the module
5. The test samples (PV-modules or components) have to be considered as a black-box
6. The modelling is based on investigation of the degradation kinetics of real state-of-the-art modules
7. A service life of 25 years is required

General methodology

Modeling the Accelerated Life Test conditions based on realistic loads



Local climate

PV-modules

Micro-climate

Materials

Degradation

Models

ALT conditions

Performance change

Service life

General methodology Step 1: **Outdoor exposure and climate monitoring**

City or reference:

Freiburg Germany

Desert

Sede Boqer

Israel

Alpes

Zugspitze

Germany

Tropical

Serpang

Indonesia

Maritime

Pozo Izquierdo

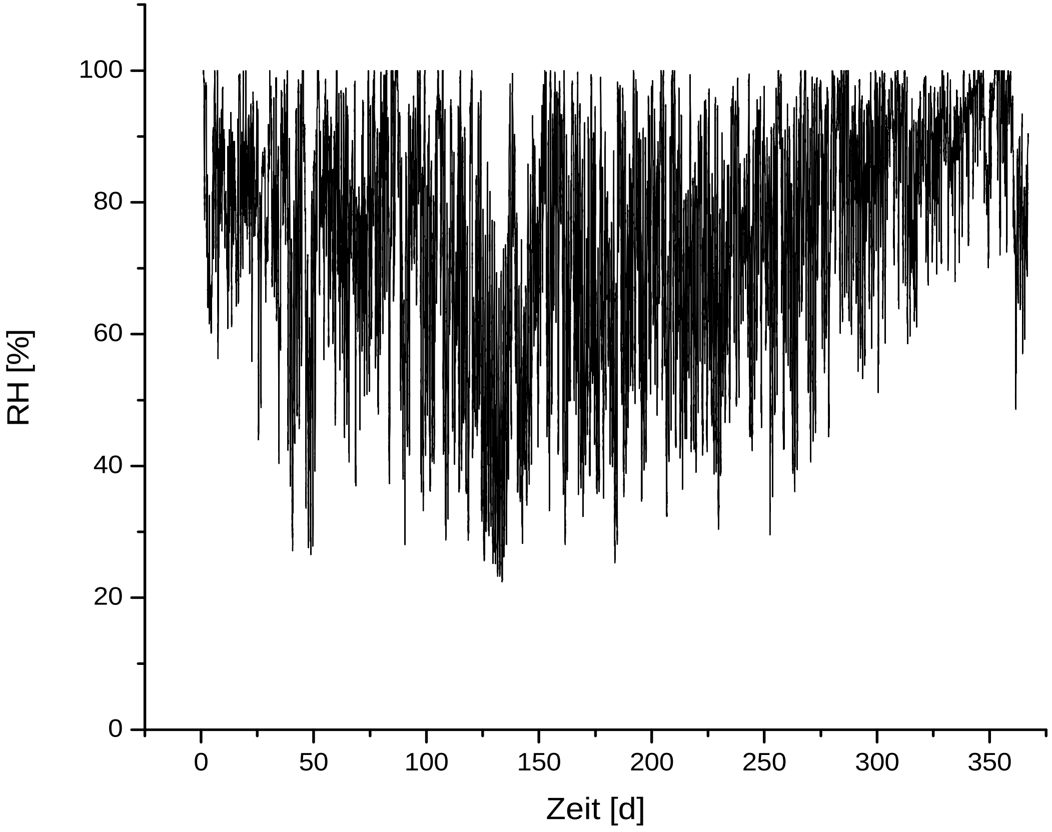
Gran Canaria

Monitoring degradation factors for modelling degradation

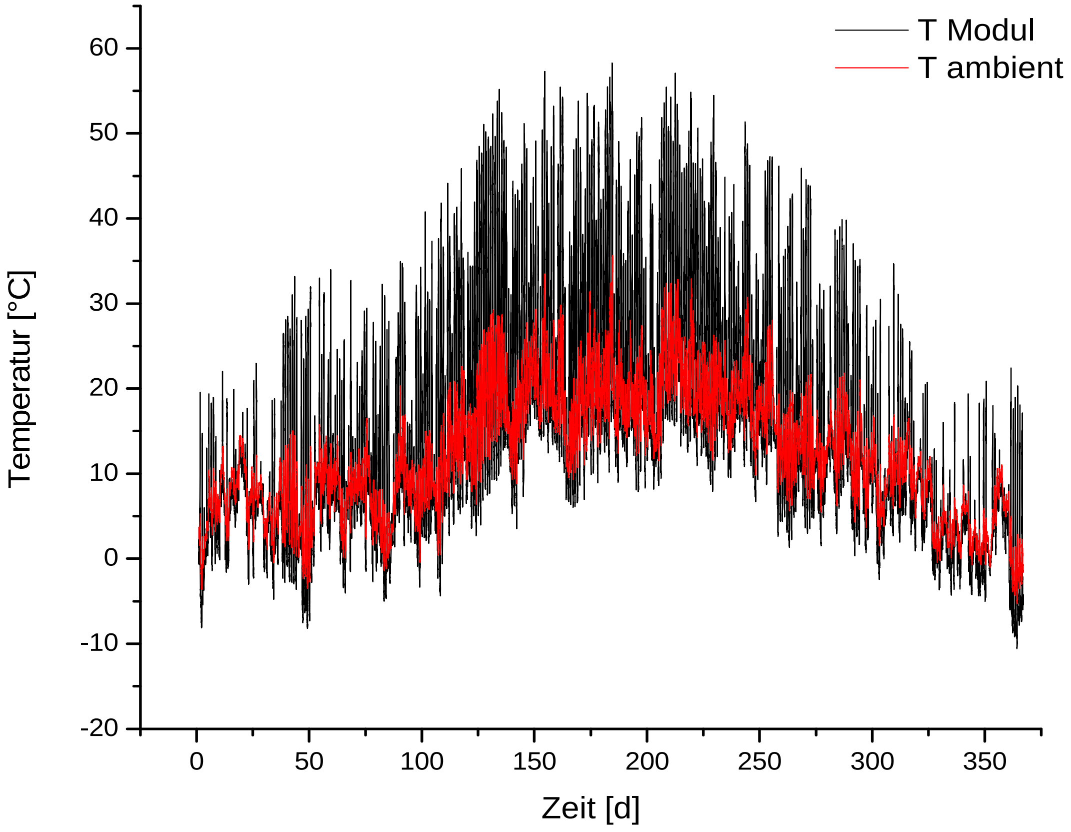
Measurement of module performance over time for validation of ALT

Monitoring in Cologne (one year)

Ambient humidity

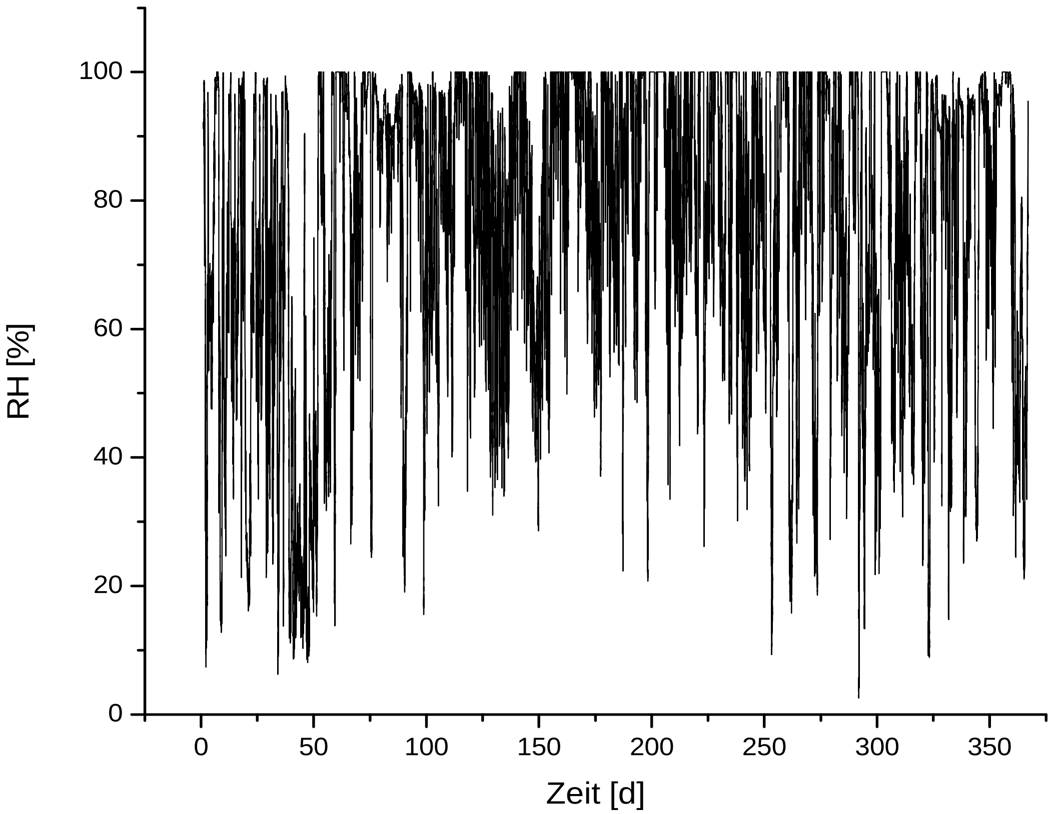


ambient and module temperatures

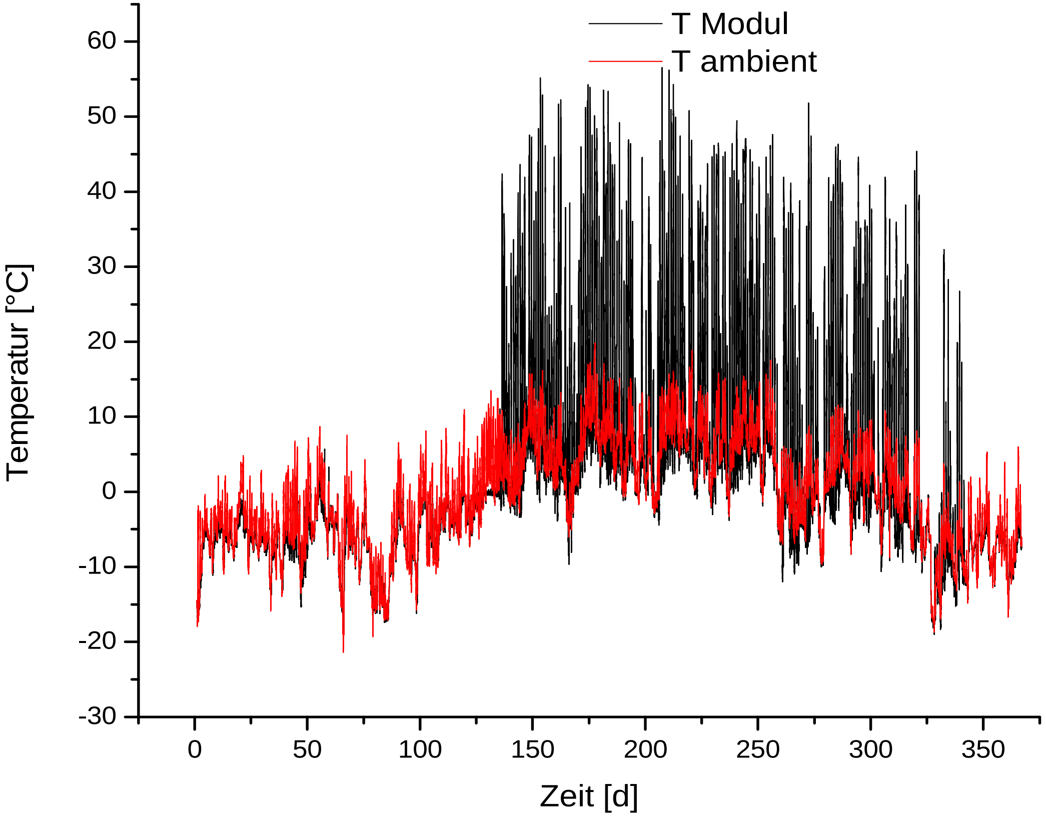


Monitoring in the Alpes (one year)

Ambient humidity

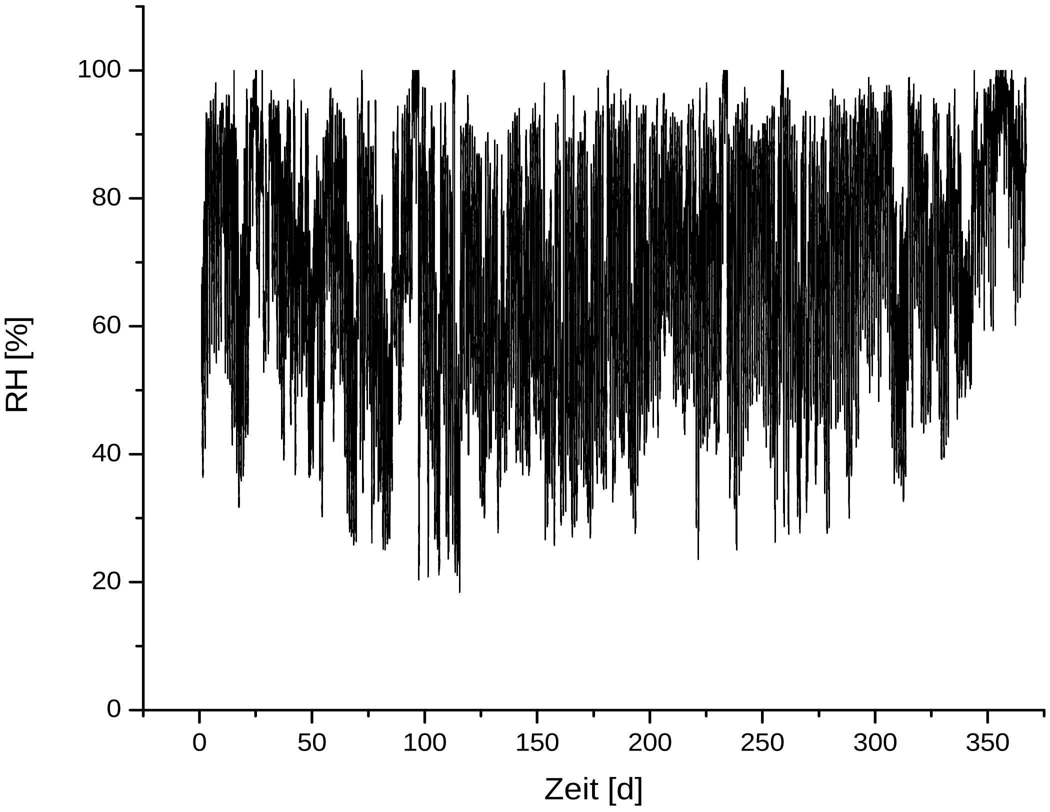


ambient and module temperatures

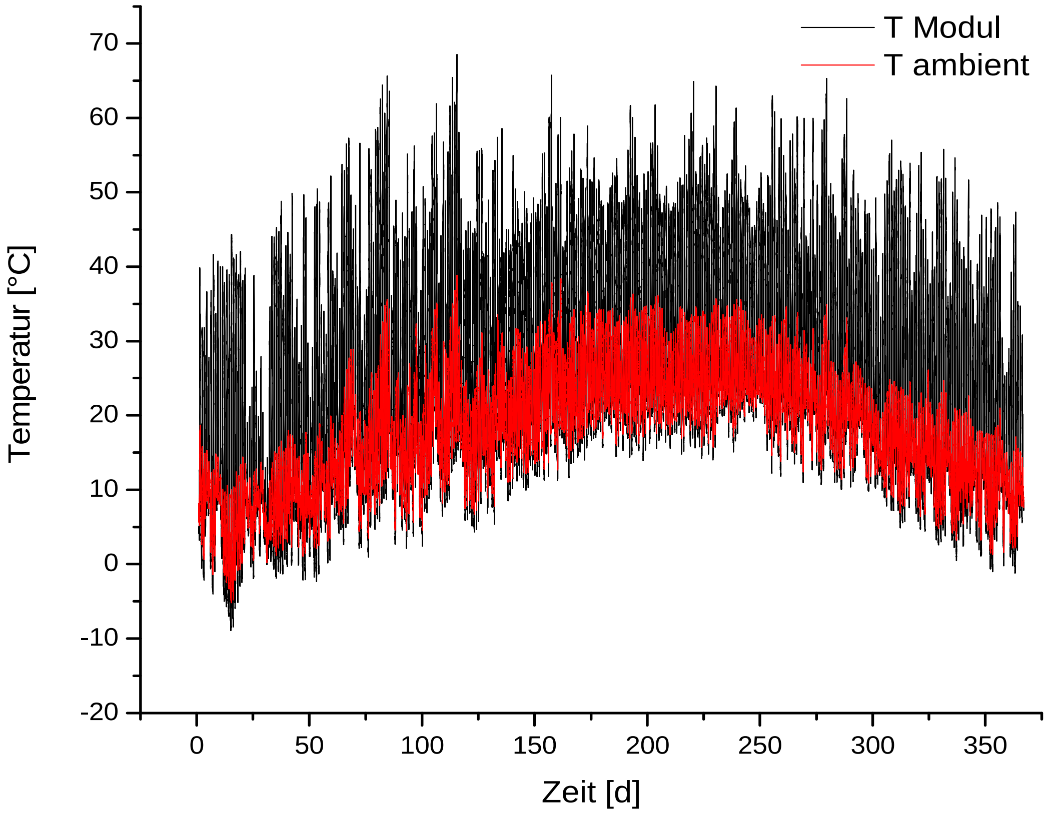


Monitoring in the desert (one year)

