Durability of Thin Film Solar Cells

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Empa, Dübendorf

Outdoor measurements and comparison of thin film solar cell technologies

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- Methods for field data evaluation
  - STC power and temperature coefficients
  - Self referencing
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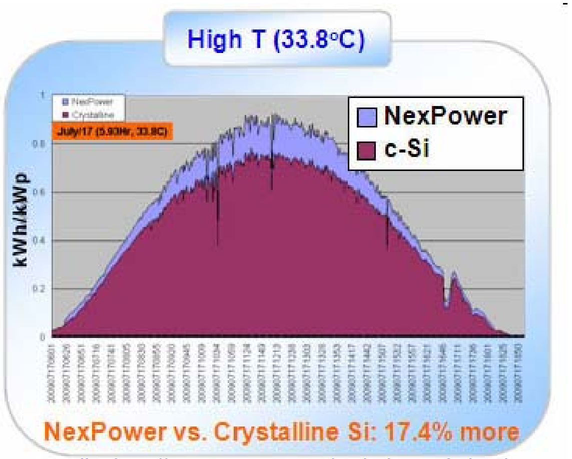
Motivation

Higher uncertainties of module parameters for thin film technologies (CIGS, CdTe, a-Si/µ-Si) compared to c-Si.

Operational parameters, energy yield and long term stability can be determined from outdoor measurements.

More energy from thin film PV – Marketing or reality?



Quelle: http://www.nexpw.com/techology_tfa.html

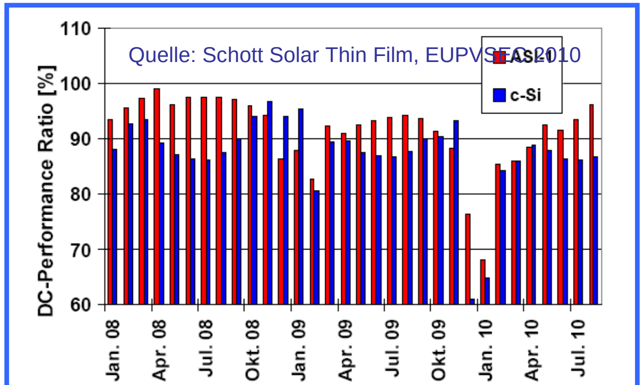
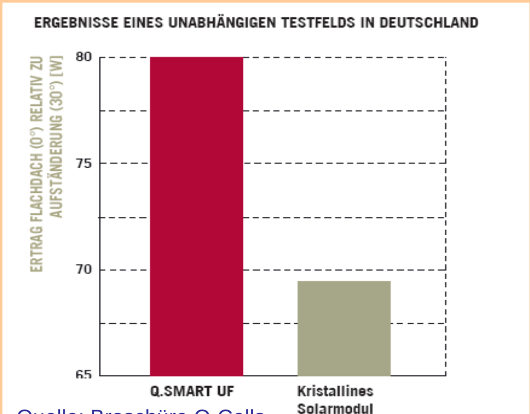


Figure 5: Monthly DC-PR monitoring over 2.5 years of two test PV systems based on ASI and c-Si modules



Quelle: Broschüre Q-Cells

More energy from thin film PV in principle possible by:

- **lower temperature coefficient**
- **good performance under low/diffuse light**
- **annealing or light-soaking effects**

Information from data sheet

ELEKTRISCHE SPEZIFIKATIONEN

Daten gemessen unter Standard-Testbedingungen (STC)*:

PowerMax® STRONG	110	115	120	125	130	135
Nominalleistung P_{nom}	110 W	115 W	120 W	125 W	130 W	135 W
Toleranz der Nominalleistung ΔP_{nom}	-0/+5 %	-0/+5 %	-0/+5 %	-0/+4 %	-0/+4 %	-0/+4 %
Modul-Wirkungsgrad η **	10,3 %	10,7 %	11,2 %	11,7 %	12,1 %	12,6 %
Apertur-Wirkungsgrad η	11,6 %	12,2 %	12,7 %	13,2 %	13,7 %	14,2 %
Leerlaufspannung V_{oc}	56,9 V	57,7 V	58,5 V	59,3 V	60,2 V	61,1 V
Kurzschlussstrom I_{sc}	3,19 A	3,20 A	3,21 A	3,22 A	3,23 A	3,24 A
Spannung im mpp V_{mpp}	40,4 V	41,6 V	42,8 V	44,0 V	45,3 V	46,6 V
Stromstärke im mpp I_{mpp}	2,72 A	2,76 A	2,80 A	2,84 A	2,87 A	2,90 A
Rückstrombelastbarkeit I_r	5,0 A	5,0 A	5,0 A	5,0 A	5,0 A	5,0 A
Max. Systemspannung V_{sys} (IEC)	1000 V	1000 V	1000 V	1000 V	1000 V	1000 V
Max. Systemspannung V_{sys} (UL)	600 V	600 V	600 V	600 V	600 V	600 V

* Bestrahlungsstärke 1000 W/m² in der Modulebene, Modultemperatur 25 °C und eine Spektralverteilung der Bestrahlung gemäß der atmosphärischen Masse (AM) 1,5.

** Ausschl. Montagerand.

Daten gemessen bei Zellen-Nennbetriebstemperatur (NOCT)* und AM 1,5:

PowerMax® STRONG	110	115	120	125	130	135
NOCT	40,0 °C	40,0 °C	40,0 °C	40,0 °C	40,0 °C	40,0 °C
Nominalleistung P_{nom}	82,0 W	85,8 W	89,5 W	93,2 W	96,9 W	100,7 W
Leerlaufspannung V_{oc}	53,3 V	54,0 V	54,8 V	55,6 V	56,5 V	57,4 V
Kurzschlussstrom I_{sc}	2,51 A	2,51 A	2,51 A	2,51 A	2,51 A	2,51 A
Spannung im mpp V_{mpp}	37,5 V	38,7 V	39,9 V	41,1 V	42,3 V	43,6 V

* NOCT: Modulbetriebstemperatur bei 800 W/m² Bestrahlungsstärke in der Modulebene, Lufttemperatur 20 °C, Windgeschwindigkeit 1 m/s und Leerlaufzustand.

Temperatur-Koeffizienten:

PowerMax® STRONG	Wert
Temperatur-Koeffizient P_{nom}	-0,39 %/°C
Temperatur-Koeffizient V_{oc}	-170 mV/°C
Temperatur-Koeffizient I_{sc}	0,10 mA/°C
Temperatur-Koeffizient V_{mpp}	-140 mV/°C

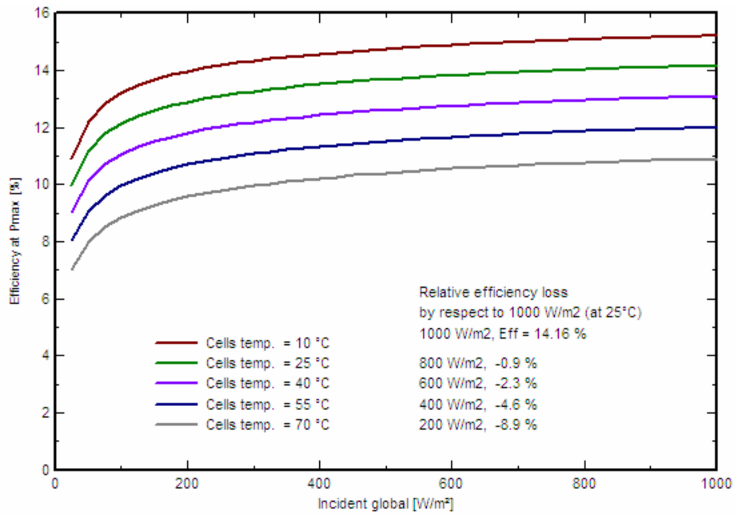
Daten gemessen bei geringer Strahlungsintensität:

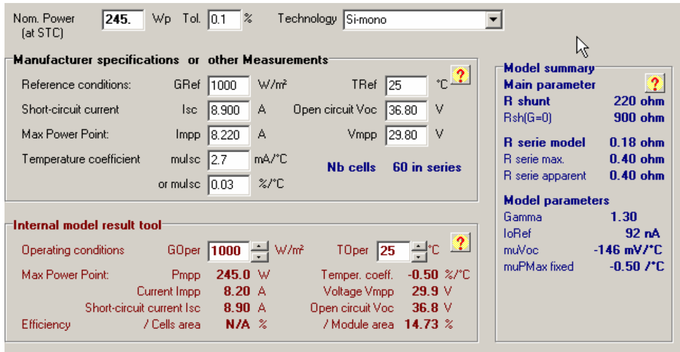
Die relative Verringerung des Modulwirkungsgrads bei einer Strahlungsintensität von 200 W/m², bezogen auf 1000 W/m² bei 25 °C Modultemperatur und Spektrum AM 1,5, beträgt 10 %. Bei 500 W/m² beträgt die relative Verringerung des Modulwirkungsgrads 1 %.

- STC power/tolerance
- Temperature coeff.
- Dependence on irradiance

Source: http://www.avancis.de/fileadmin/media/portal/produkt/Datenblatt_PowerMax-STRONG.pdf

Information from simulation programs





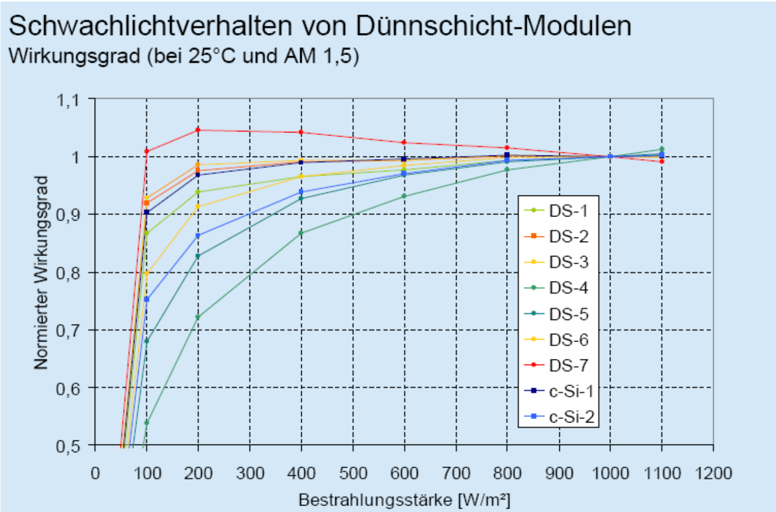
Source: PVSYST

Data for

- **STC power/efficiency**
- **Temperature coefficients**
- **Dependence on irradiance**

Where are these data from??