Ambient humidity

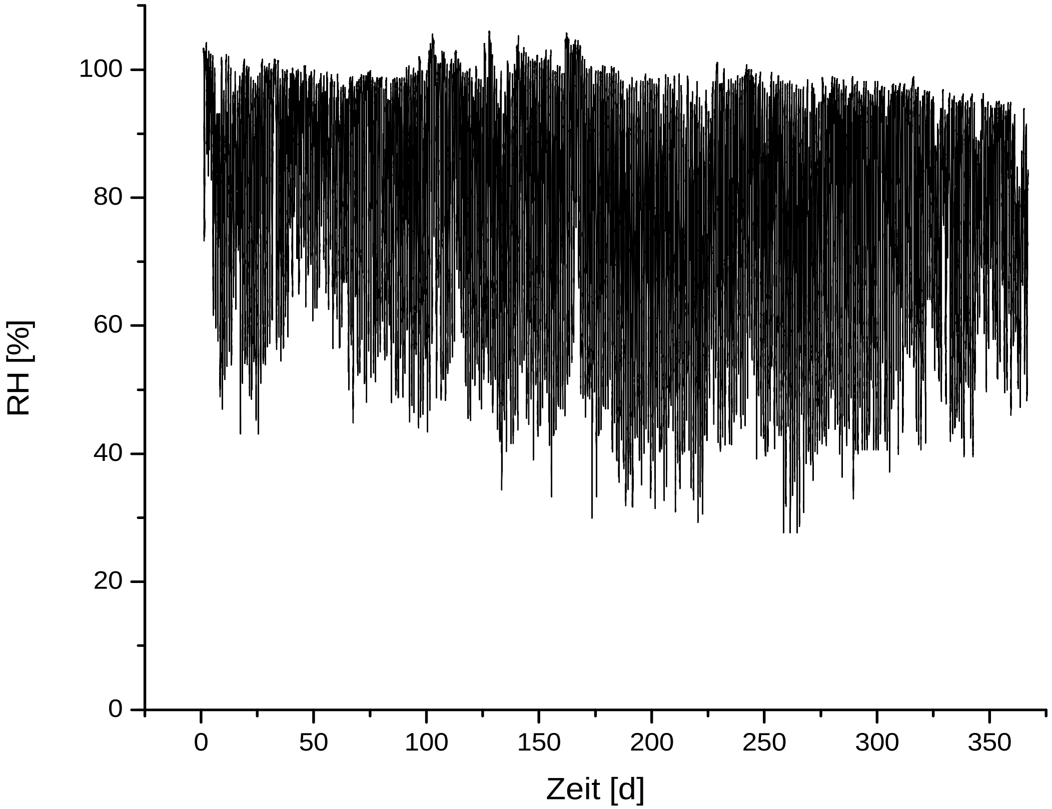


ambient and module temperatures

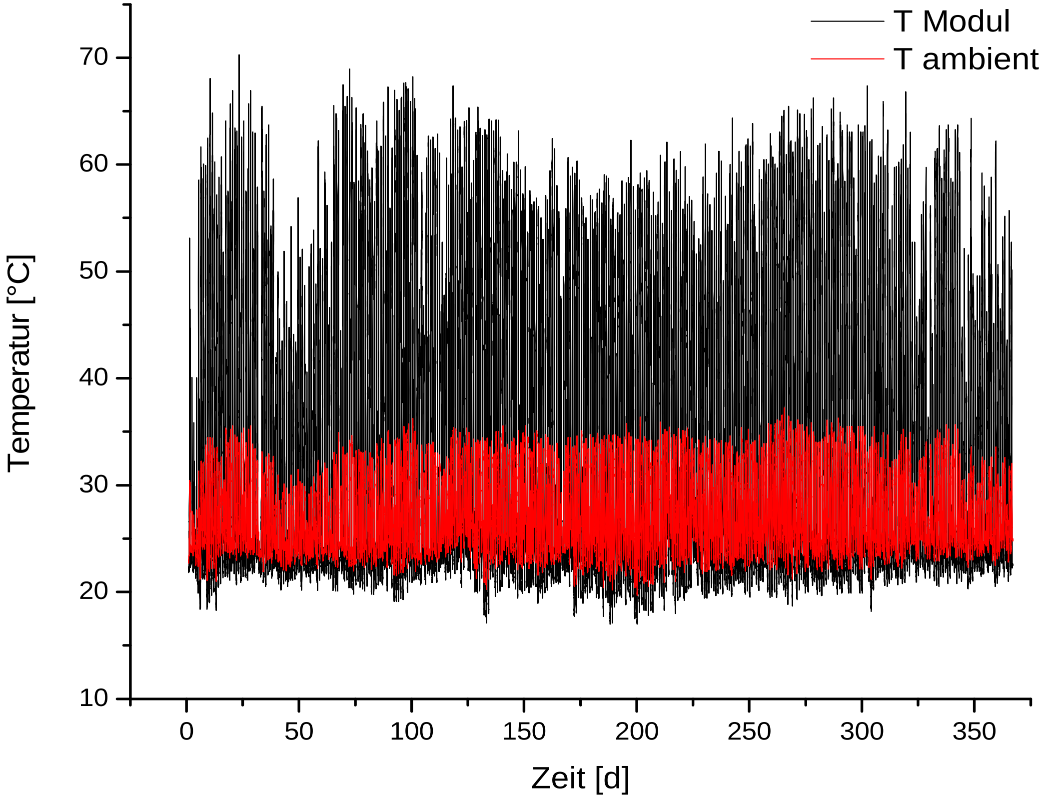


Monitoring in tropical Serpong (one year)

Ambient humidity



ambient and module temperatures



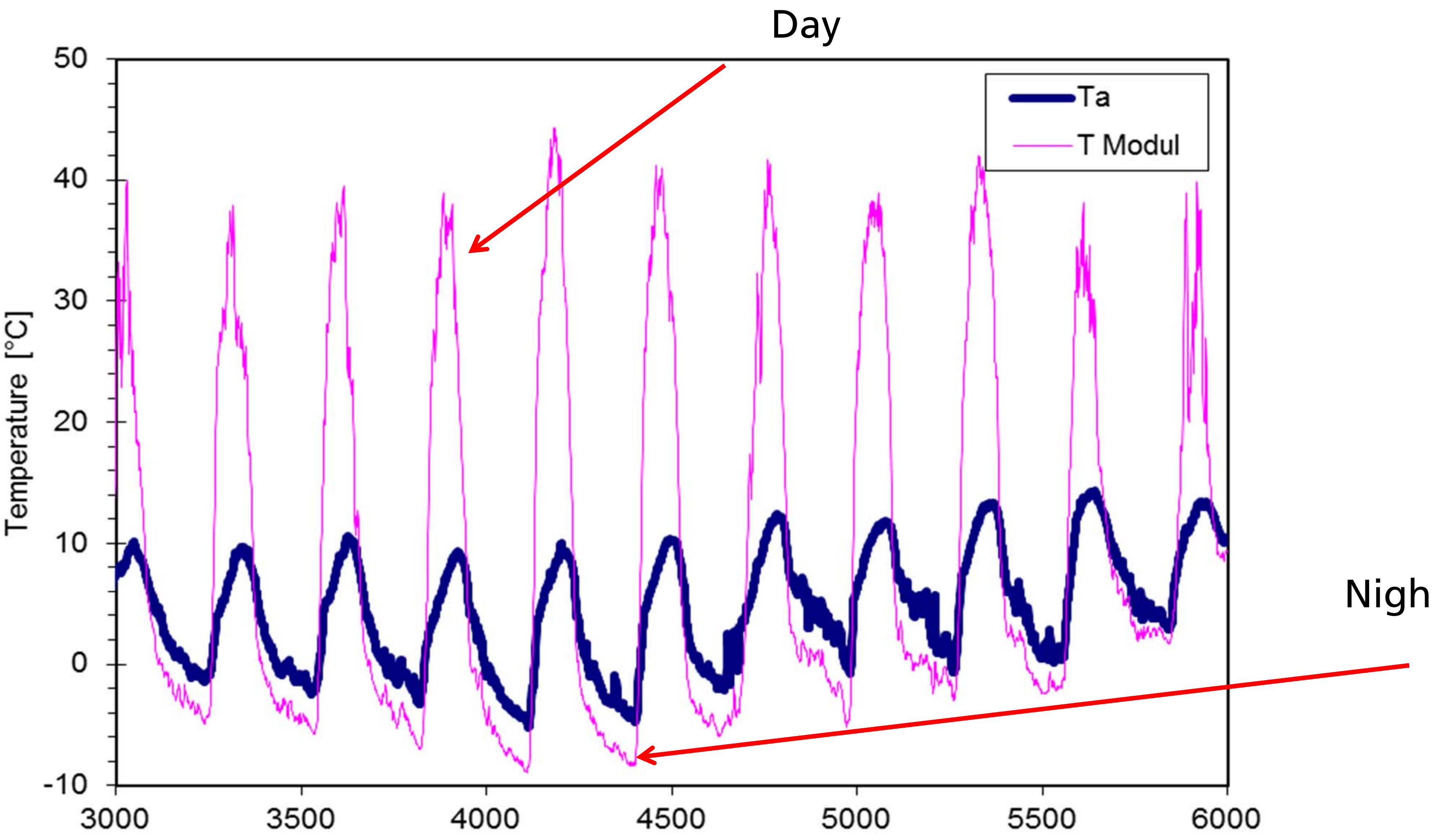
General methodology Step 2: **Micro - climate**

Micro-climate : = stresses for the material caused by interaction of materials and ambient climate

1. **Module temperature** modeled by solar irradiation, ambient temperature, wind speed
2. **Module surface humidity** modeled by module temperature, ambient temperature and humidity
3. **UV-radiation** modeled from solar irradiation and spectral transmittance of laminated materials
4. **Temperature cycles** of module temperature
5. **Leakage current** as function of voltage, module temperature and surface humidity
6. **Salt concentration** correlated with wetting/drying cycles
7. …….

Micro-climate of modules

Module – Temperature in the desert



Day

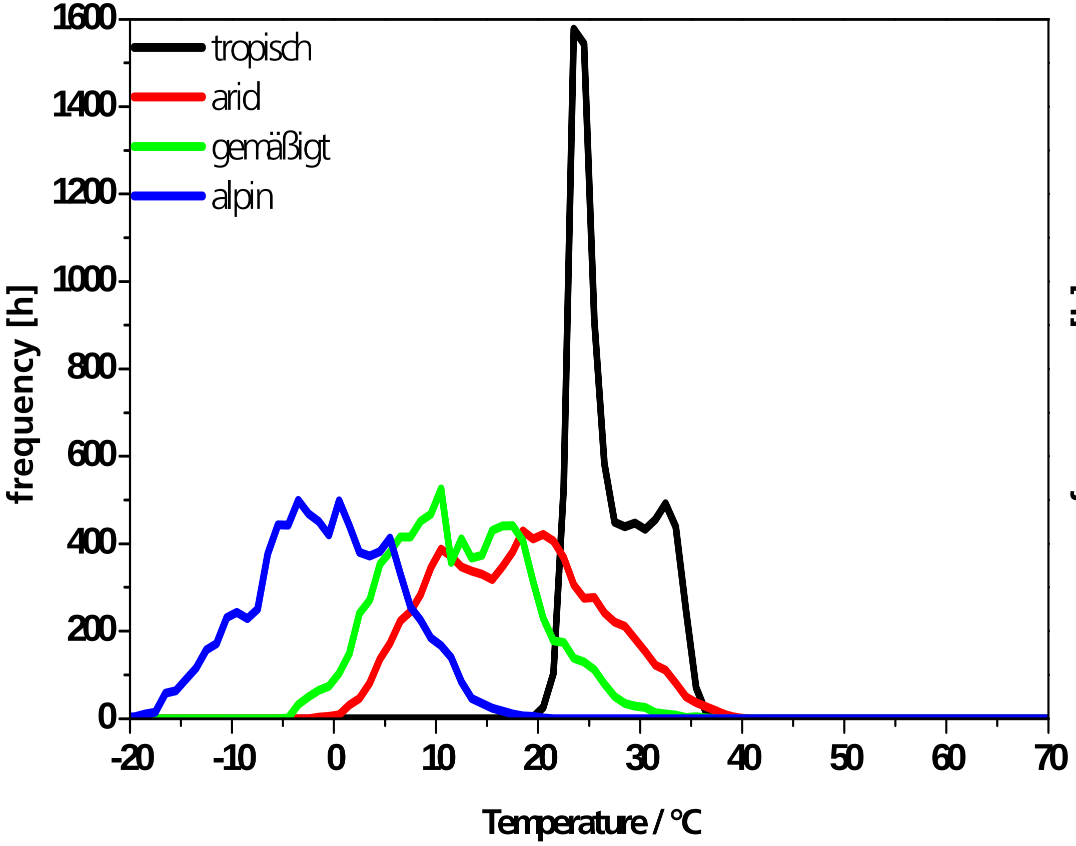
Night

Micro-climate of modules

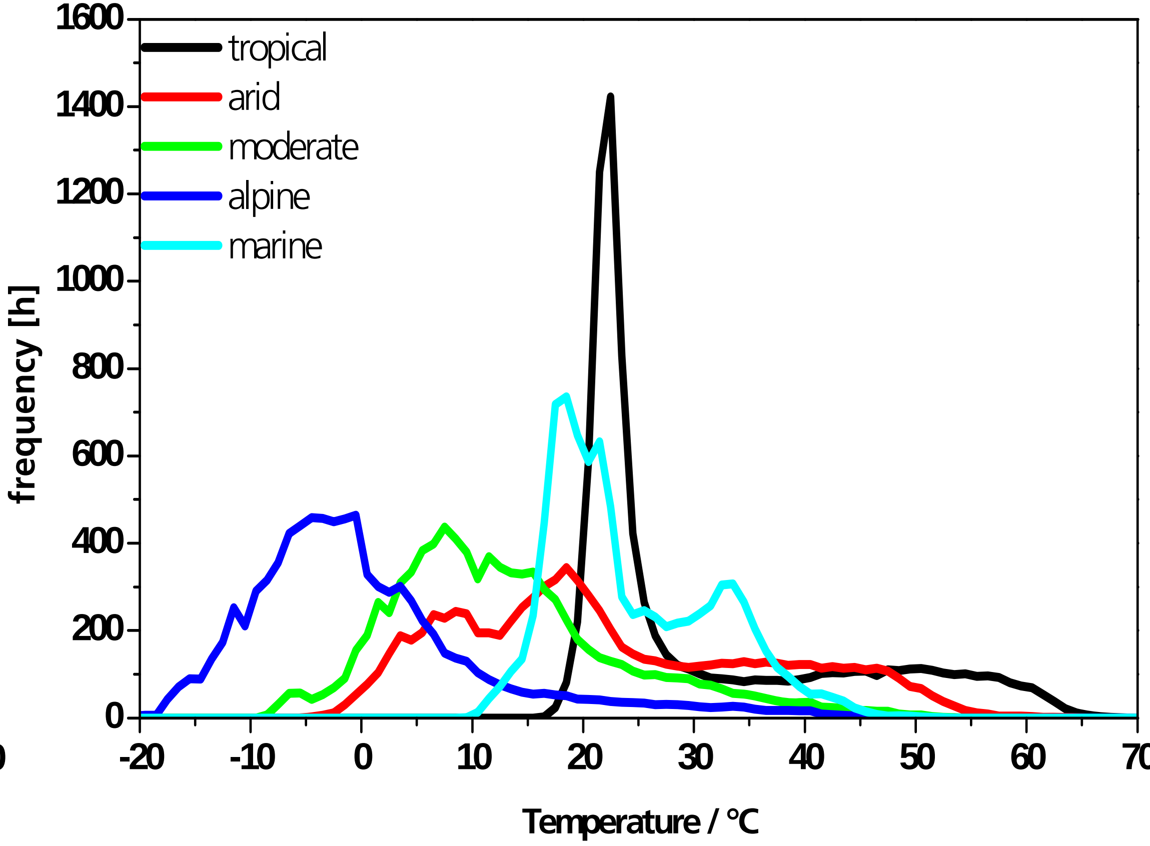
Outdoor weathering with temperature monitoring

Macro-climate => Micro-climate

Ambient temperature

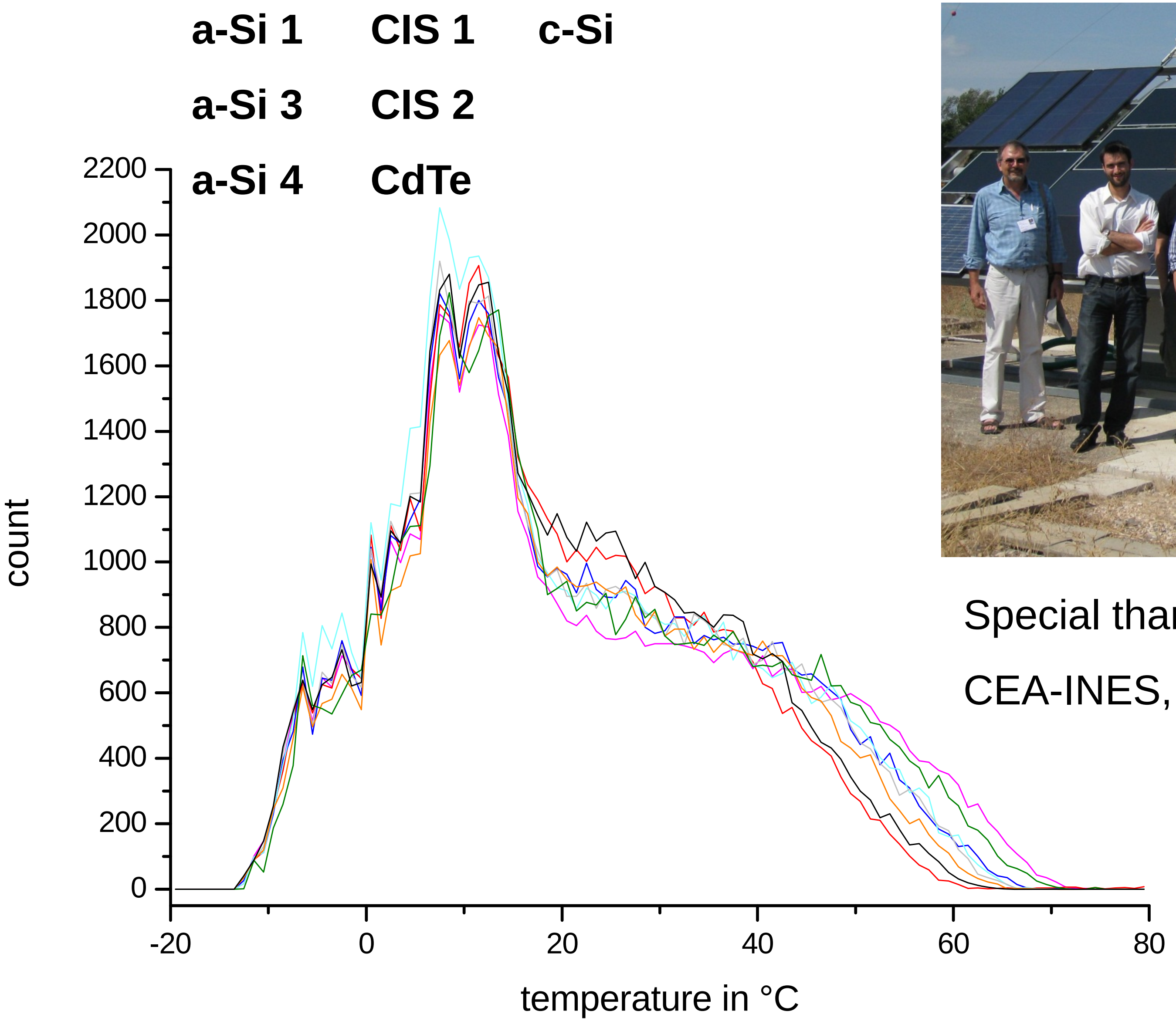


Average module temperatur e(c-Si)



Histogram of measured module temperatures in Cadarache, F

What about Thin Film Modules?



Special thanks to Antoine Guerin de Montgareuil, CEA-INES, Cadarache, France

Module temperature for one year

Physical modeling of module temperature for each of the different modu types using David Faiman‘s approach (could be King, Fuentes……as well)

Macro – climate => Micro – climate

Irradiation, wind, ambient temperature => T_{mod}

$$T_{\mathrm{mod}} = T_{amb} + \frac{H}{U_0 + U_1 \cdot \mathrm{v}}$$

T_{mod}	module temperature
T_{amb}	ambient temperature
v	wind velocity
H	solar radiation

	U1	U0
a-Si 1	10,7	25,7
a-Si 3	5,8	25,8
a-Si 4	4,3	26,1
CIS 1	3,1	23,0
CIS 2	4,1	25,0
CdTe	5,4	23,4
c-Si	6,2	30,0

U_0 , U_1 = module dependent parameters

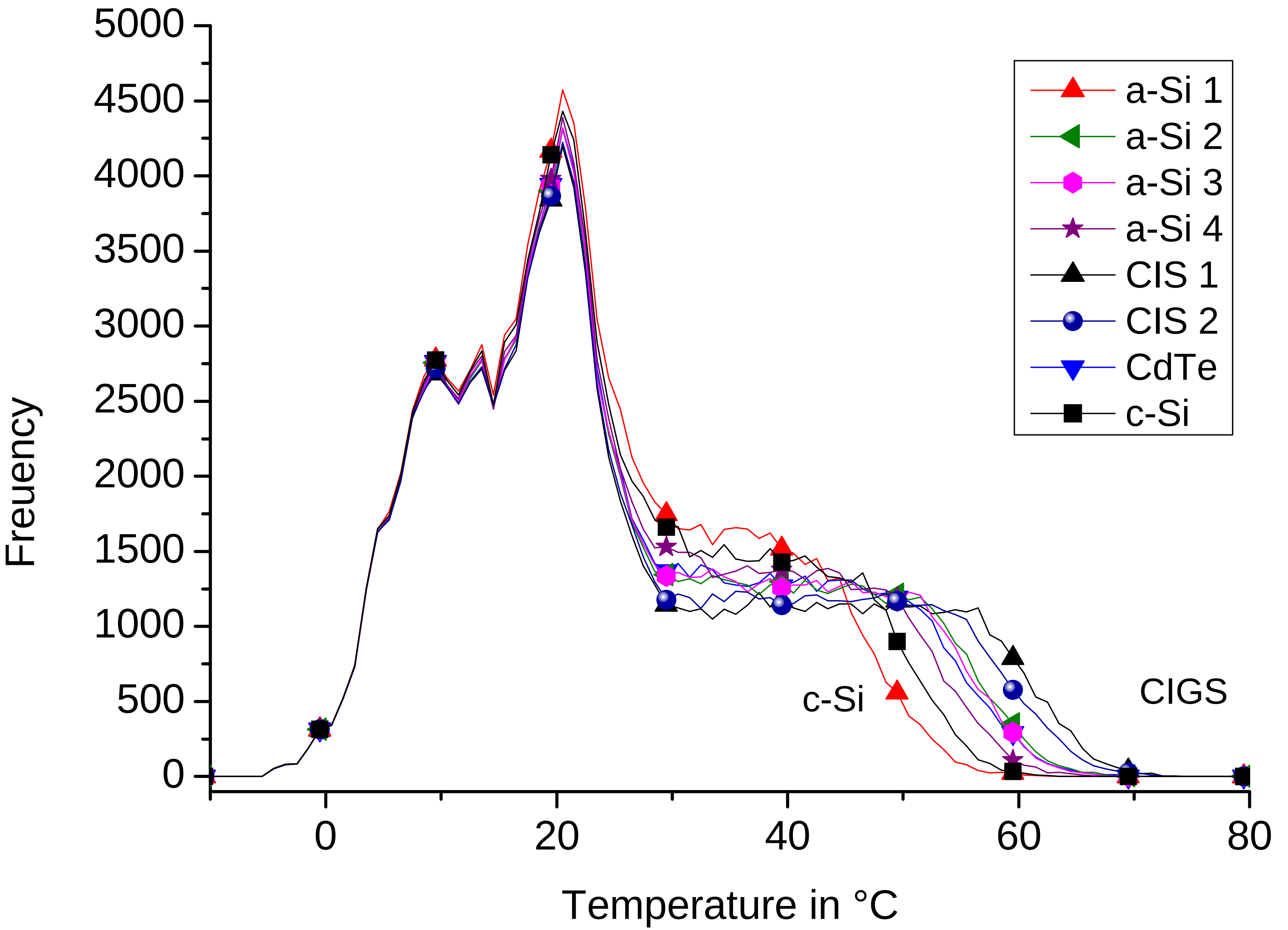
Neglected: IR-radiation exchange and natural convection

The parameters U are module-specific but location independent

M.Koehl et.al.: Modelling of the nominal operating cell temperature based on outdoor weathering, Sol. Energy Mat. Sol. Cells (2011)

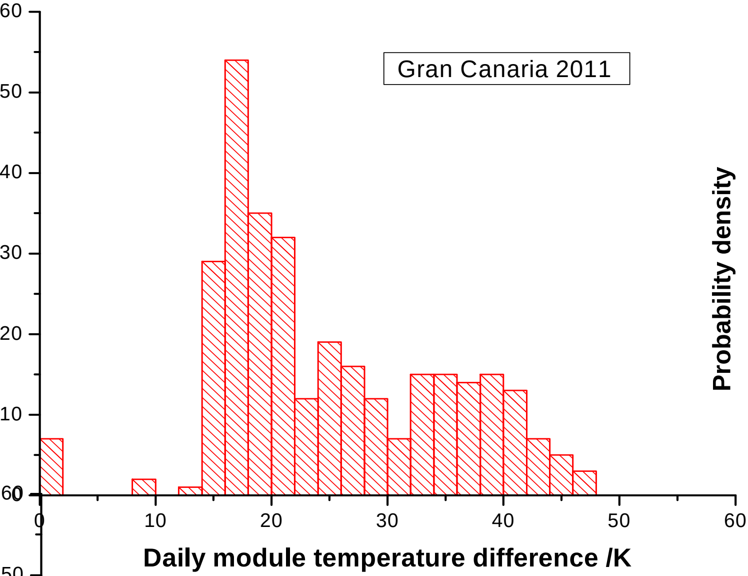
Micro-climate of Modules

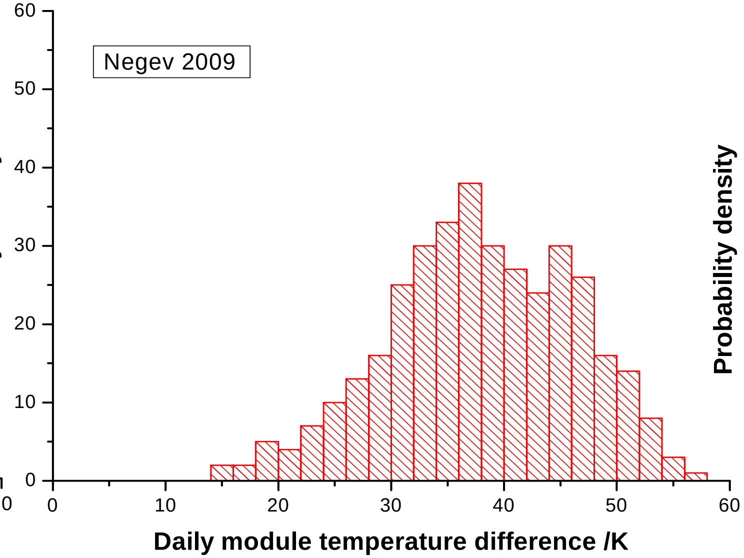
Histogram of simulated module temperatures for one year in the Negev

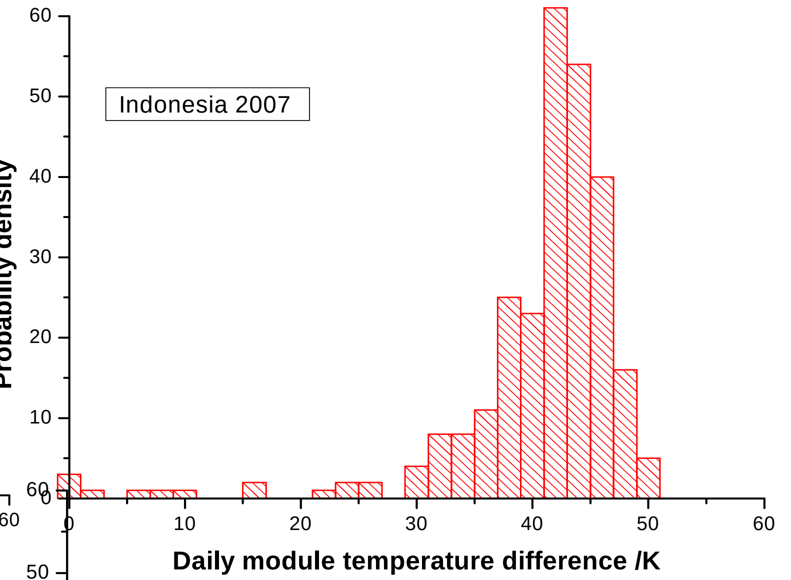


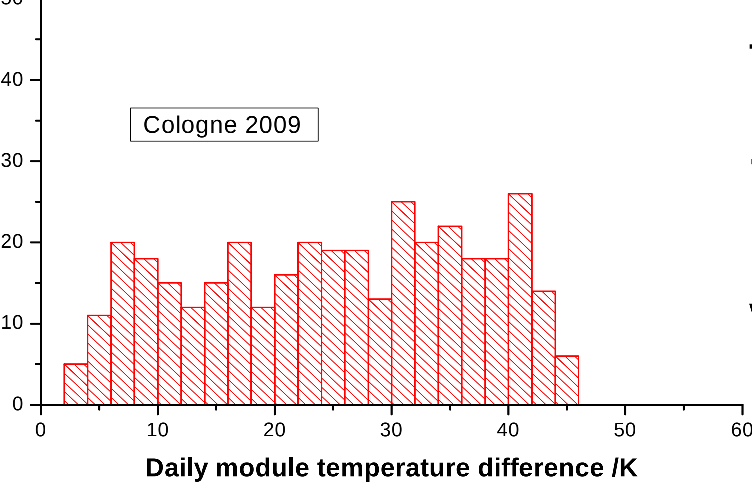
Micro-climate of modules

Daily temperature cycling during one year







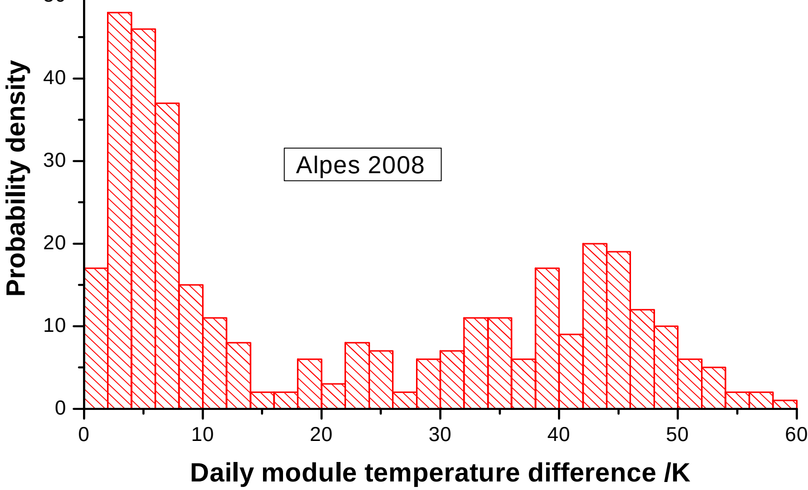


Type approval testing:

200 cycles from -40 to 85°C

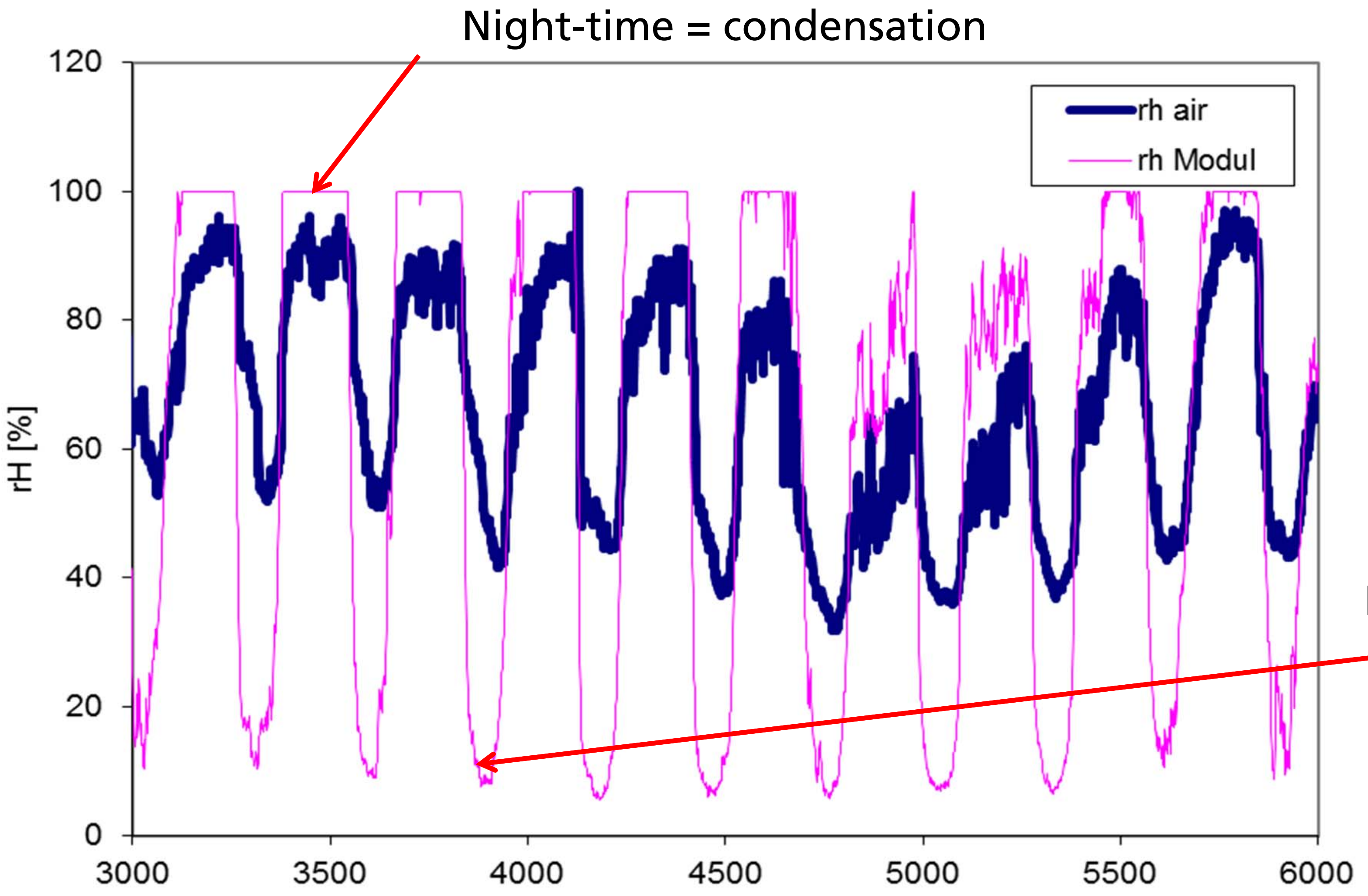
Max. changes 100 K/h

With current injection



Micro-climate of modules

Surface humidity – desert



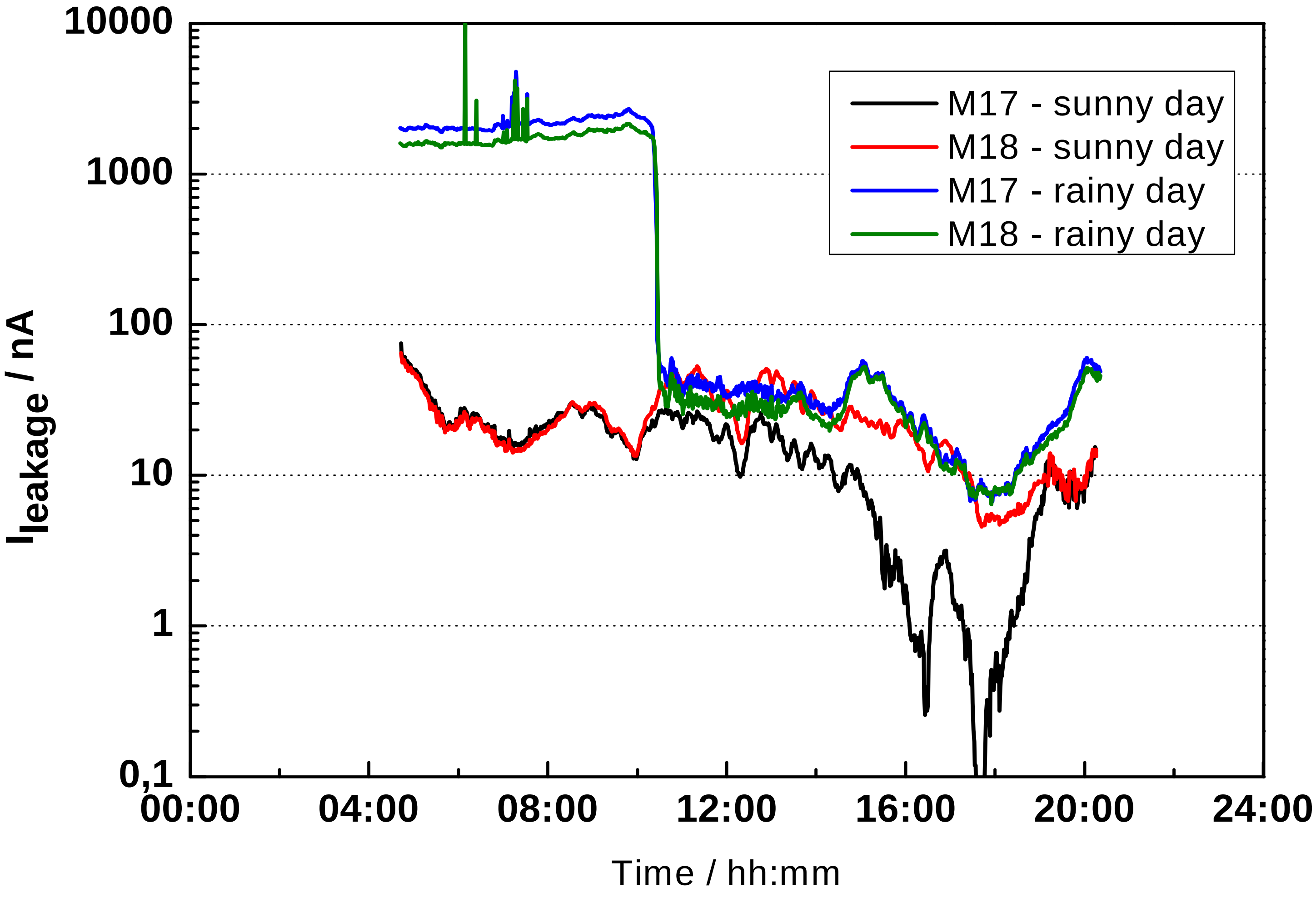
Night-time = condensation

Day-time = Drying

Micro-climate of modules

Leakage currents as source of Potential Induced Degradation

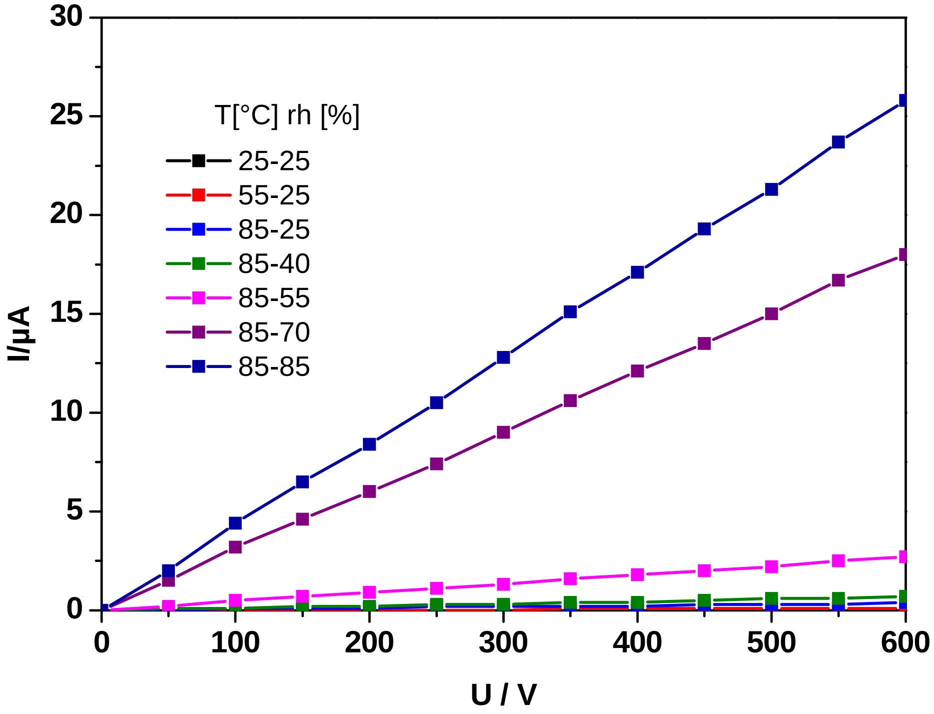
Leakage currents depend on the module temperature, the voltage and the surface humidity

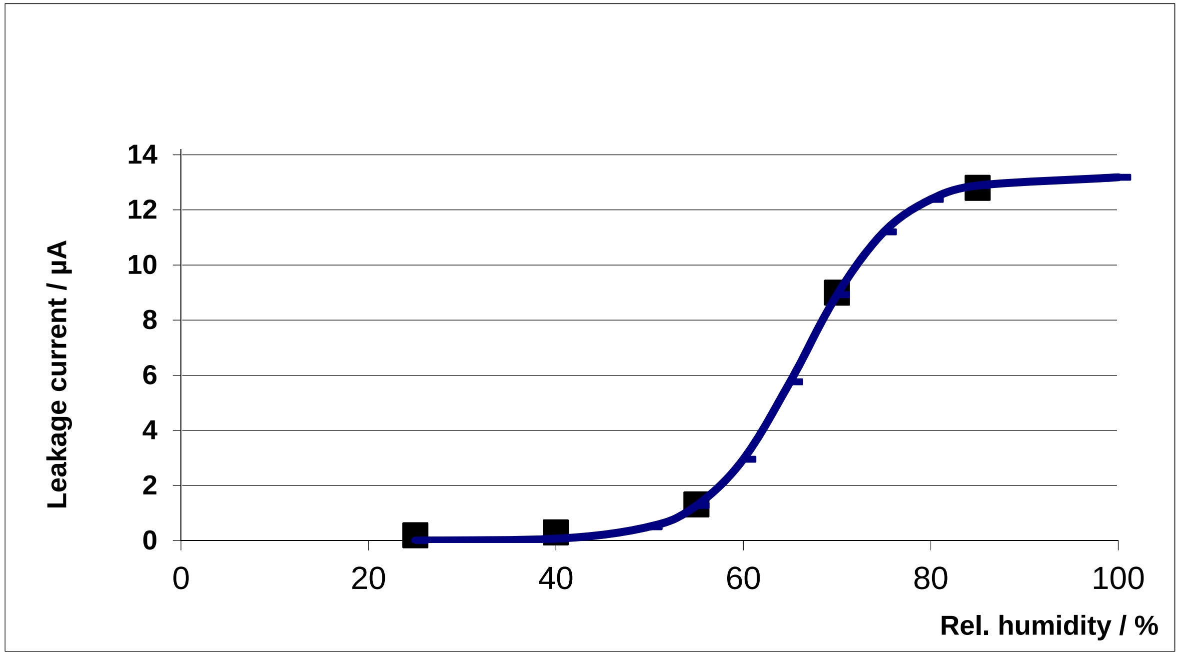


Micro-climate of modules

Humidity and potential-induced degradation (PID) of modules

Leakage current as function of potential, relative humidity and temperature





I =G/(1+ exp(-G*(rh-0,35)*1,75) *(G/f(0)-1))
with G = 13µA

Hoffmann, S., M. Koehl, Effect of Humidity and Temperature on the Potential Induced Degradation, accepted by PIP, 2012

General Methodology Step 3: **Time-transformation functions**

Modelling of the degradation processes as function of the degradation factors

Time-transformation functions

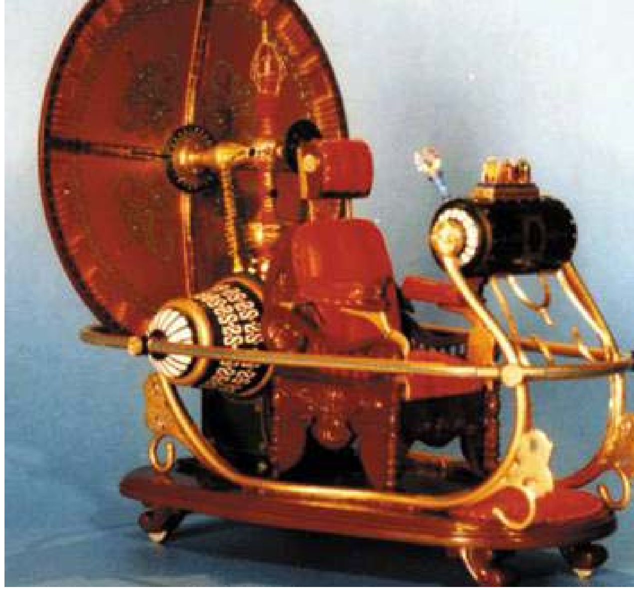
1. Module temperature: Arrhenius, Eyring
2. Module surface humidity impact: power law, TOW
3. UV-radiation: Dose-function, reciprocity?
4. Temperature cycles of module temperature: Coffin-Manson
5. Potential induced degradation
6. Salt concentration correlated with wetting/drying cycles: ?
7. …….

Time-transformation functions

Changes of performance or degradation indicator $\Delta P = \Delta t_i *($

Temperature	$+ A \exp[-E_A / RT_i]$
Humidity	$+ B f(rh)_i \exp[-E_B / RT_i]$
UV-radiation	$+ C I^n_i \exp[-E_C / RT_i]$
Temperature cycles	$+ D f(\Delta T)_i \exp[-E_D / RTi]$
Potential-induced Deg.	$+ E f(P)_i \mathbf{fp(rh)}_i \exp[-E_E / RT_i]$
Salt	$+ F f(S)_i \mathbf{fp (rh)}_i \exp[-E_F / RT_i] \ldots\ldots\ldots\ldots)$

Simple deterministic model for aging processes: Time-transformation functions



Changes of property P after the testing time Δt_i

Degradation factor: $\Delta P = \Sigma^{m}_{i=1} \{\Delta t_i \,($

Temperature	$+ A \exp[-E_A / RT_i]$
Moisture	$+ B\, f(rh)_i \exp[-E_B / RT_i]$
UV-Radiation	$+ C\, I^n_i \exp[-E_C / RT_i]$
T cycles	$+ D\, f(\Delta T)_i \exp[-E_D / RT_i]$
Potential I D	$+ E\, f(P)_i\, f_p(rh)_i \exp[-E_E / RT_i]$
Salt	$+ F\, f(S)_i\, f_p\, (rh)_i \exp[-E_F / RT_i]$
………	$+\ldots\ldots X\, I^n_i\, f(X)\,_i \exp[-E_X / RT_i] \ldots..)\}$

Sample dependent degradatio
process parameters

General methodology Step 4: **Accelerated life testing conditions**

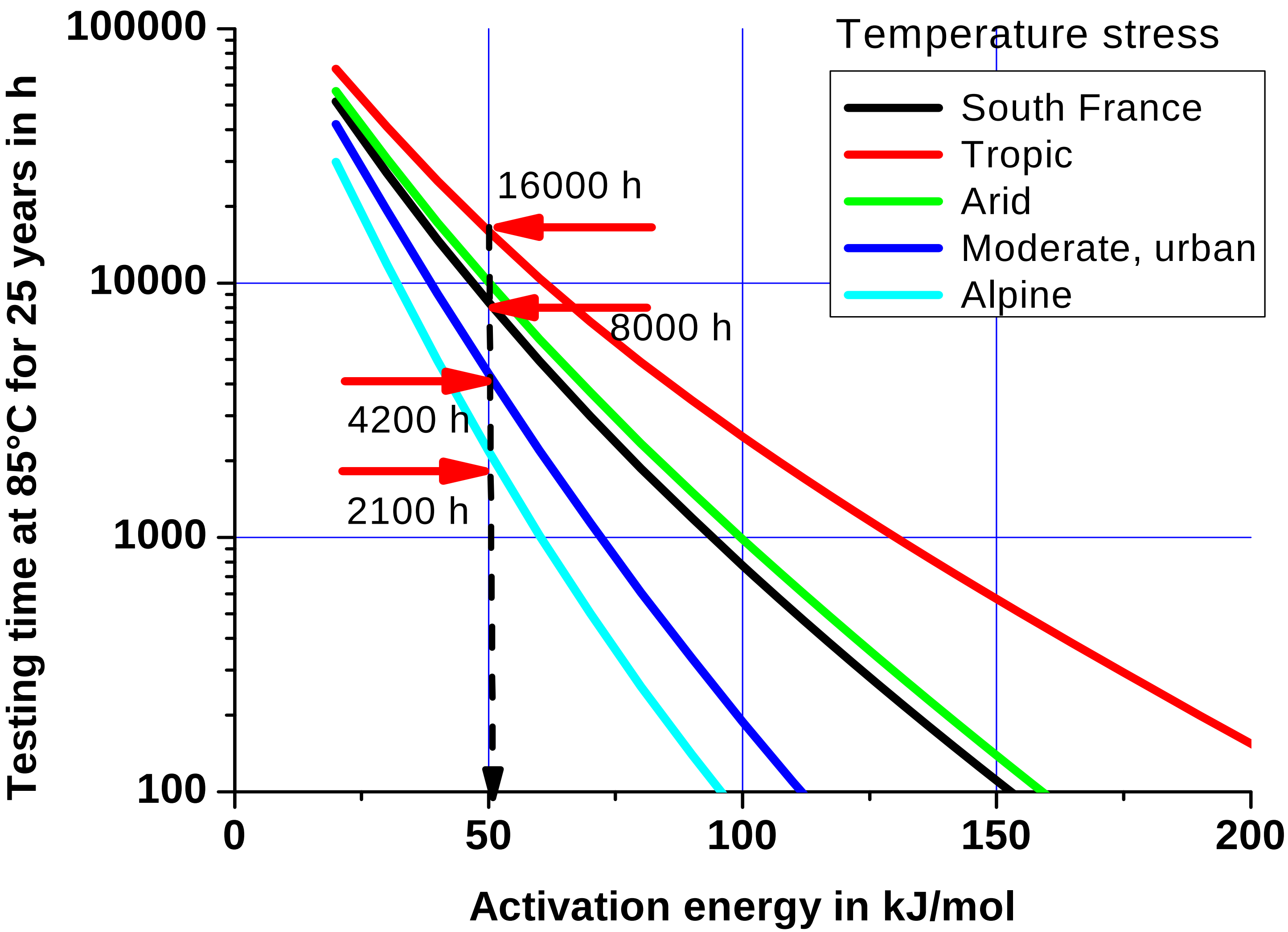
ALT – conditions for different locations: temperature impact