Information from simulator measurements



Quelle: TÜV Rheinland

Measurement according to IEC 61853 (PV Module Performance Testing and Energy Rating):

- **Irradiance 100, 200, 400, 600, 800, 1000, 1100 W/m²**
- **Temperature 15, 25, 50, 75 °C**

Restrictions for thin film flasher measurements:

- **Metastability effects**
- **Crystalline Si reference cells**
- **Current mismatch for tandem cells**
- **Transient effects**

Results from outdoor module characterization

- **<u>STC power</u>:**
  - data collection days to weeks
  - spectrum dependent on location and season
  - stability presupposed

- **<u>Energy generation</u>, Performance Ratio (PR):**
  - typically 1 year
  - comparison of different technologies (benchmark c-Si)
  - valid for selected site

- **<u>Parameter determination</u>:**
  - typically 1 year
  - power, Voc, Isc,.. under STC
  - temperature coefficients, operation temperature
  - dependence on irradiance, incidence angle, spectrum

- **<u>Long term stability</u>**
  - several years

Energy and Performance Ratio

- **Energy Yield:**

$$Y = E_{counter} / P_{nom} \qquad (kWh/kWp)$$

- **Performance Ratio (PR)**

$$PR = Y / E_{POA} \qquad (\%)$$

- **Which P_{nom} ? Label? Flasher or outdoor measurement?**
- **Measured irradiation in module plane (E_{POA}) depends on sensor**

Outdoor measurements at ZSW

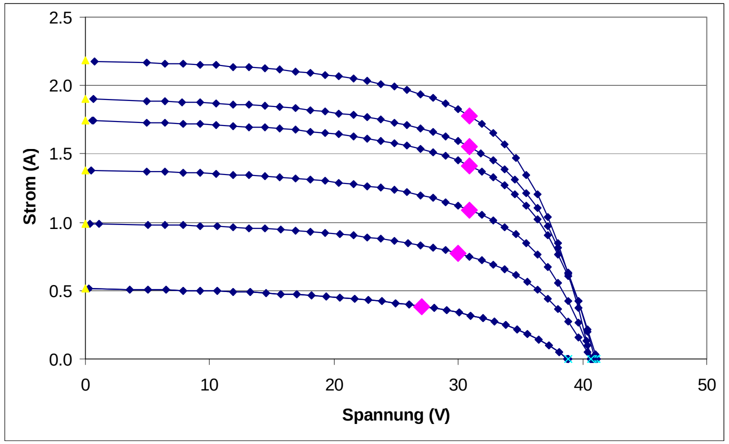
- Widderstall (since 1988)
- Girona/Spain (since 2011)

- Module measurements
  - module kept at MPP
  - I-V characteristics (1 per minute)
  - Tmod
  - Pyranometer and c-Si ref. cell
  - Ta, GHI, DHI, DNI, TNI, v_{wind}

- Generator measurements
  - 1kW, identical inverters
  - DC, AC voltage and current
  - Tmod, POA irradiance

- PID-test stand

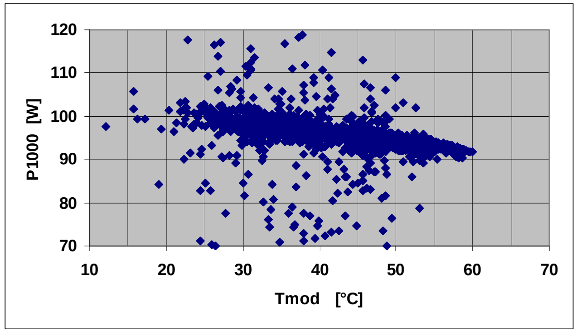
Outdoor measurements at ZSW

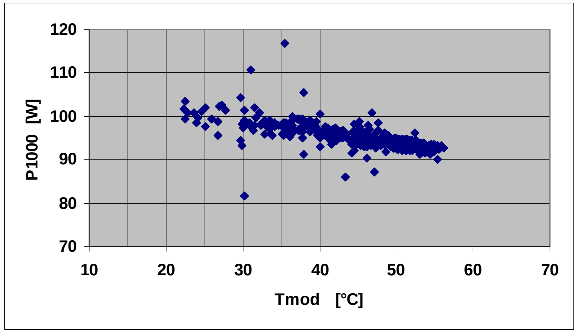


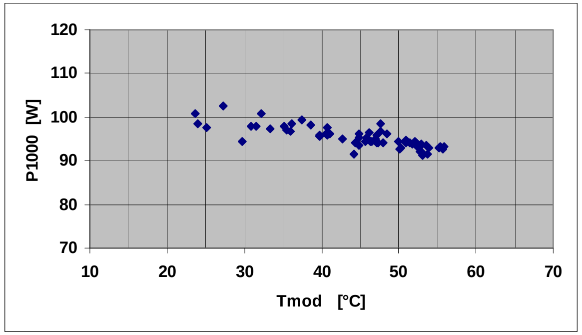
Module I-V characteristics

Power and temperature coefficient:
(1) Selection of irradiance interval

Calculation of P1000 (linear scaling with reference irradiance)







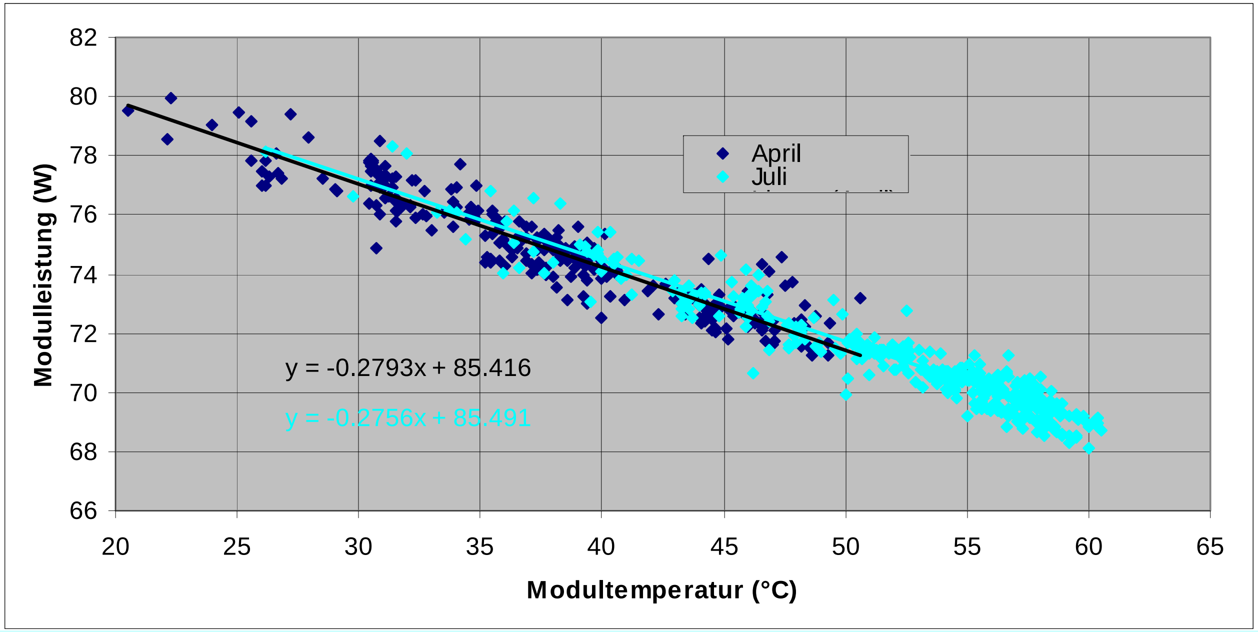
Data collection September, Widderstall, Si-TF module

1000 W/m² +/- 10%	1000 W/m² +/- 2%	1000 W/m² +/- 0,2%
2854 Data points	492 Data points	74 Data points

Reasonable range:

- **Irradiance interval +/-1 to 2 %**
- **some 100 to 1000 data points**

Power and temperature coefficient:
(2) Different measurement periods



Measurement months April and July, Widderstall, CIGS module

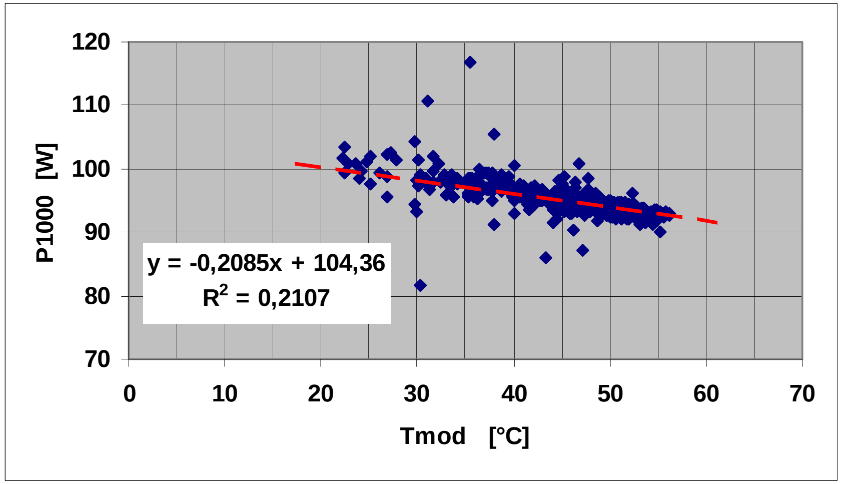
- **Higher module temperature in July**
- **No change of STC module power**

Power and temperature coefficient:
(3) Evaluation

P1000 vs. Tmod

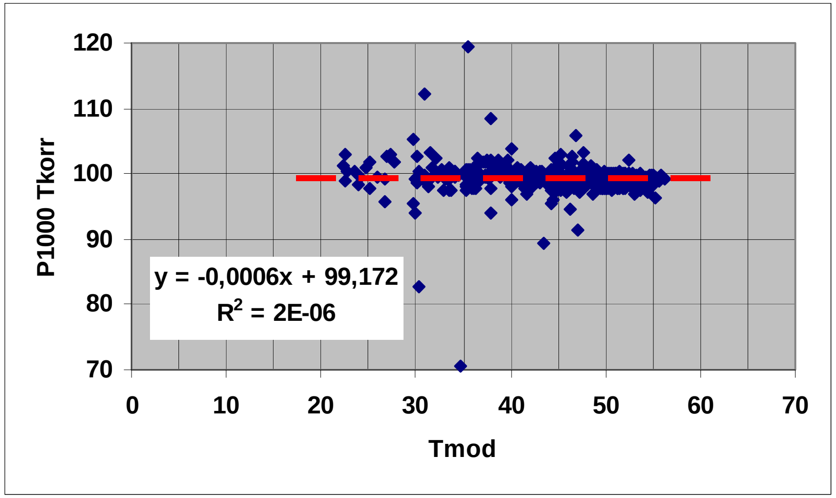
- Determination of Tcoeff. from slope (-0,21 %/K)