Accelerated life testing
Equivalent lab tests

(same changes of performance
or degradation indicator
as after service life)

by integration of the outdoor stresses

Difference in testing time between 8 and 20

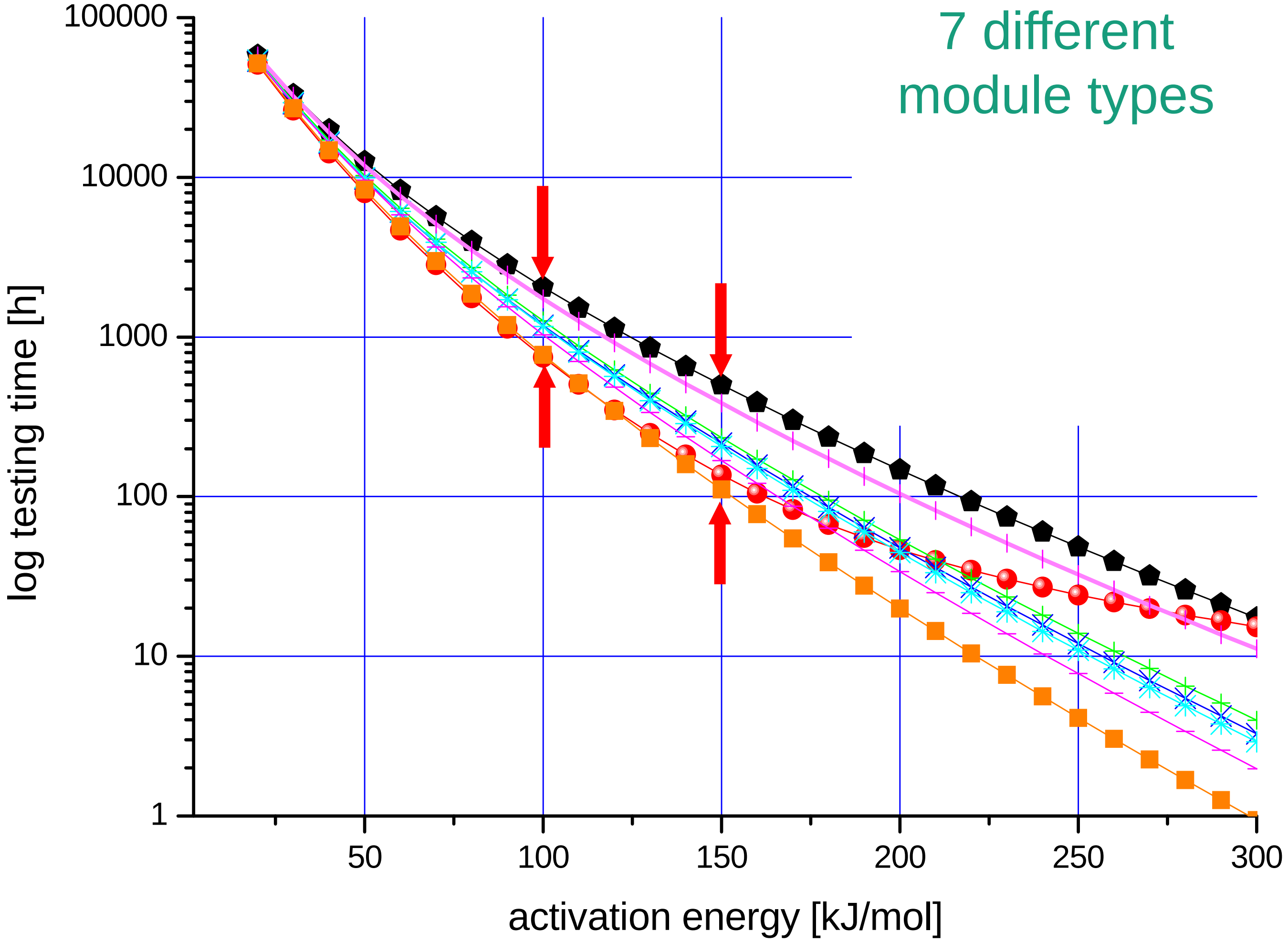


Fraunhofer ISE

Corresponding temperature testing times at 85°C for 25 a exposure in Cadarache, France

based on monitored module temperatures

testing times @ 85°C for different thin film modules exposed in Cadarache



Different cell-types:

Factor 2 – 4 in testing time (depending on the degradation processes)

In the range of damp/heat

ALT – conditions for different locations: UV-radiation impact

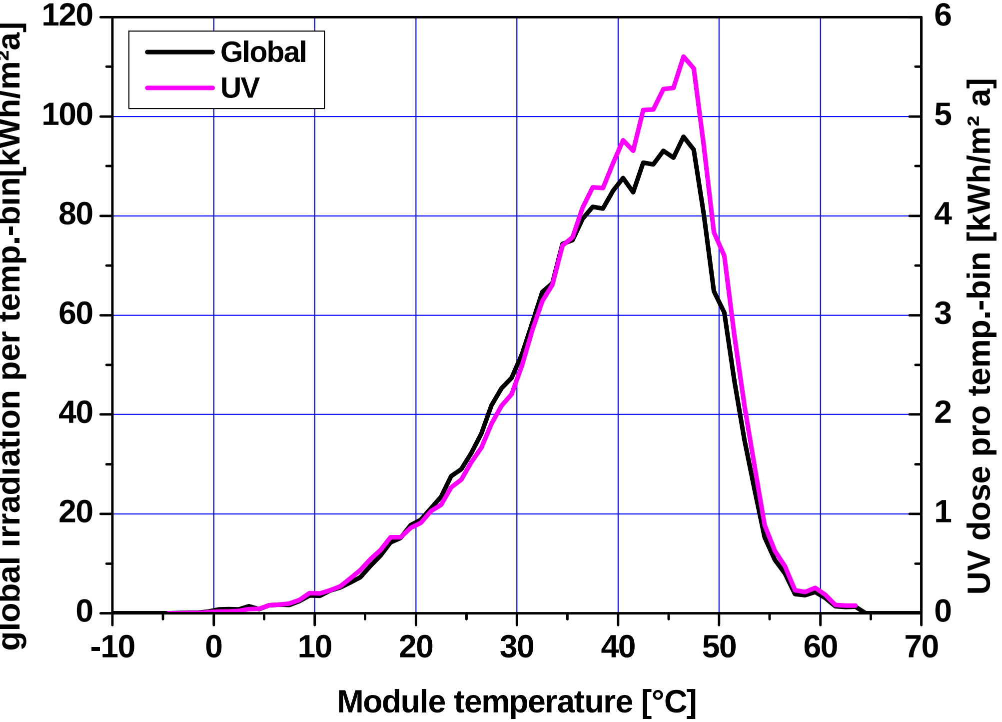
Outdoor testing with radiation monitoring for one year in the desert

Cumulated dose of UV- and solar radiation:

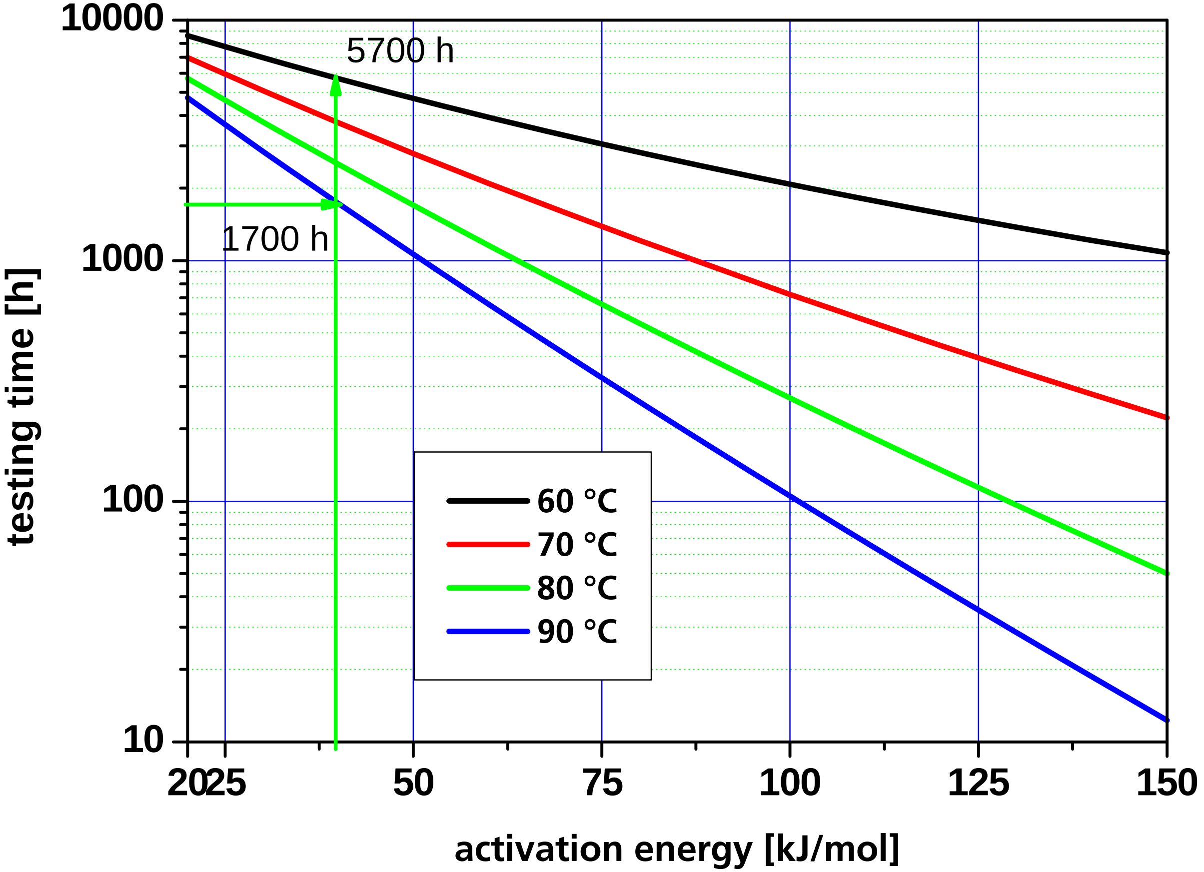
120 kWh/m² (about 8 x IEC)

Reciprocity: $p = 1$

$$t_{test} = (I_i / I_{test})^p \, \Delta t_i \cdot \exp\left[-(E_a / R)\cdot(1/T_{test} - 1/T_i)\right]$$



equivalent testing times for five suns UV test for desert climate loads

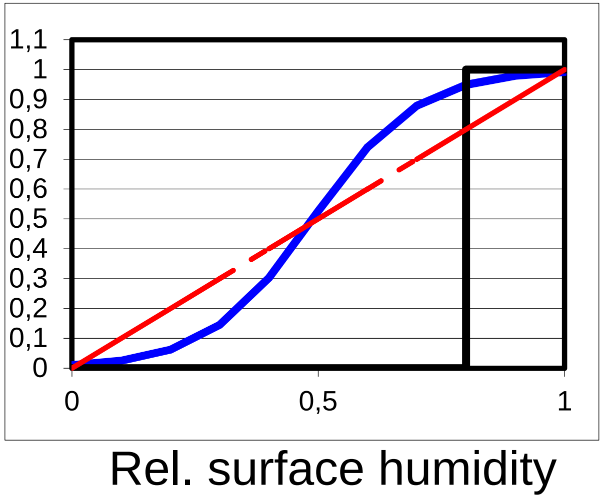


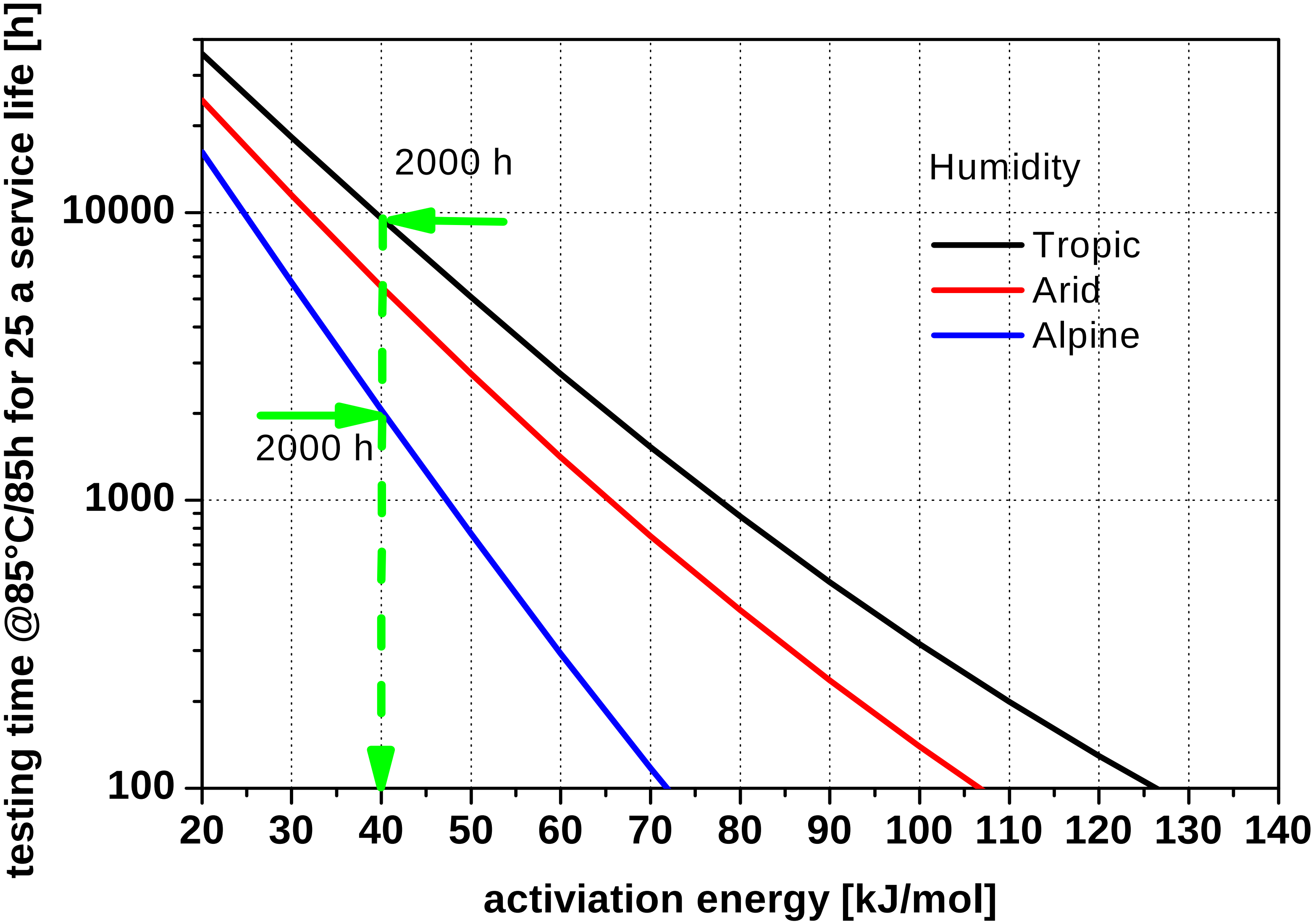
UV = 5.X % of solar radiation

ALT – conditions for different locations: humidity impact

Effective surface humidity

$rh_{eff} = 1/(1+ 1000/\exp(rh*k))$





M. Koehl et. al., Solar Energy Materials & Solar Cells 99 (2012) 282–291

Simulated histograms of the relative humidity

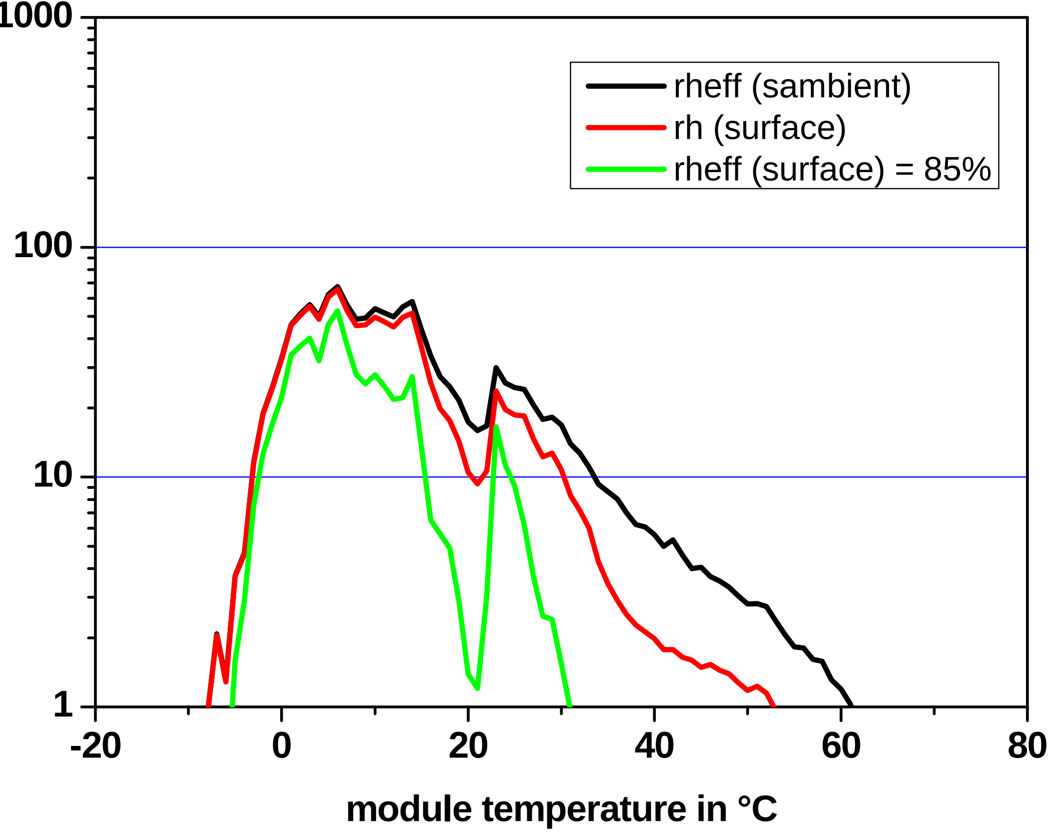
Ambient humidity = partial pressure / saturation pressure (T_{amb})

Surface humidity = partial pressure / saturation pressure (T_{modul})

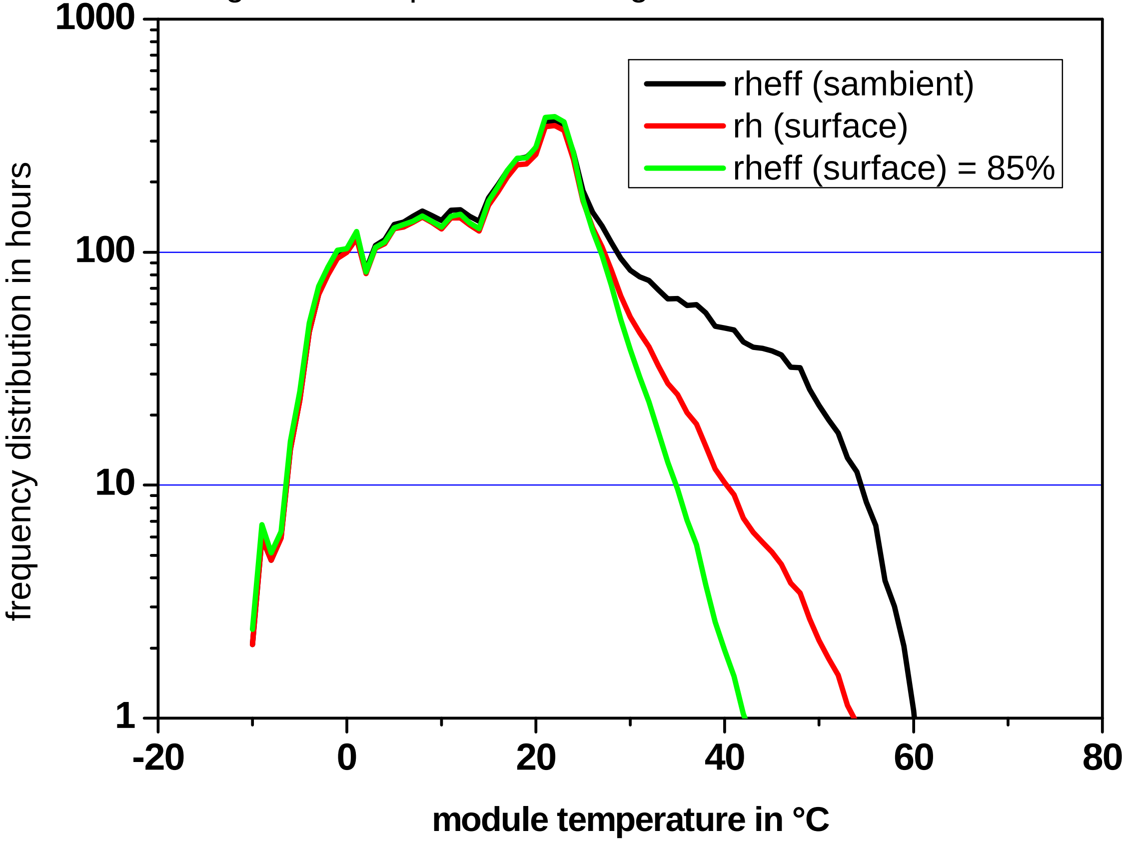
Eff. Humidity: $rh_{eff} = 1/(1+ \exp(-rh*k) *(1/f(0)-1))$

Humidity dose: $\Delta t_{eff} = \Delta t * rh_{eff} \ / 0.85$

Desert Rock 2007-01-01-bis-2007-12-31_ (type TF)
histogram of the periods with high moisture

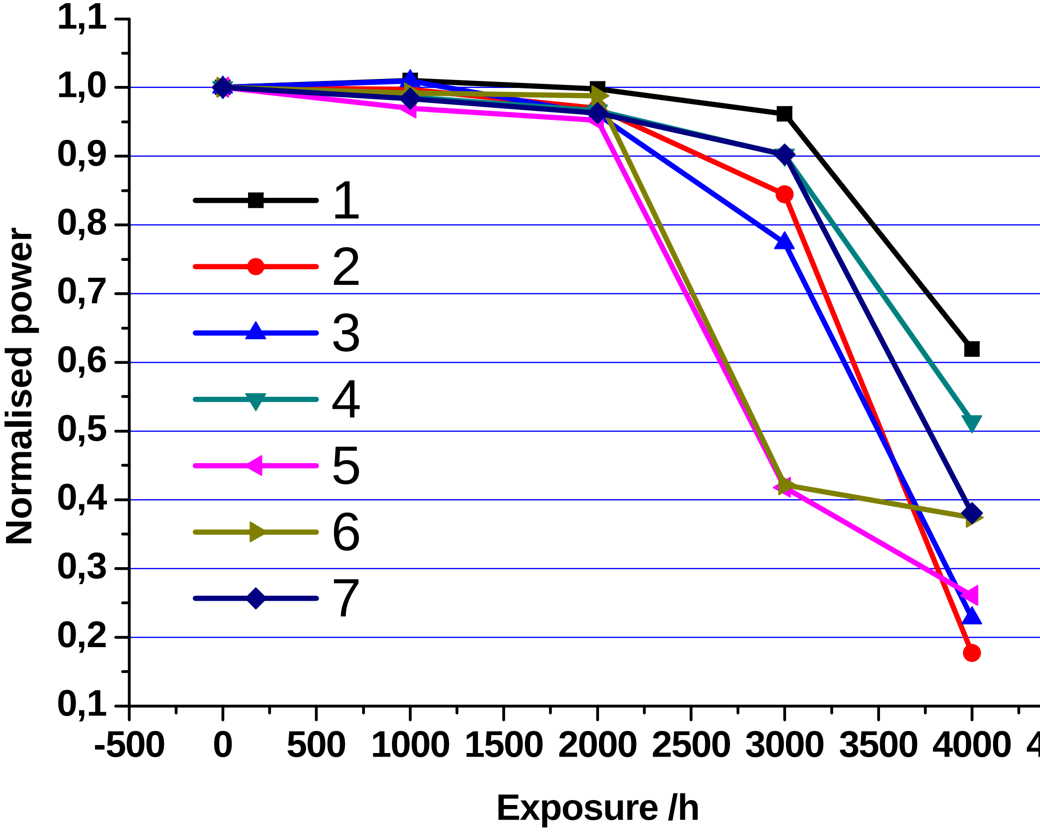


Goodwin Creek 2007-01-01-bis-2007-12-31_ (type cSi)
histogram of the periods with high moisture

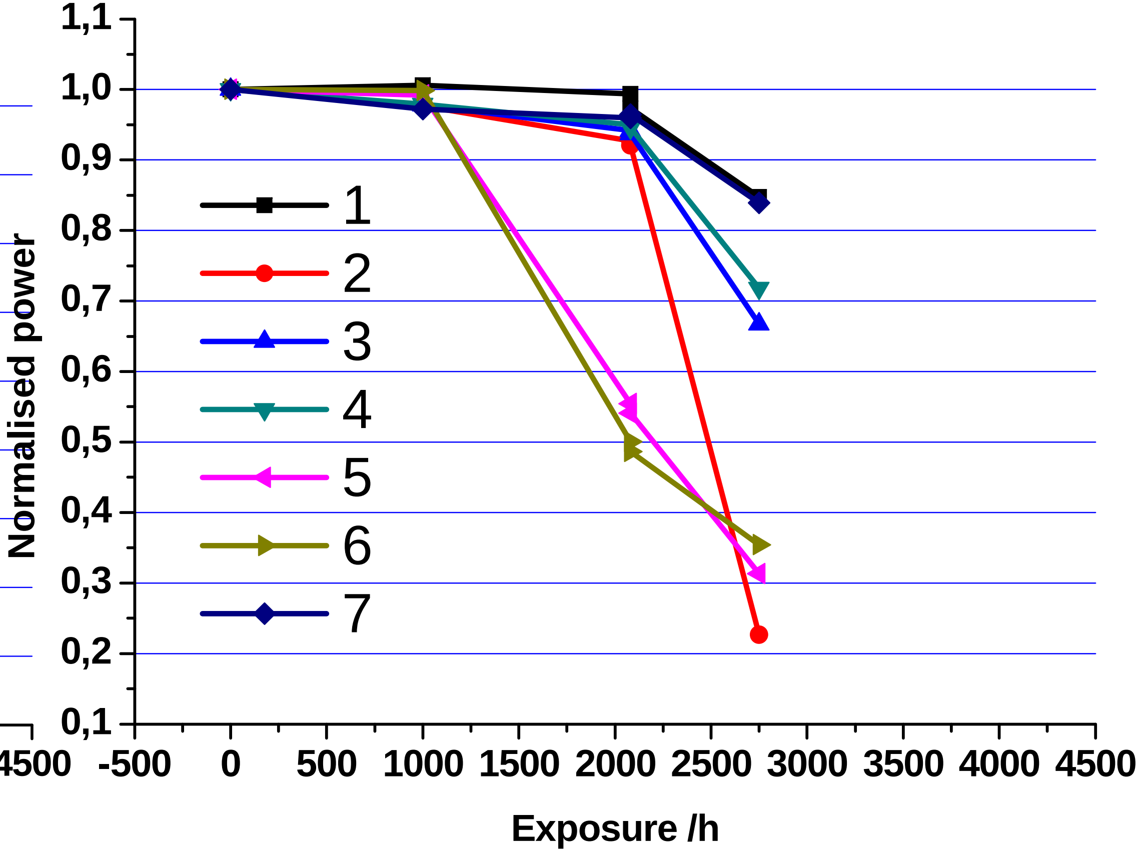


General methodology Step 5: **Accelerated life testing**

Seven different commercial c-Si modules



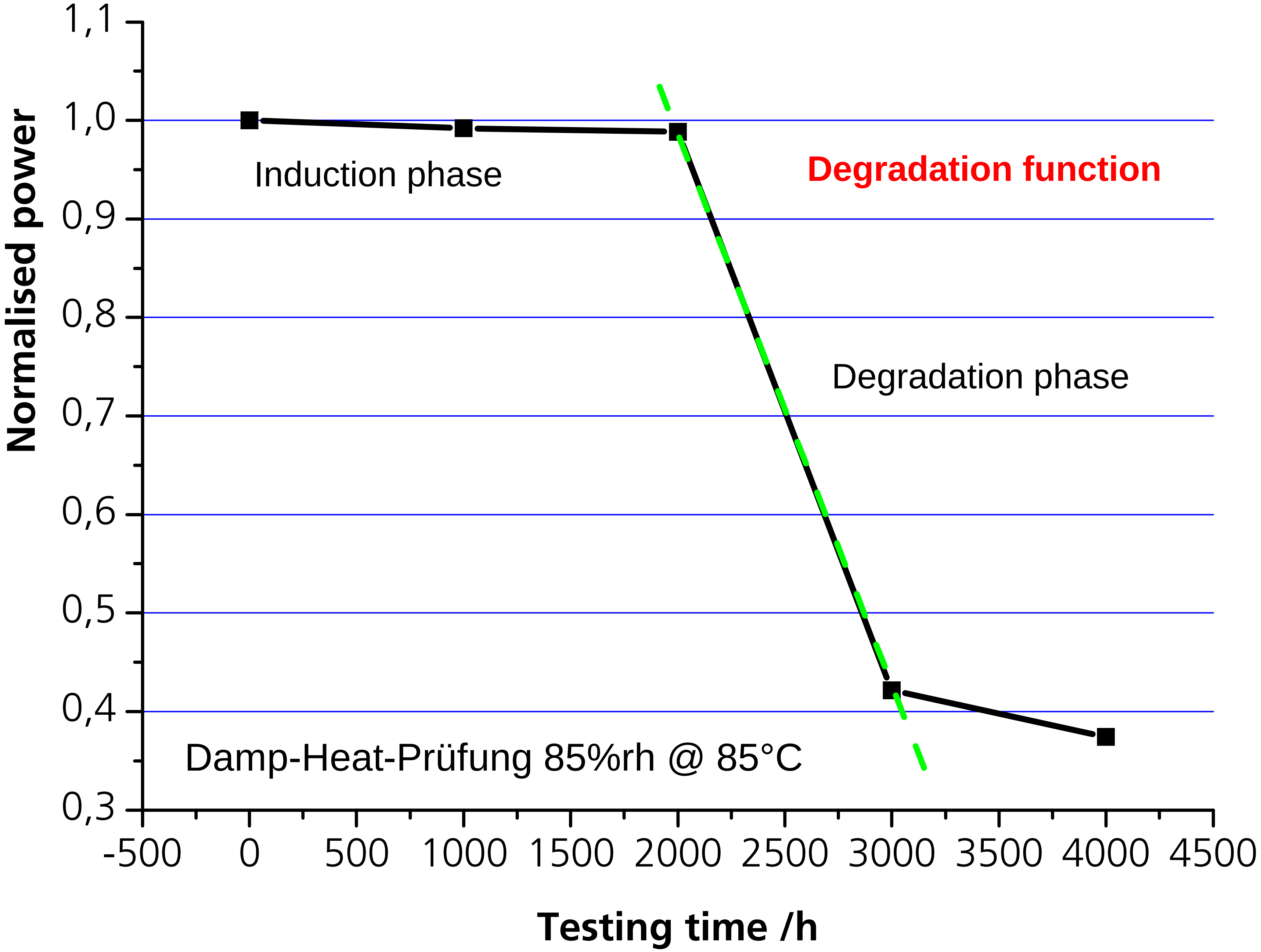
Damp-Heat at 85°C and 85% rel. humidity



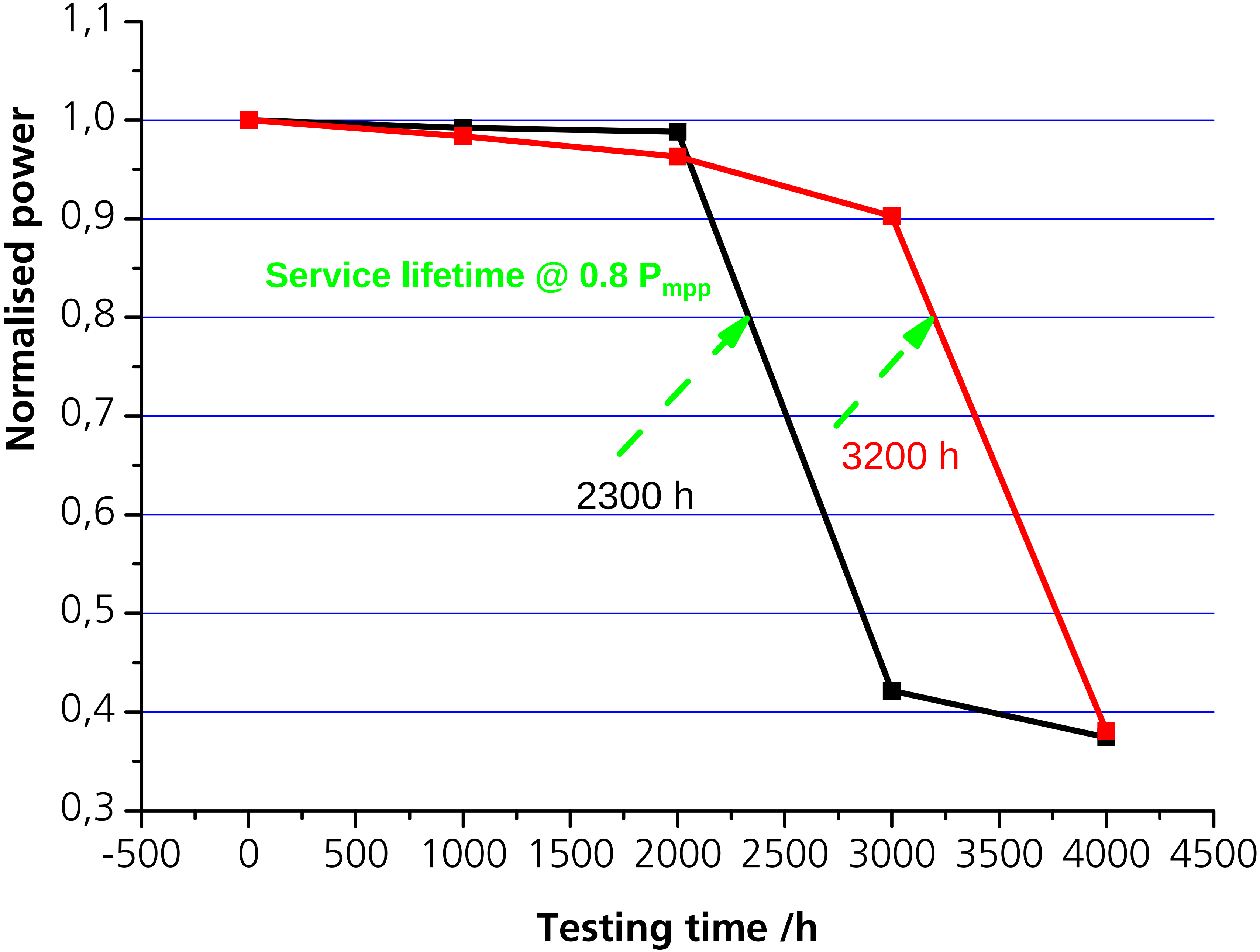
Damp-Heat at 90°C and 85% rel. humidity

M. Koehl et. al., PV reliability (Cluster II): Results of a German four-year joint project - Part I, results accelerated ageing tests and modelling of degradation, 25th EU-PVSEC (2010)