  Moderate degree of correlation



P1000 T-corr. vs. Tmod

- STC power 99,2 W

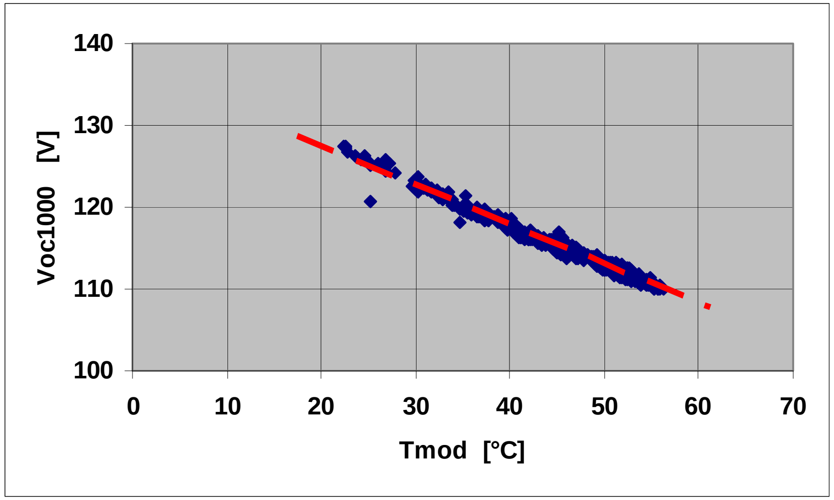


- Deviation by time constants of
  - pyranometer
  - module back temperature

Power and temperature coefficient :
(4) Improvement of accuracy

Voc1000 vs. Tmod

- **Determination of STC-Voc**
- **Determination Tcoeff Voc**
- **Correction of Tmod using Voc1000 → Teff**

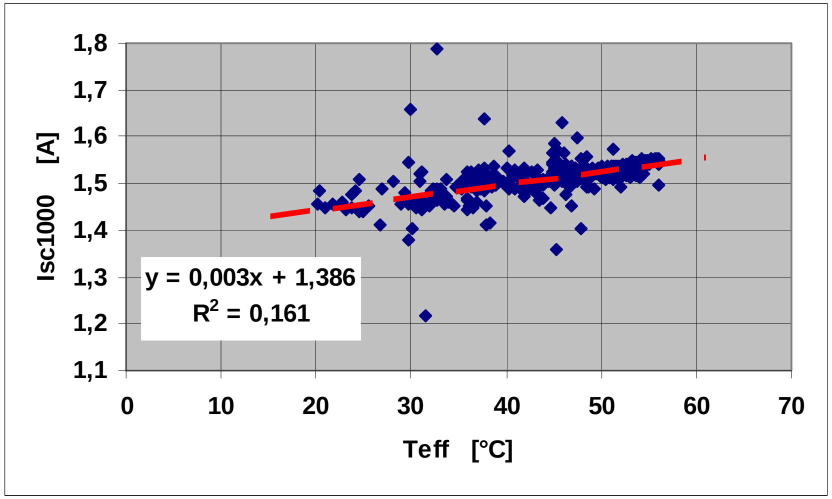


Isc1000 vs. Teff

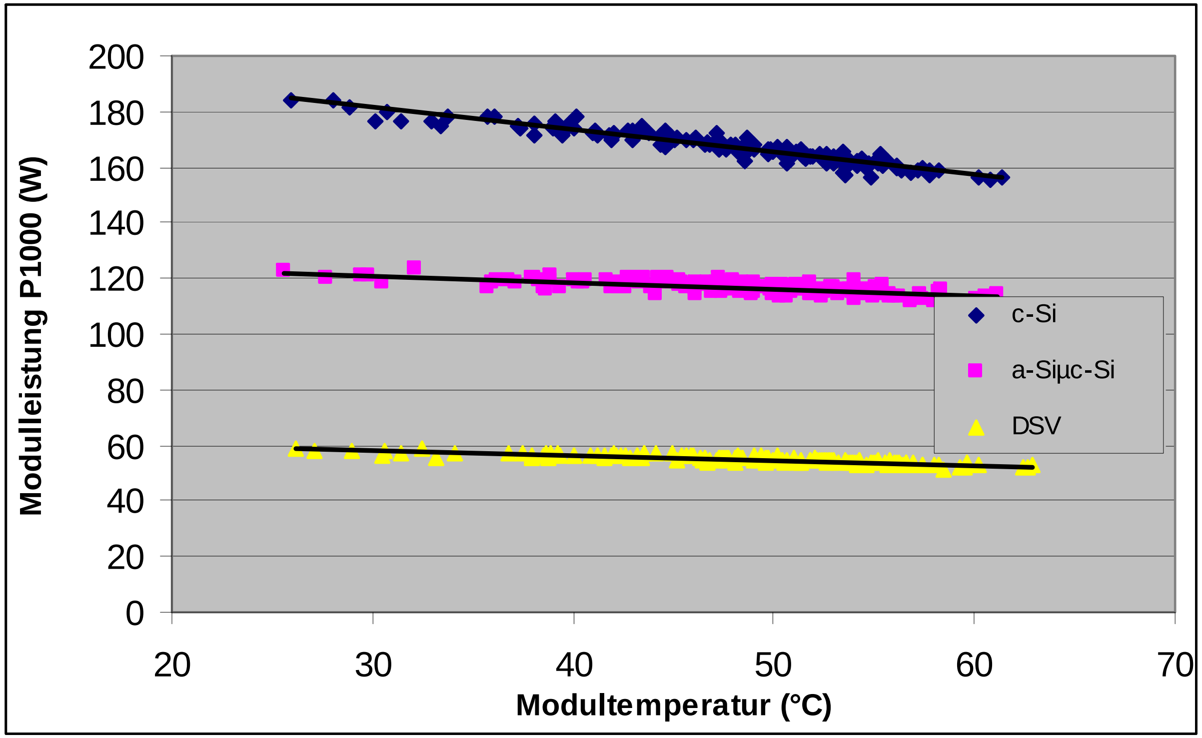
- **Determination of Isc@STC**
- **Definition: Eeff = Isc/ Isc@STC**

Module used as irradiance sensor

=> "Self referencing"



Power and temperature coefficient :
Example c-Si, a-Si/µc-Si, CdTe



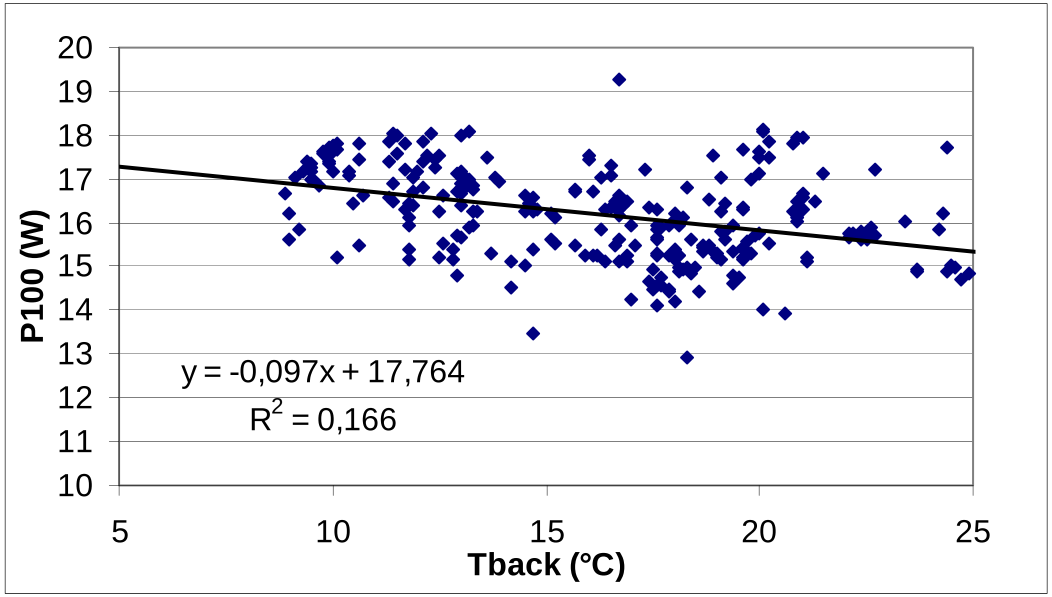
	c-Si	a-Si/µc-Si	CdTe
Pmpp @ 25 °C (W)	185.2	122.4	59.1
Tk Pmpp (%/K)	-0.42	-0.2	-0.29

Parameter determination under low irradiance

June 2011, irradiance interval (Pyranometer) (98…102) W/m²

Linear Correction of measured power to100 W/m²

Plot vs. back temperature



Spectral- and incidance angle influences

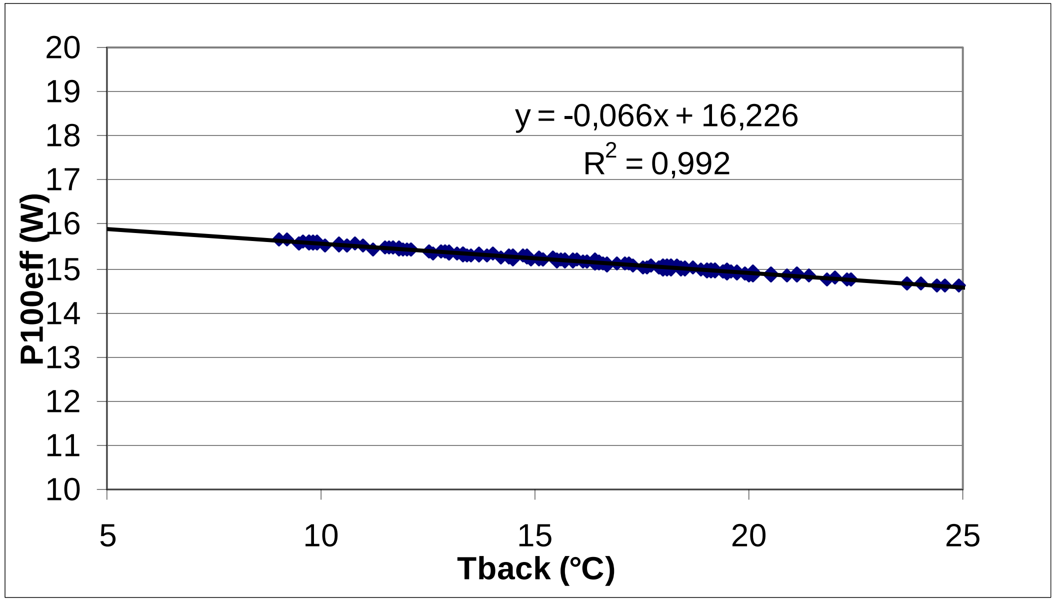
→No accurate evaluation possible!