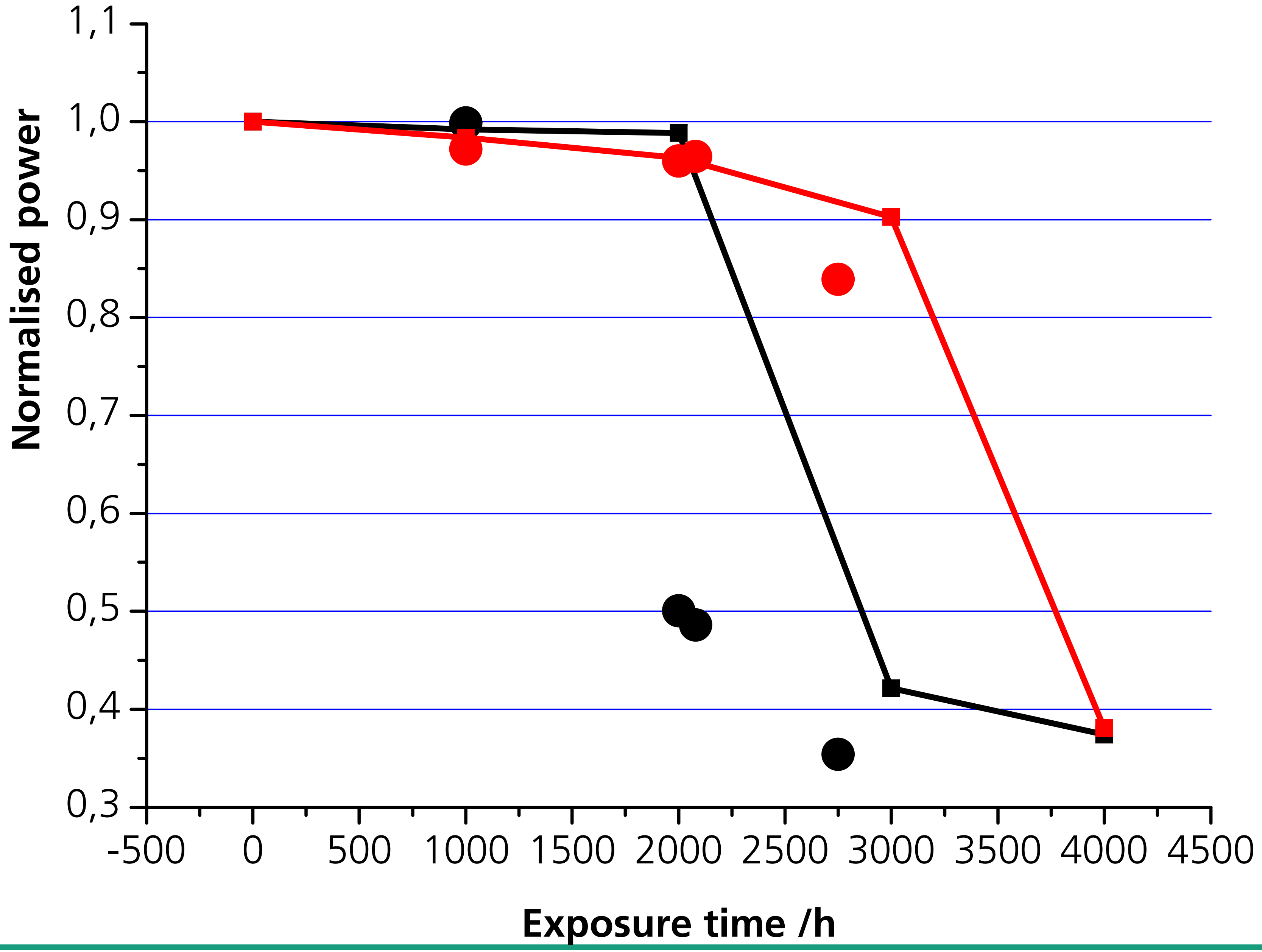
Damp-heat testing at 85%rh and 85°C, module 1



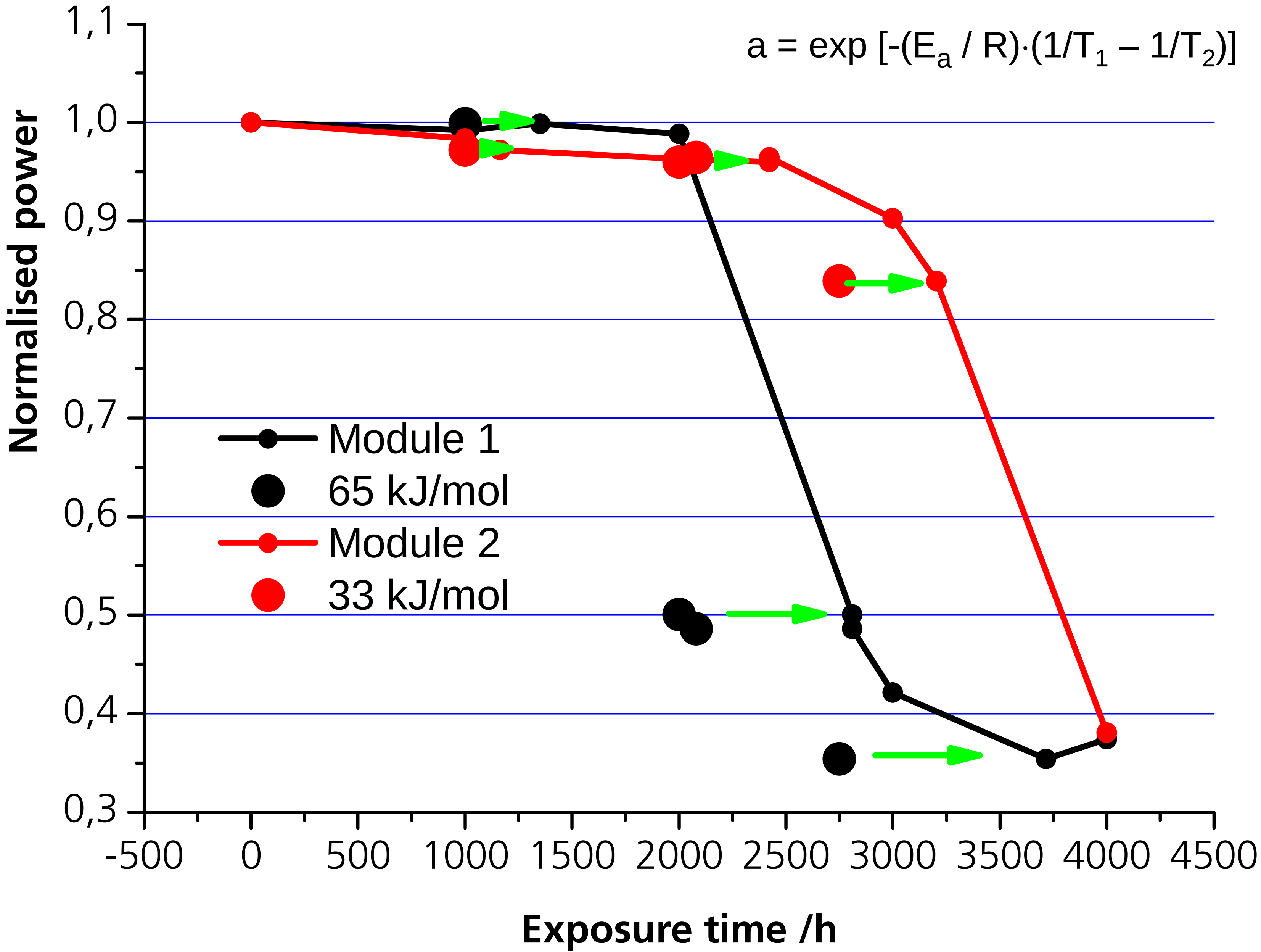
Damp-heat testing at 85%rh and 85°C, module 1 and module 2



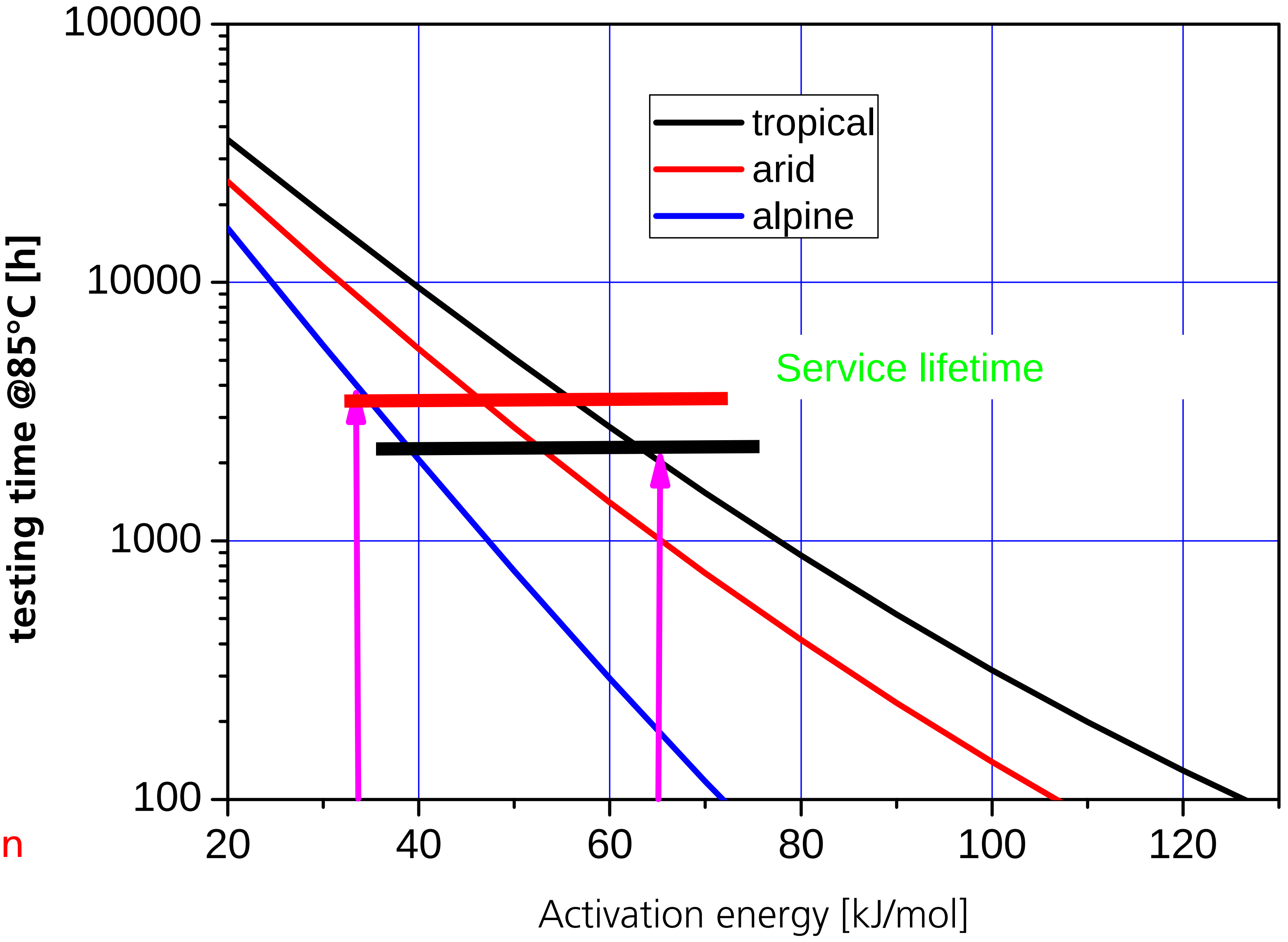
Damp-heat tests at 85%rh@85°C and 85%rh@90°C (large dots), Module 1 and module 2



Damp-heat tests at 85%rh@85°C and 85%rh@90°C (large dots), Module 1 and module 2



Equivalent testing times (25 years at 85%rh @ 85°C



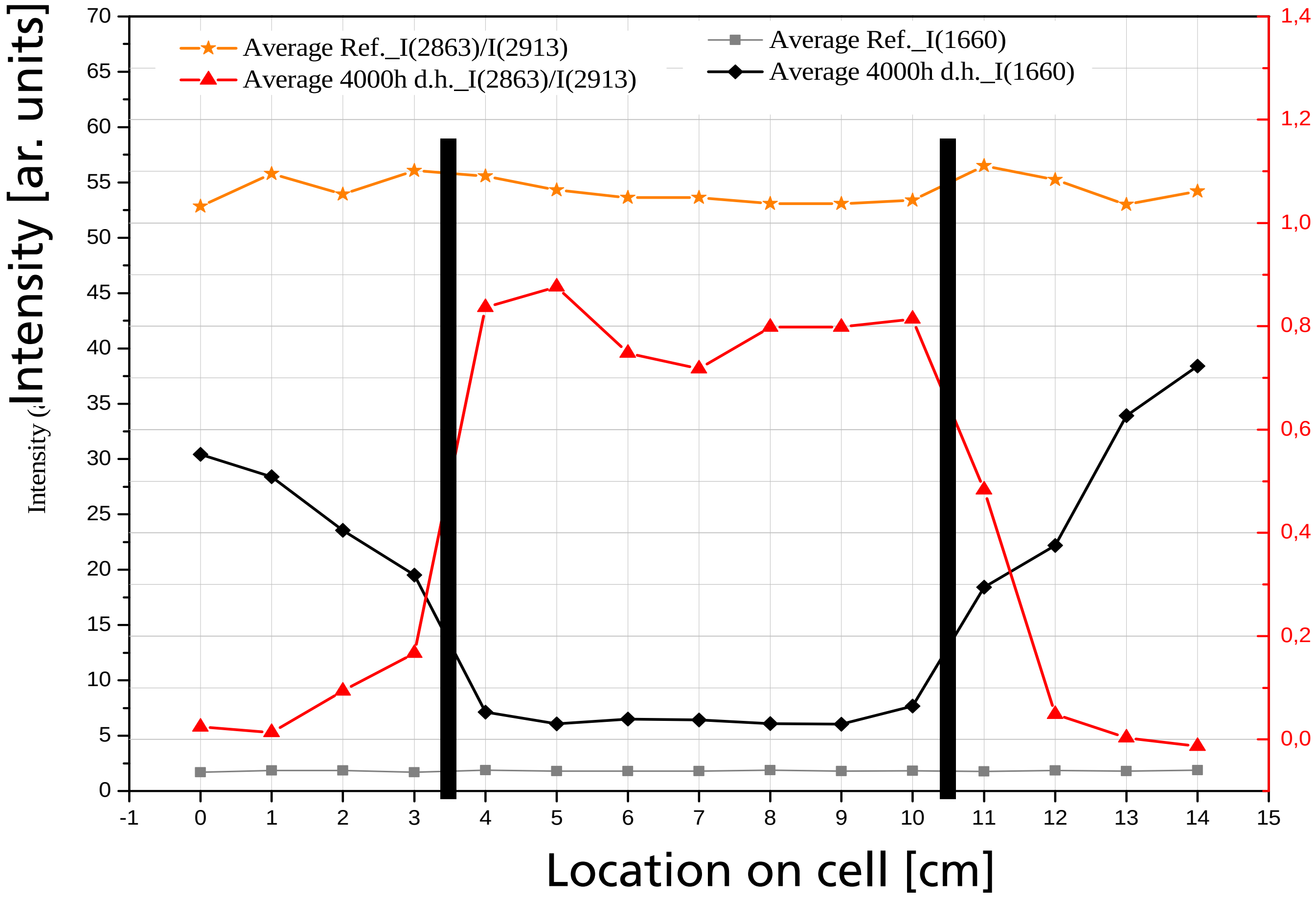
Module 1 would be
suitable for all climates

Module 2 would survive in
the mountains

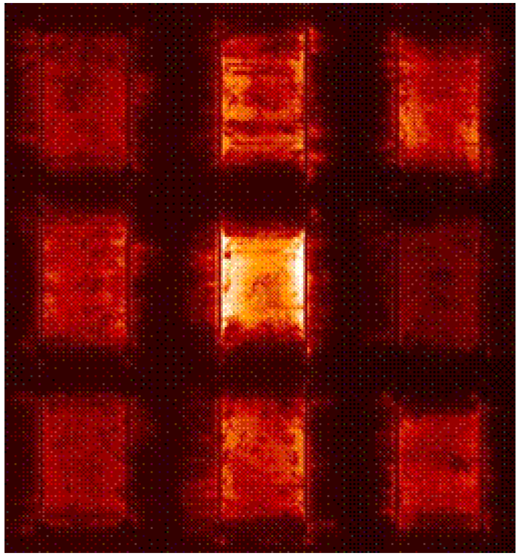
General methodology Step 6: **Analysis of materials degradation**

Polymer Analysis with Raman-Spectroscopy and cell analysis by electroluminescence

Comparison of Vinyl-Band (red) and fluorescence back-ground (black) initial data and after 4000h damp-heat testing