Parameter determination under low irradiance

June 2011, Self referencing Eeff = (0.098…0.102) suns

Linear Correction of measured power to 0.1 suns

Plot vs. back temperature

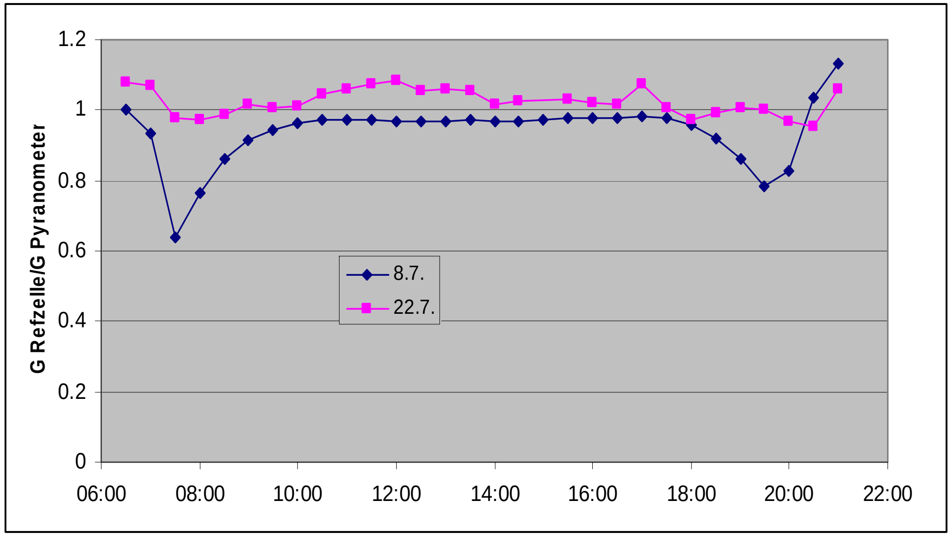


Accurate evaluation possible! → low irradiance degradation

Self referencing of irradiance

ZSW Testfeld WIdderstall

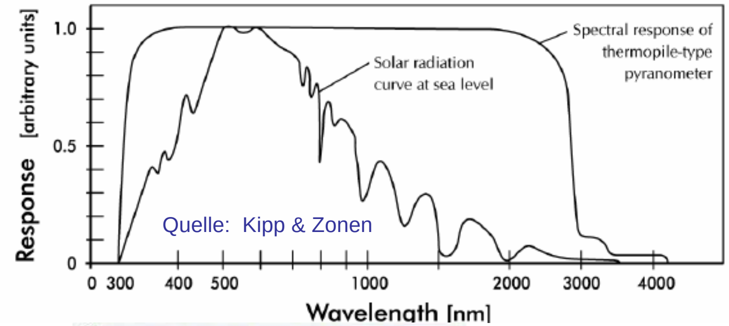
Reference cell or pyranometer?

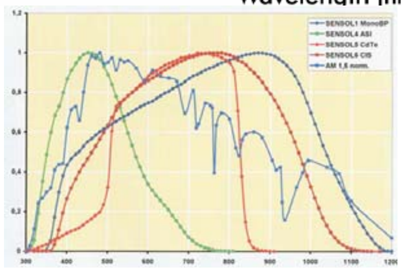


Ratio of c-Si sensor to pyranometer sunny (8.7.) und cloudy (22.7.) day

- **Moderate deviation under direct irradiation around noon time and under diffuse light**
- **strong deviation under direct light morning/evening (incidence angle, spectrum)**

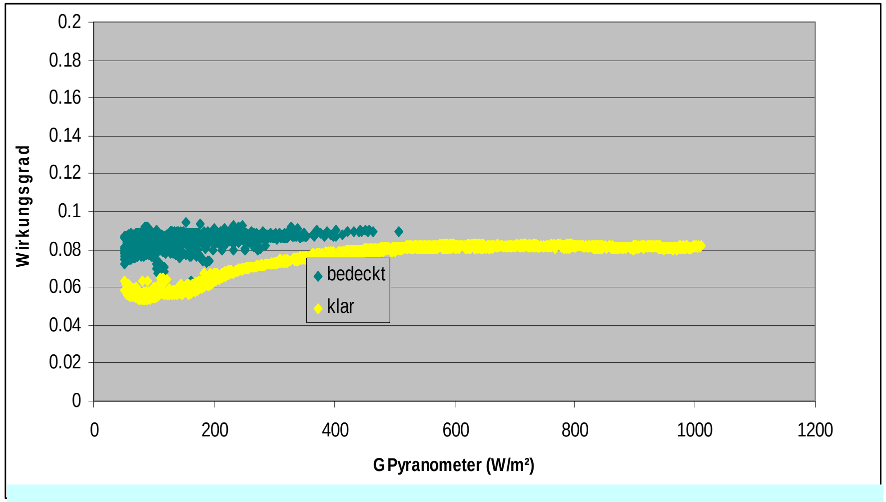
Pyranometer



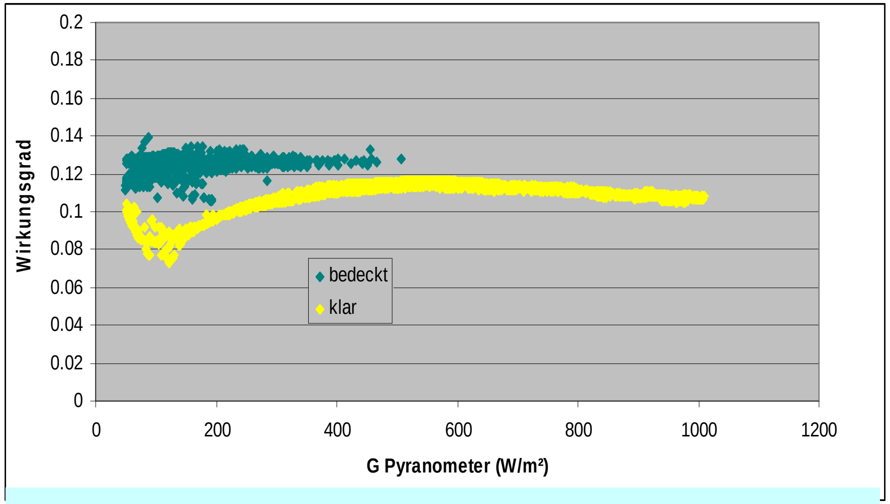


ISET Sensors

Efficiency vs. pyranometer irradiance



a-Si/µc-Si: Efficiency vs. G



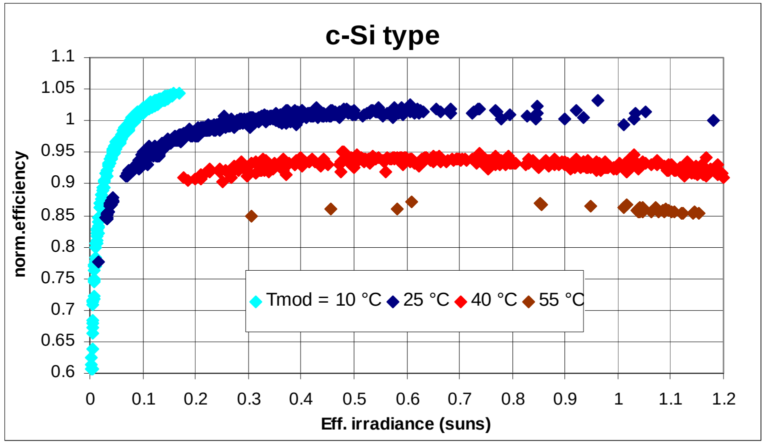
c-Si: Efficiency vs. G

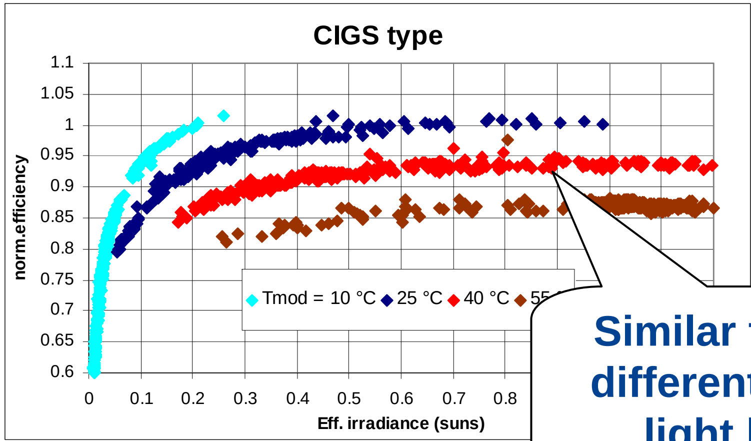
Data are as measured:

- **Cloudy day:**
  high efficiency
- **Sunny day:**
  strong influence of spectrum and incidence angle morning/evening
  Temperature influence at noon
- **NO UNIQUE FUNCTION!**

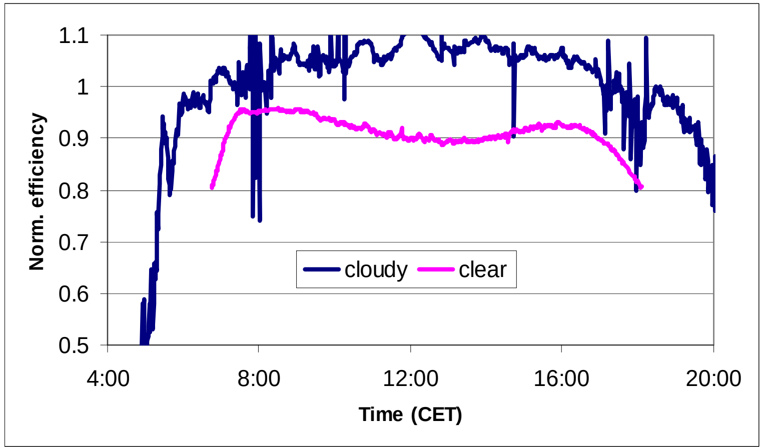
Efficieny vs. effective irradiance (1)

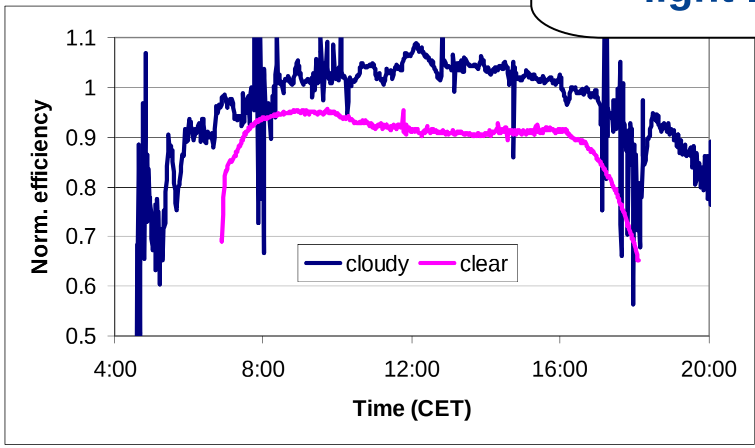
Normalized efficiency vs. effective irradiance with parameter Tmod (top) and daily profile cloudy/clear (bottom)





Similar to c-Si, different at low light level

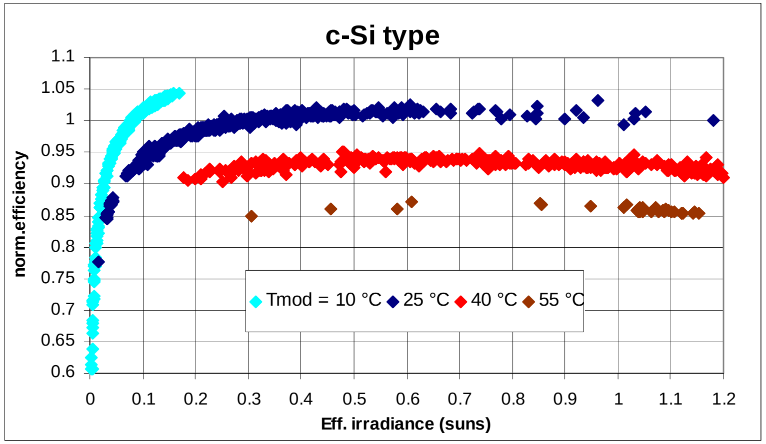


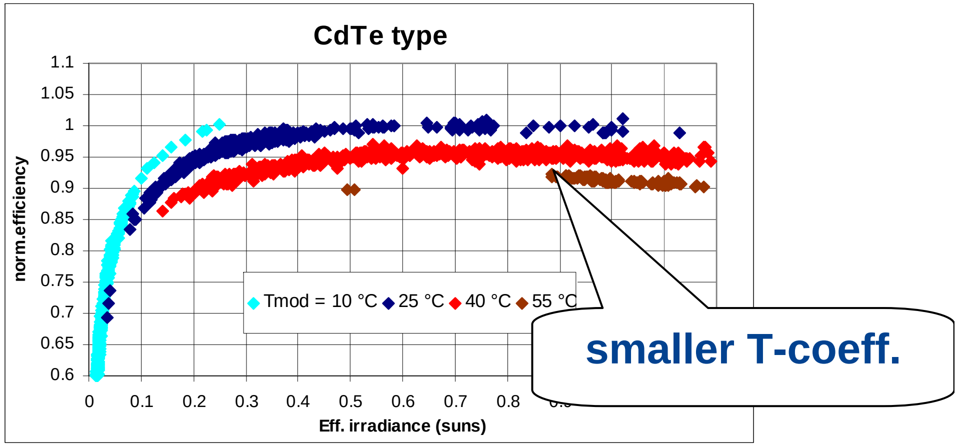


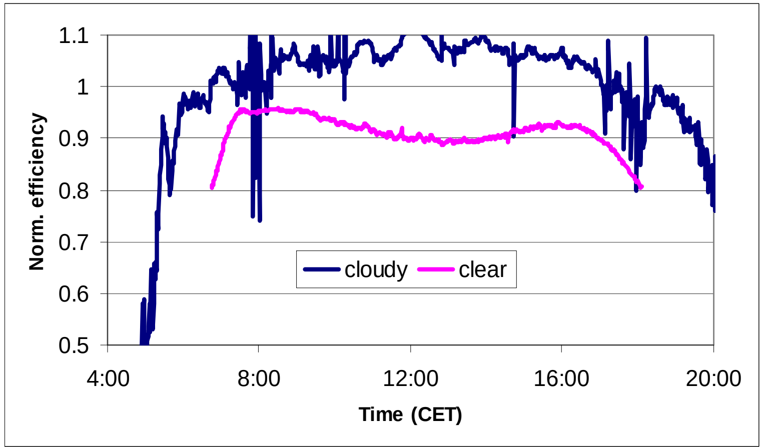
c-Si **CIGS**

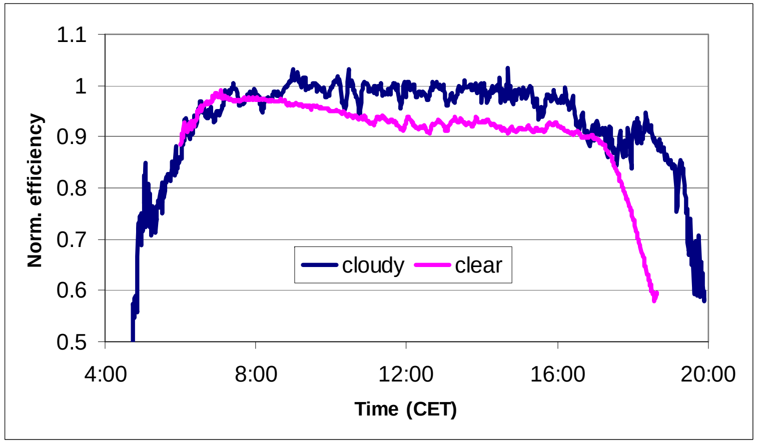
Efficieny vs. effective irradiance (2)

Normalized efficiency vs. effective irradiance and daily profile cloudy/clear







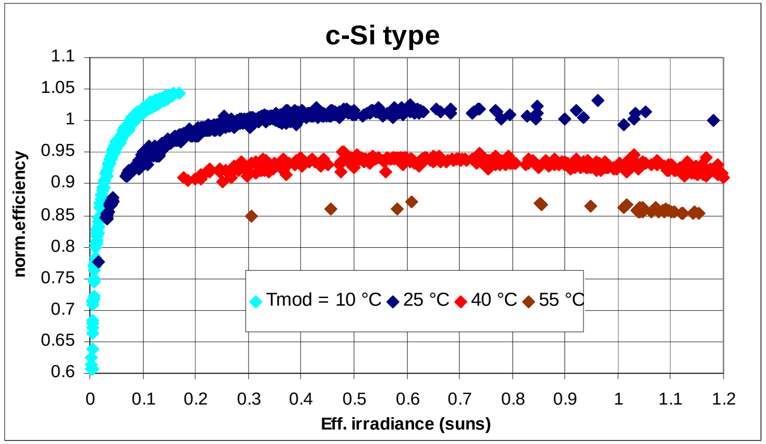


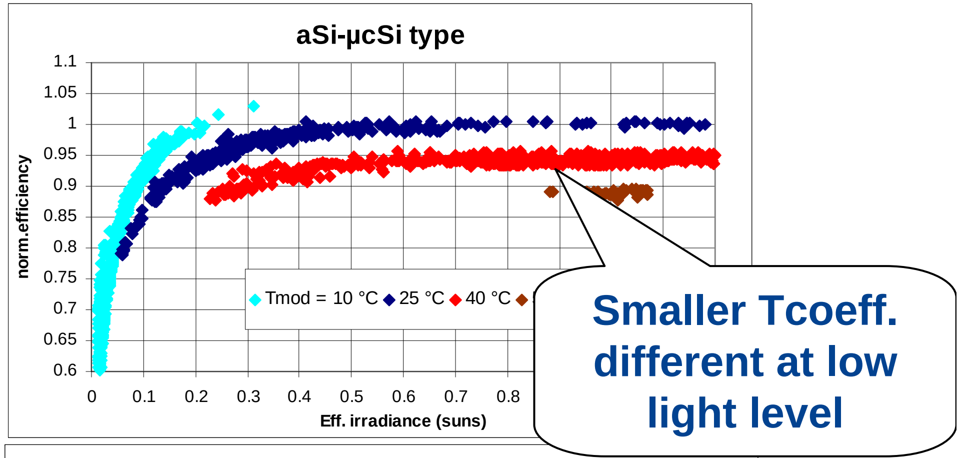
c-Si

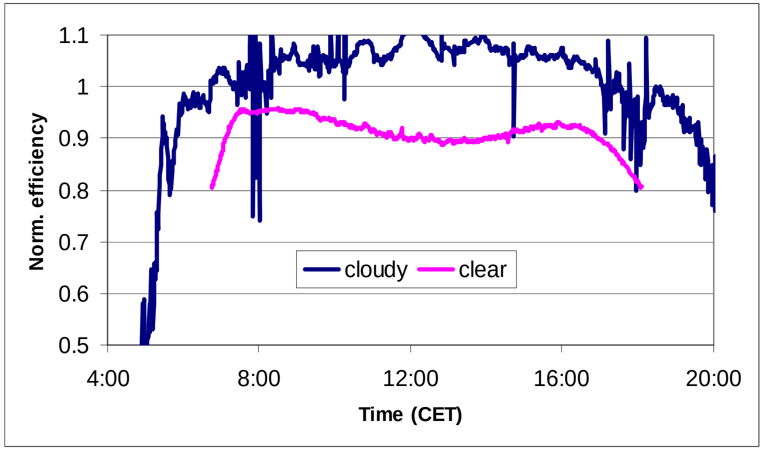
CdTe

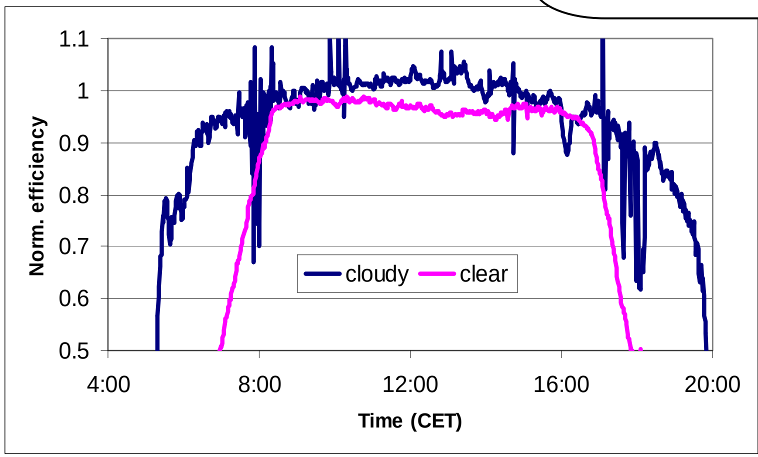
Efficieny vs. effective irradiance (3)