Elektroluminescence-image of degraded cells

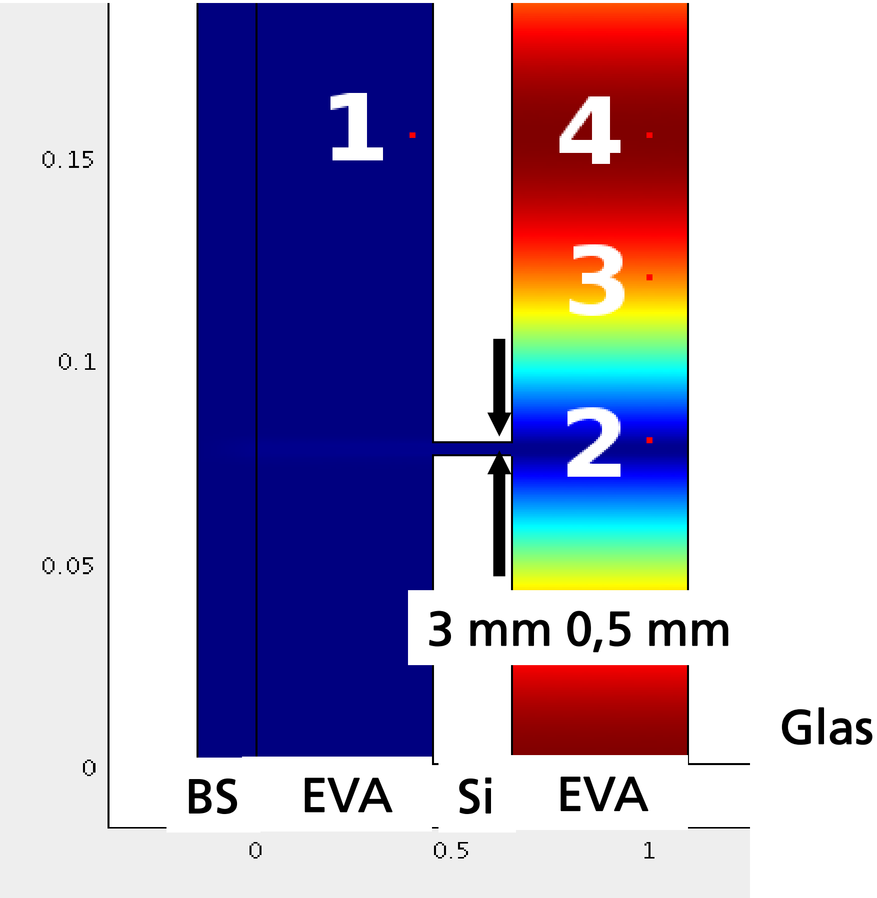


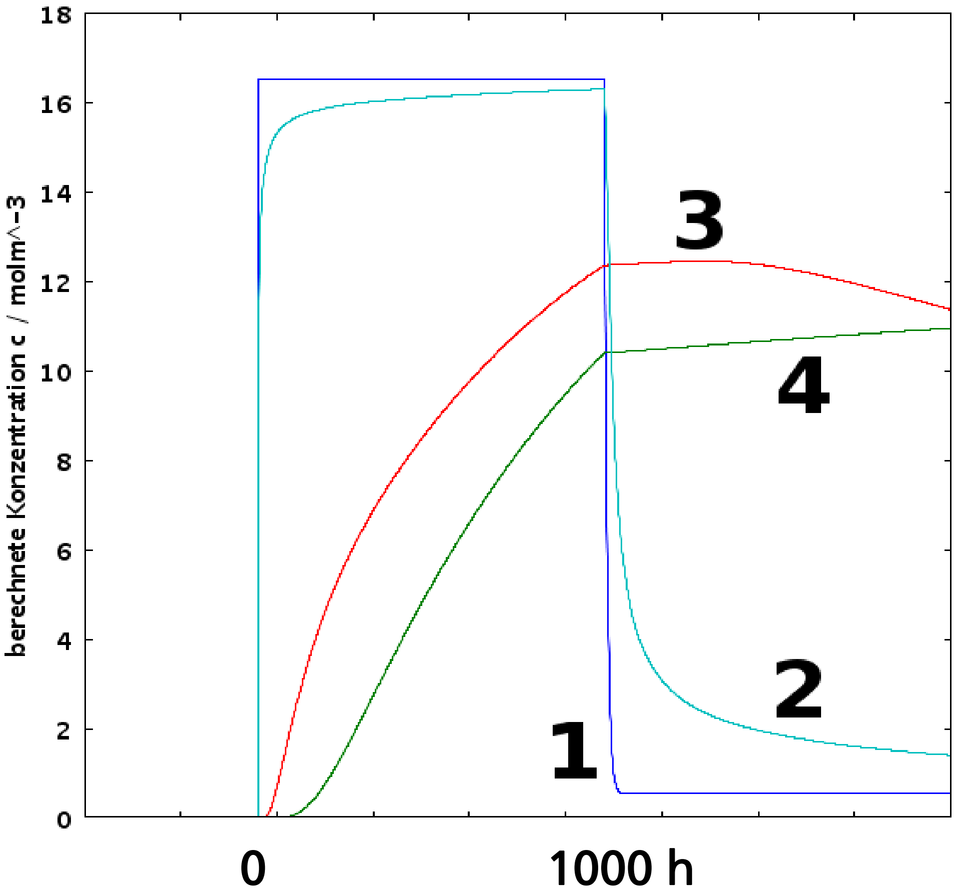
eike et.al.: Non-destructive degradation analysis of encapsulants in PV modules by Raman Spectroscopy, Sol. En. Mat. Sol. Cells (20

General methodology Step 7: **Simulation of materials degradatio**

Numerical simulation of energy and mass transport

Water vapour permeation and -diffusion in the back-sheet and the Encapsulant during damp-heat testing (85%rh @85°C)



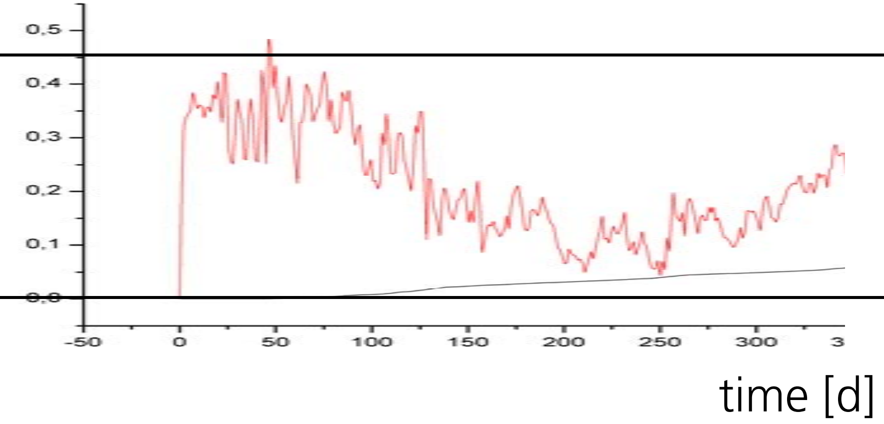


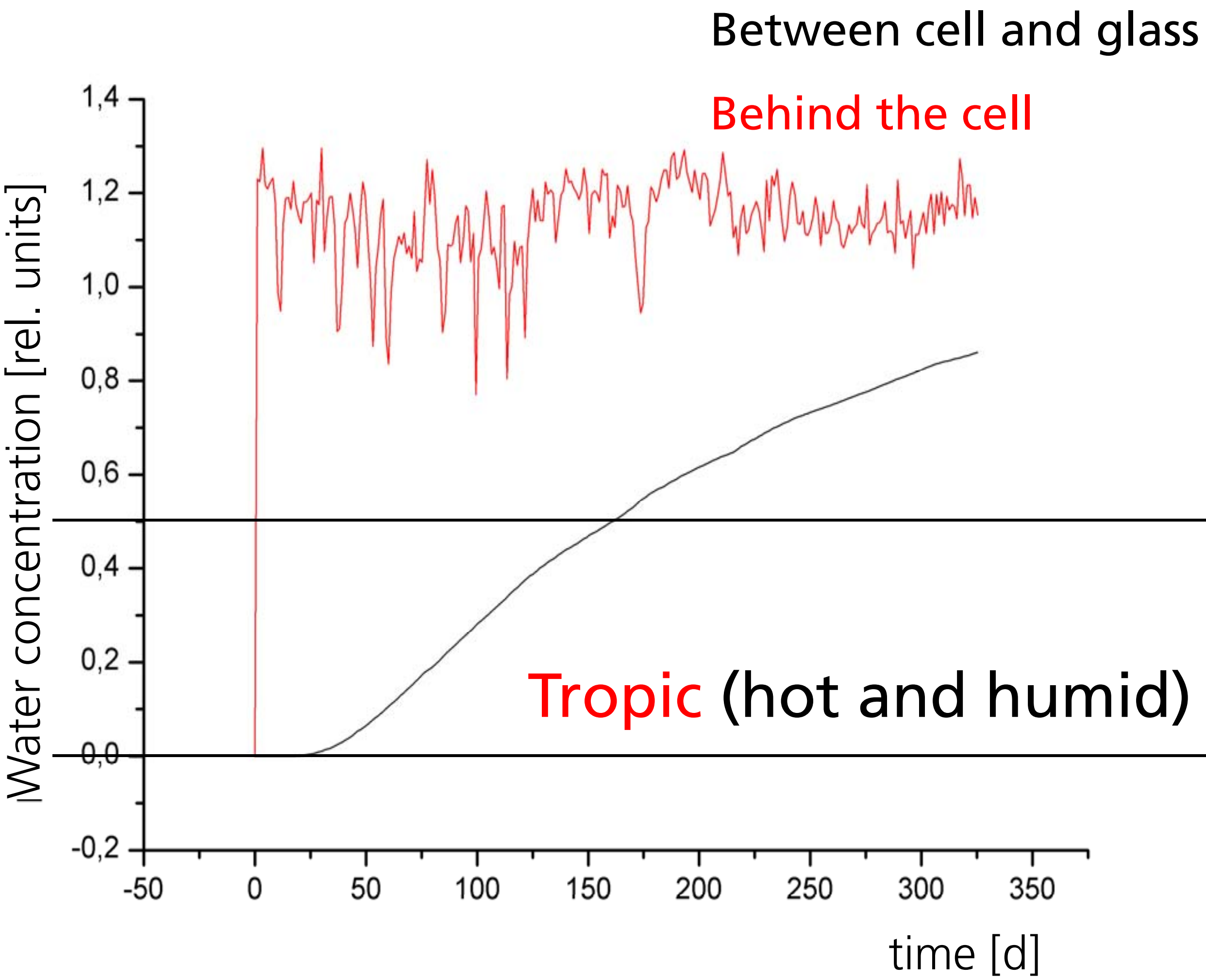
Numerical simulation of energy and mass transport

Water vapour permeation and - diffusion in the Back-sheet and in the Encapsulant during damp-heat testing (85%rh @85°C)

Simulation with real climate data

Alps (cold and dry)





Tropic (hot and humid)

What happens with PV – modules in operation?

Degradation processes are induced or caused by transport phenomena

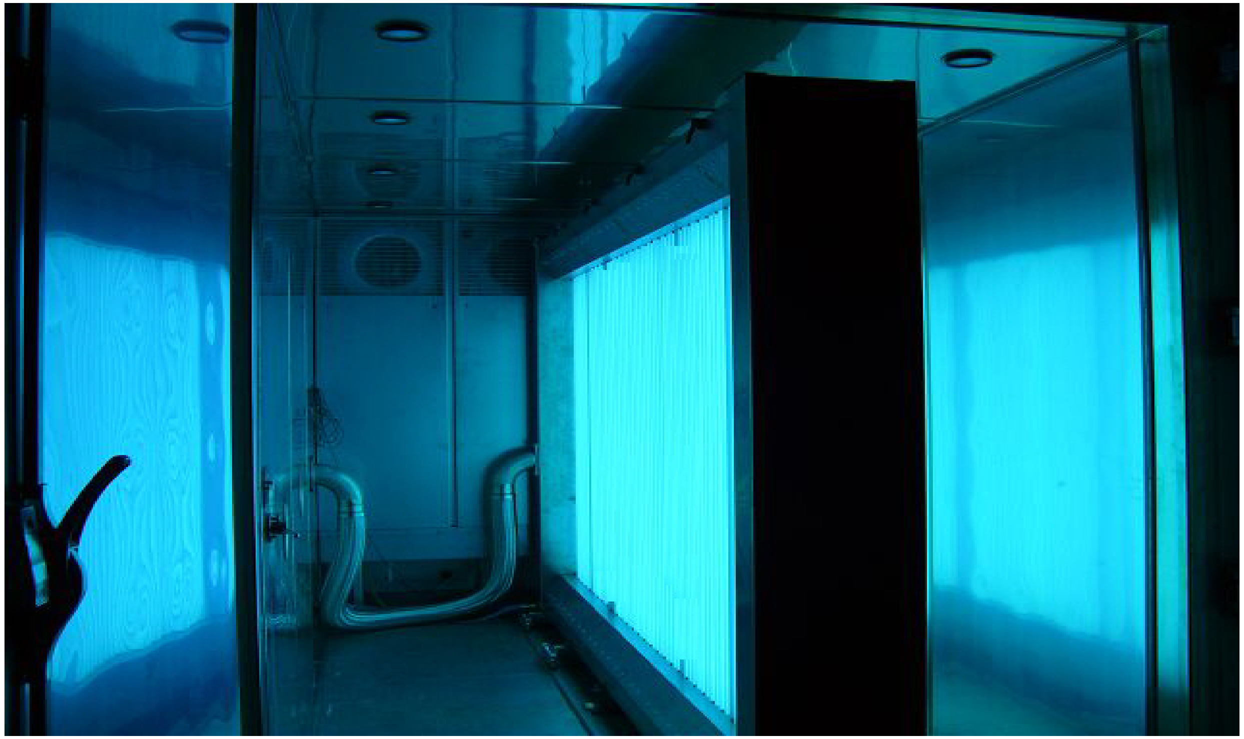
Time constant	energy	mech. tension	charge	mass
about zero	light			
seconds		vibrations		
minutes	heat	thermo-mech		
hours to years			ions	oxygen, water vapo
years				pollutants (salt, etc.

General methodology Step 8: **Service life testing**

Multiple stress testing

200-250 W/m²	0 – 100°C
2*3*1,6m²	0 – 85%rF

UV-source for combined UV and humidity tests



Physical limits of combined testing

- Testing with radiation requires large areas (expensive)
- Concentration is needed for acceleration (4-5 X)
- Highly efficient irradiation sources require lamp cooling
- Water cooling limits the freezing at temperature cycling
- Solar simulator (incl. VIS and NIR) causes heating of the samples
- Cooling of the samples spoils high humidity by condensation at the heat exchanger
- How to integrate mechanical loads

Summary

Modelling the micro-climatic stress conditions

Time-series of climatic data

ambient temperature and humidity, solar irradiation, wind speed

Modeling the module temperatures

ambient temperature, solar irradiation, wind speed, module-specific coefficients (mounting situation might be considered)

Modeling the UV-radiation

5.5% of the solar radiation, module temperature

Modeling the effective surface humidity

ambient temperature and humidity, module temperature

Summary

Modelling the ALT conditions

Use a simple time-transformation function (Arrhenius based, eg)

Time, module temperature and other degradation factors, but separately first

Modeling the module temperature stress

as function of the material-specific activation energy,

(could be eventually included in damp-heat testing)

Modeling the UV-radiation impact

as function of the material-specific activation energy (which is low, UV-dose more importan

Modeling the moisture test

Higher test temperatures needed, as function of the material-specific activation energy,

Single constant stress testing

One test:

Infant mortality, quality lests
type approval testing acc. to IEC or UL

Enhanced stress testing:

Infant mortality, higher quality requirements
offered by a number of test labs

Degradation over time:

Performance, materials or degradation indicator over time
=> Changes of micro-climate (stress) because of material changes
stability beyond infant mortality, induction periods,
stress factor sensitivity

Needed for service life testing:

Performance or degradation indicator over time until failure

Conclusions

Single cyclic stress testing

Temperature cycling:

Thermo-mechanical stress
No scientific base for type approval testing acc. to IEC or UL

Which relaxation time at which temperature?

Temperature cycling with humidity:

Closer to reality, takes into account temperature dependence of water vapour permeation

Voltage cycling or UV-radiation cycling:

Dark periods allow recovery or diffusion of reactants

Needed for service life testing:

Investigation of relaxation times and diffusion processes
Frequency and amplitudes of dynamic mechanical testing

Multiple stress testing

Reasons:

Material changes caused by a degradation process due to stress factor 1 might change the micro-climate from stress factor 2

A combination of stress factors might cause new degradation processes (Photodegradation and hydrolysis, hydrolysis and corrosion)

Problems:

How to design life-tests for cdegradation changed micro-climatic stress?

How to define accelerated life tests with similar acceleration factors for all stress factors taking into account different time constants?

Needed for service life testing:

A big number of unknown factors have to be determined:

$$\Delta P = A\ \Delta t_i\ \exp[-E_A/RT_i] + B\ \Delta t_i\ f(rh)_i \exp[-E_B/RT_i] + C\ \Delta t_i\ I^n_i \exp[-E_C/RT_i] +$$

$$D\ \Delta t_i\ f(\Delta T)_i \exp[-E_D/RTi] + E\ \Delta t_i\ f(P)_i\ f_p(rh)_i \exp[-E_E/RT_i] + F_{pq}\ \Delta t_i\ f(S_p)_i\ f(S_q)_i \exp[-E_{pq}/RT_i]$$

Experimental design for a respective number of tests at different stress levels

Thanks for your attention

To my colleagues

Daniel Philipp
Franz Brucker
Stefan Hoffmann
Philipp Huelsmann
Markus Heck
Stefan Brachmann
Karl-Anders Weiss
Stefan Wiesmeier

To our partners

TÜV Rheinland
Schott Solar
Solarfabrik
Solarwatt
Solarworld
Solon

solar | glass Scheuten SCHOTT solar solar fabrik SOLARWATT SOLARWORLD SOLON AG für Solartechnik Fraunhofer ISE

Workshop on Reliability of PV-Modules

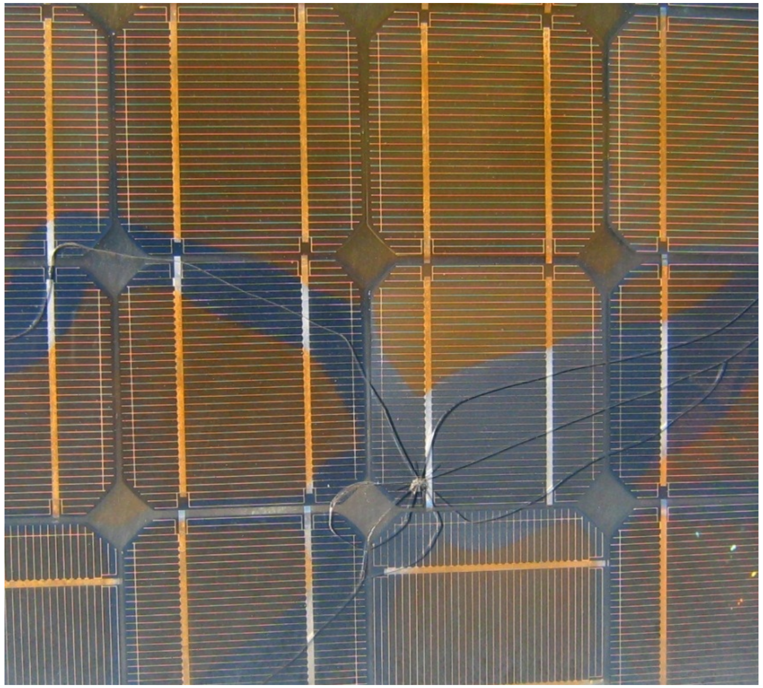
Testing

Analysing

Simulating module - reliabilty

Organised by Fraunhofer ISE and SUPSI

www.supsi.ch/go/pv-module-reliability



Lugano

Switzerland

Mai 3 – 4 2012

Meeting of the IEC TC82 WG2

After the Workshop in Stresa

Structure of the workshop

The topics will be presented by experts and further developed in small discussion groups.

Block I: Mechanics

Block II : PID -Humidity (Potential induced degradation)

Block III : UV –Humidity

Block IV : Failure modes and effects

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Block V: Materials

Plenary discussion with presentation of discussion results

Optional: Visit of the outdoor exposure test site of ISAAC Supsi