Normalized efficiency vs. effective irradiance and daily profile cloudy/clear







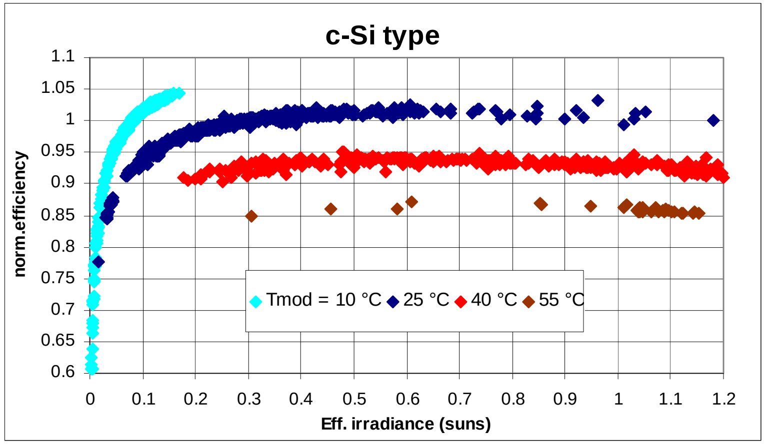


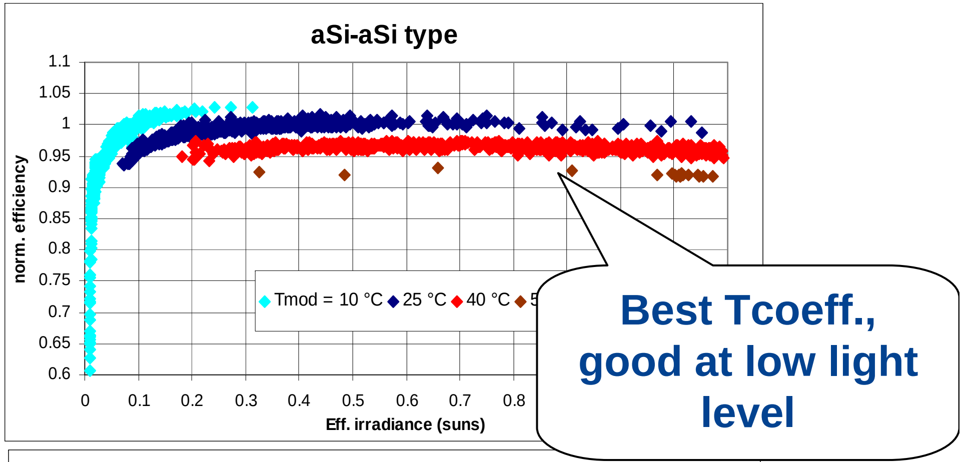
c-Si

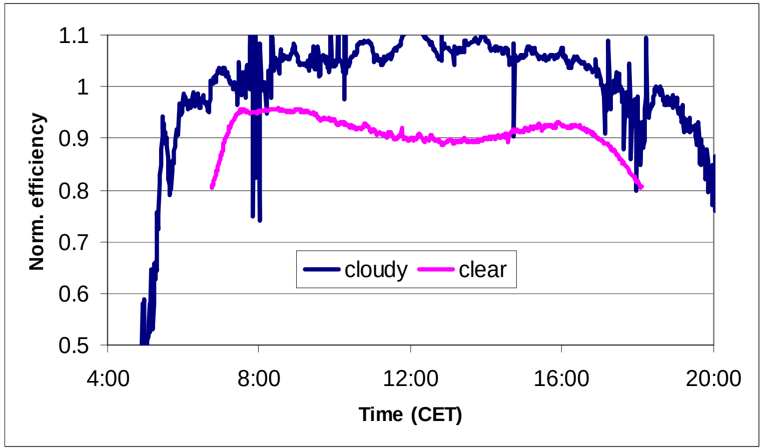
a-Si/µc-Si

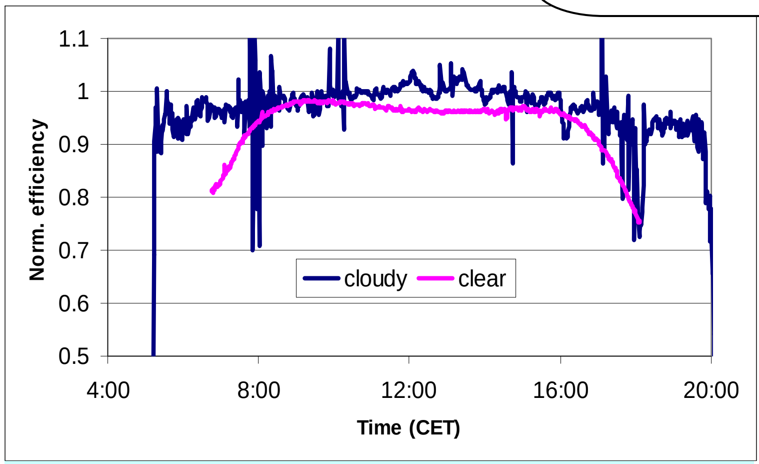
Efficieny v s. effective irradiance(4)

Normalized efficiency vs. effective irradiance and daily profile cloudy/clear









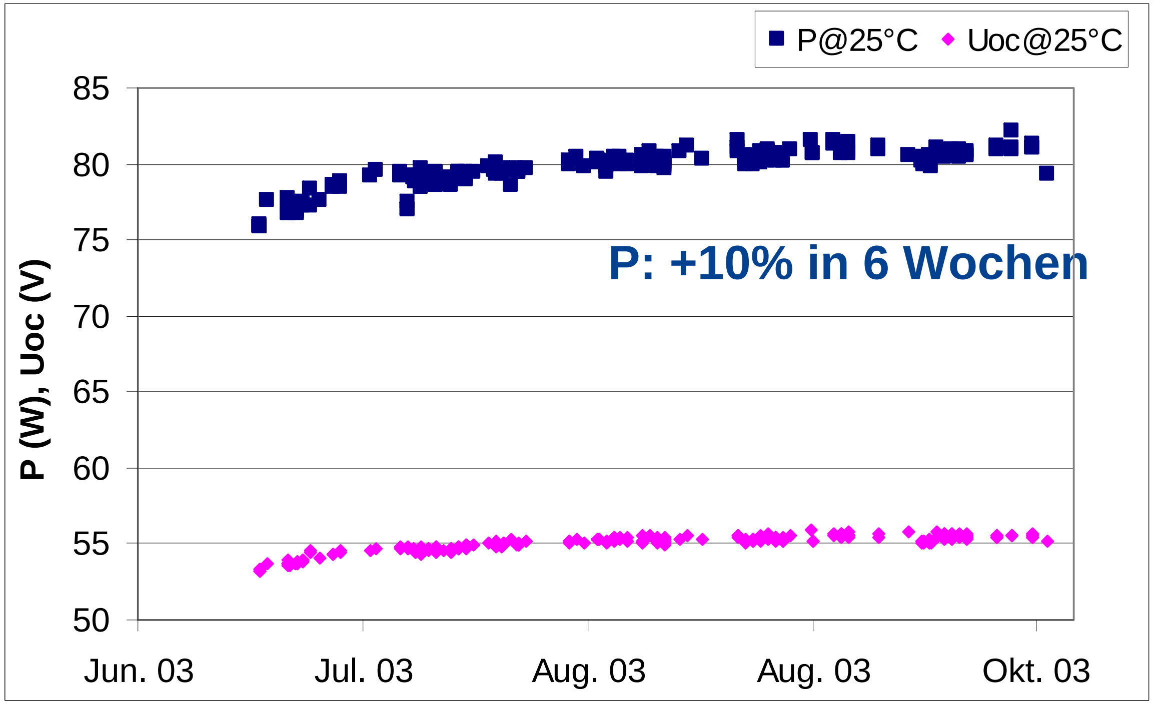
c-Si

a-Si/a-Si

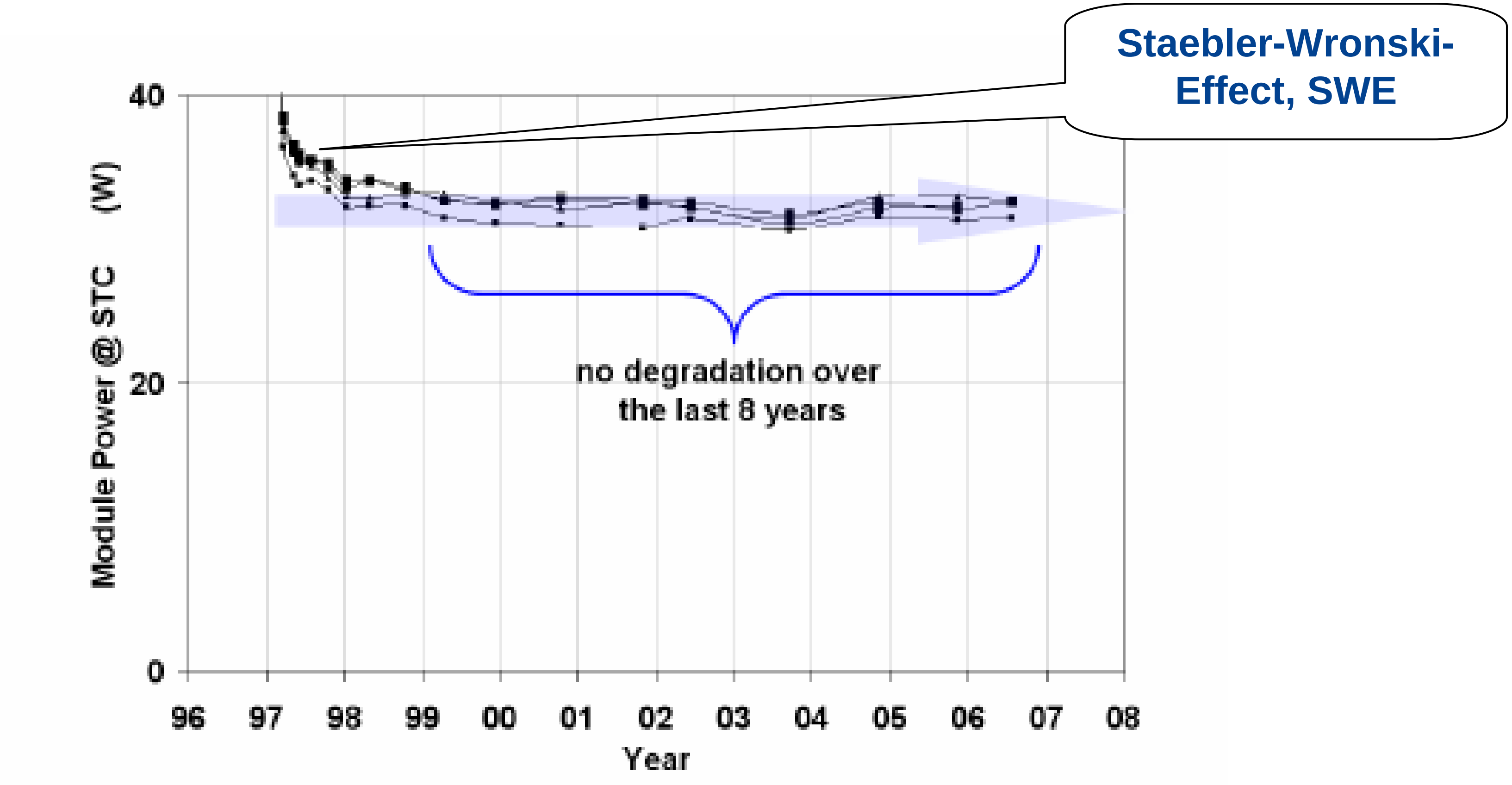
Long term stability

ZSW Test Field WIdderstall

Initial Light-Soaking of CIGS Module

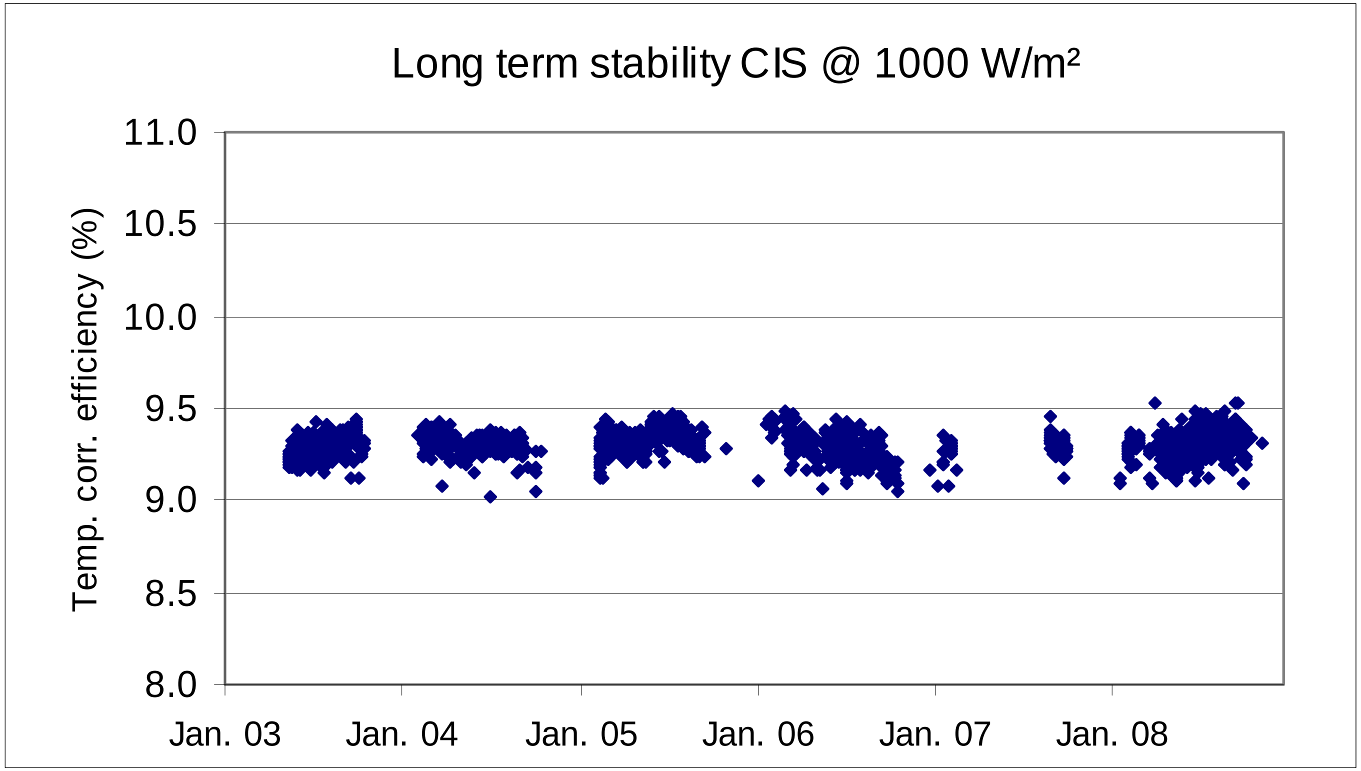


Initial degradation of a-Si/a-Si Modul



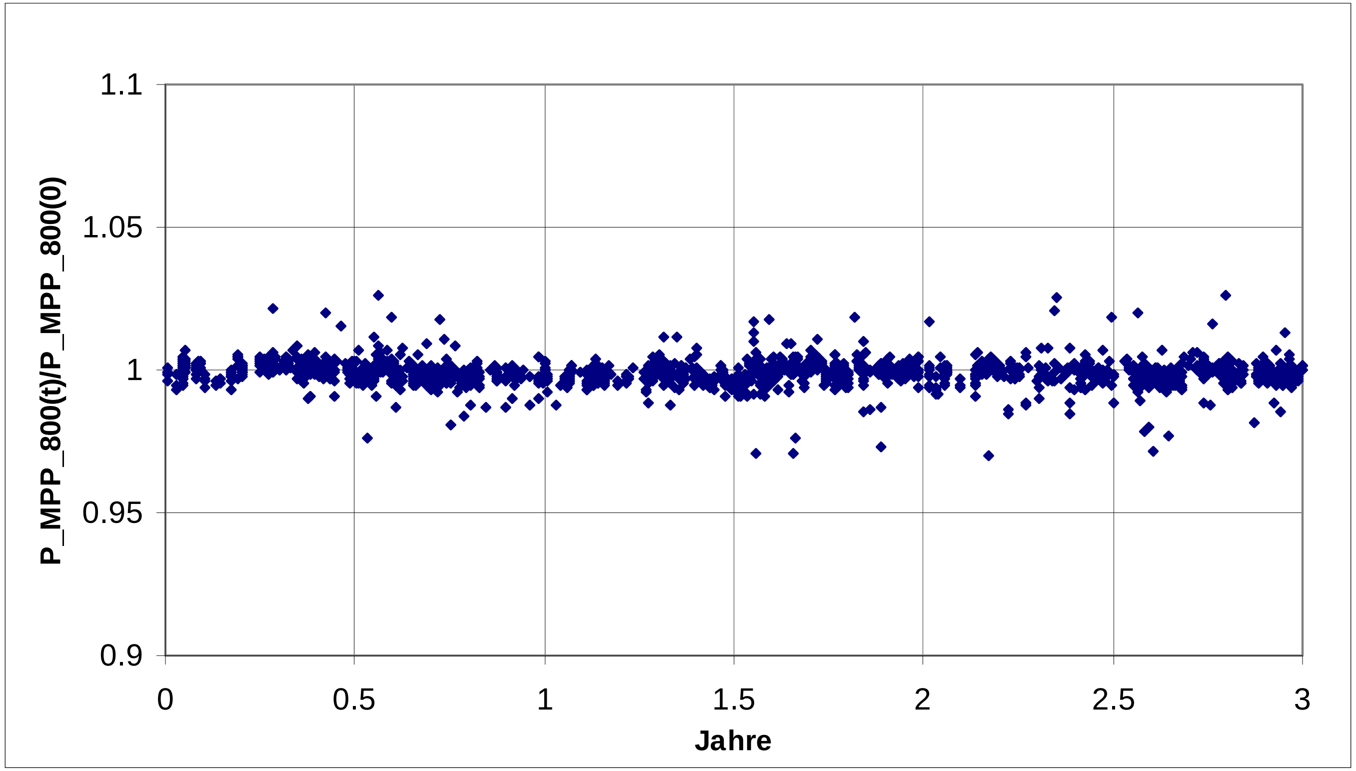
Source: Schott Solar, 21st EU PVSC

Long term stability of CIGS Module



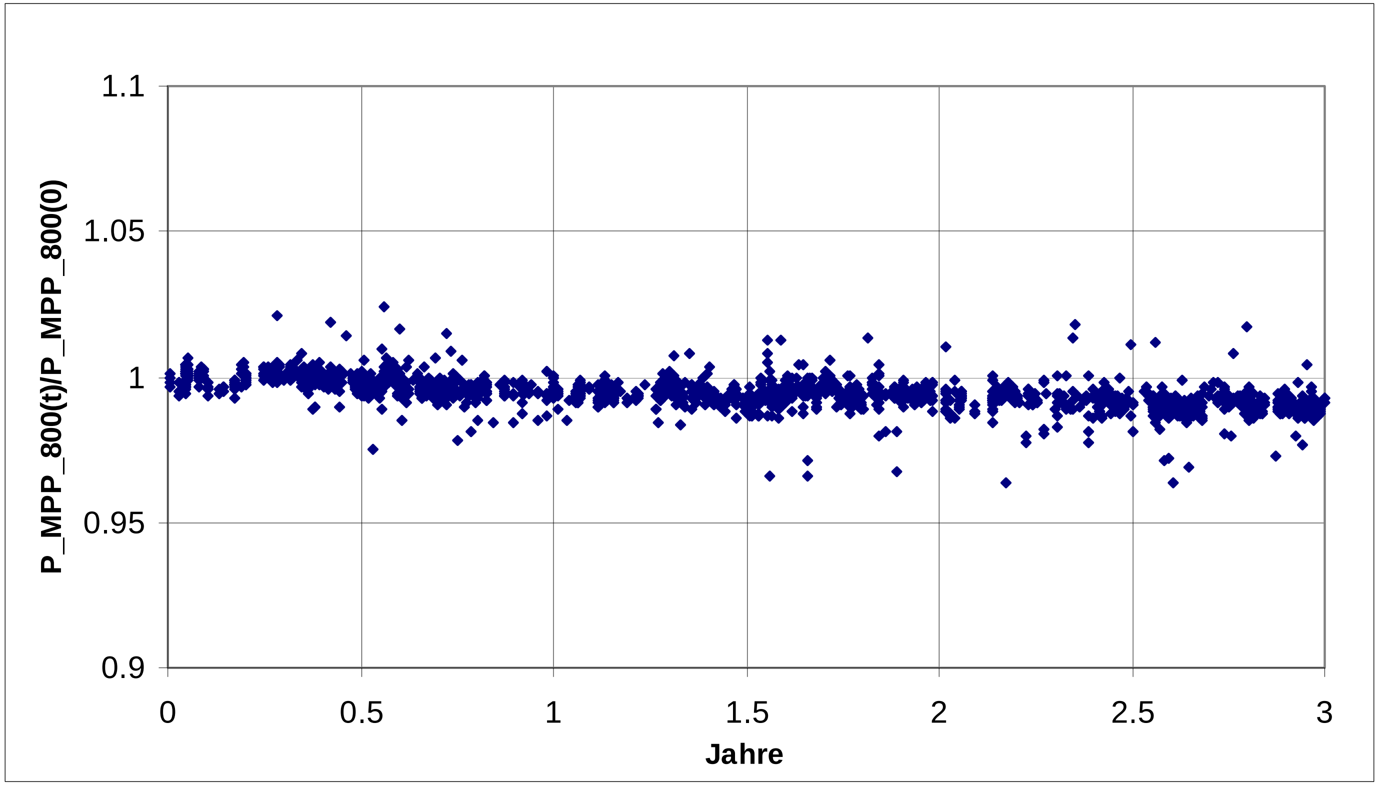
Measurement close to AM1.5 and normal incidence, then temperature correction

Long term stability of CIGS Module @ 800 W/m²



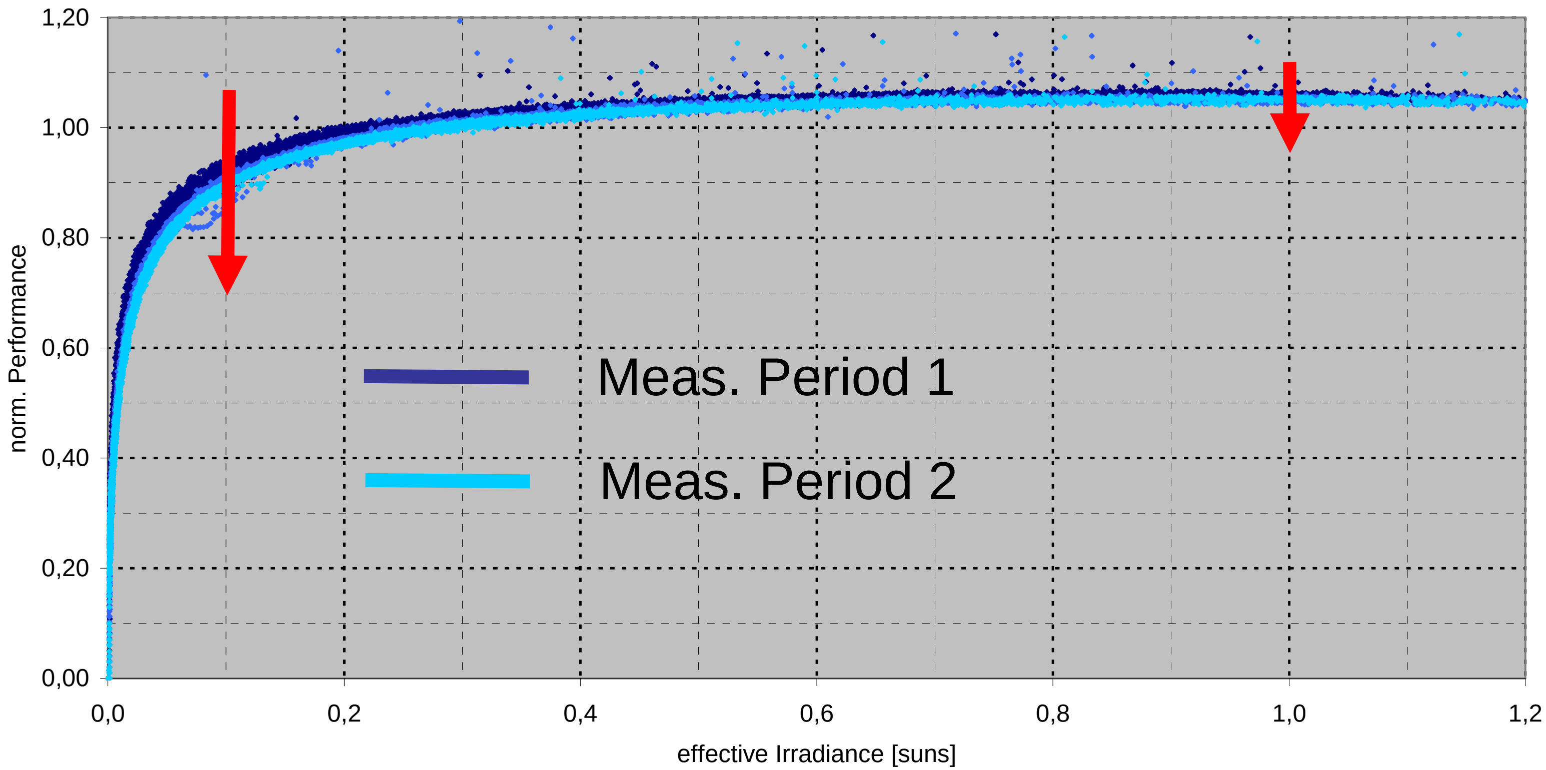
Continuous evaluation possible

Which degradation rate can be detected?



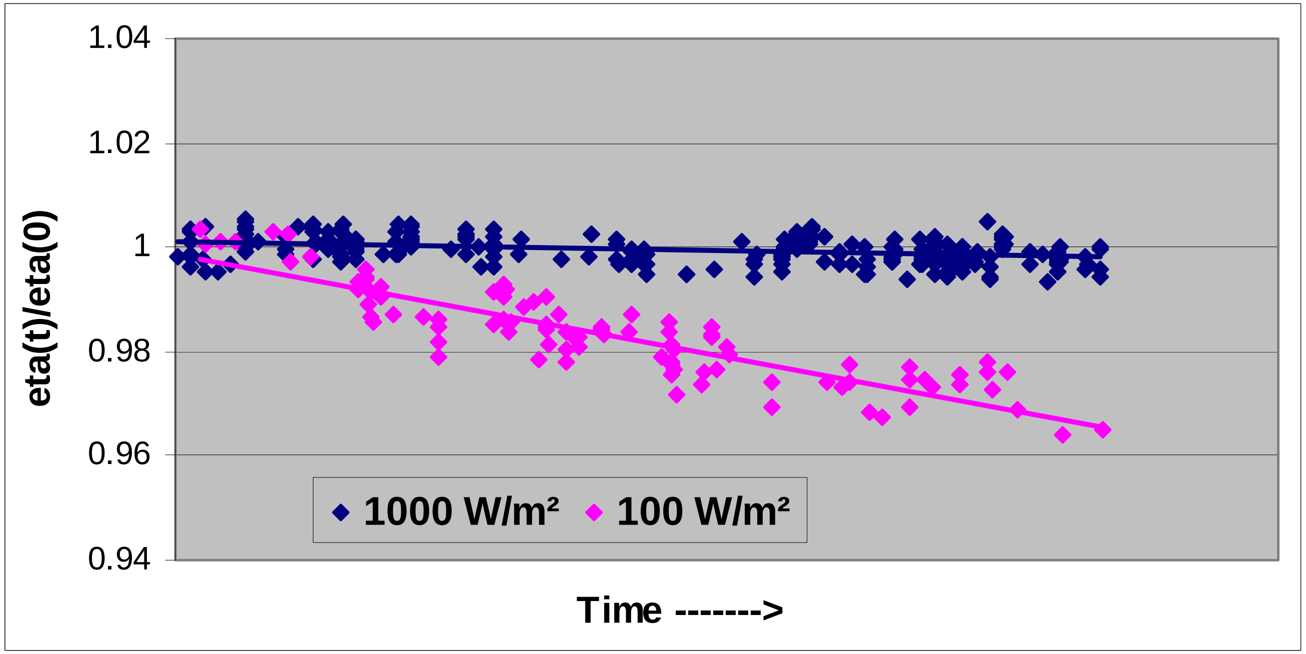
Here assumed 0,3 % per year

Effective efficiency, corrected to reference temperature and normalized to P_{nom}



Low light level degradation / STC-Degradation

Outdoor measurements



Different kinetics

Potential Induced Degradation

(1) Leakage current indoor

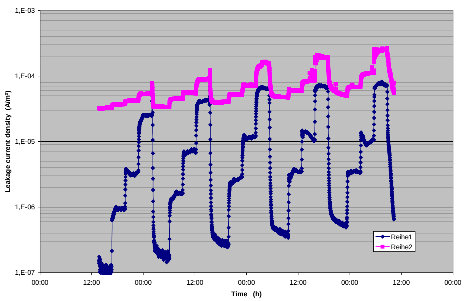
35....85 °C
50…95 %
-1000 V
some hours

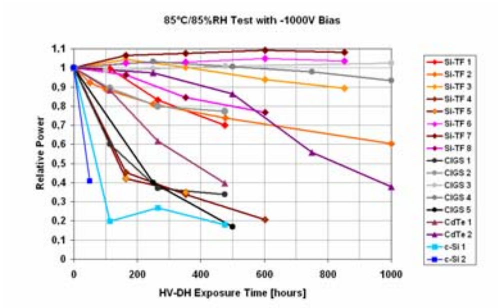
(2) Power degrad. indoor

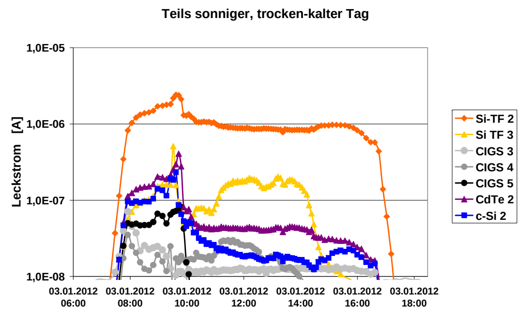
85 °C
85 %
-1000 V
1000 h

(3) Leakage current outdoor

Module temperature
Humidity
Generator Voltage
months to years





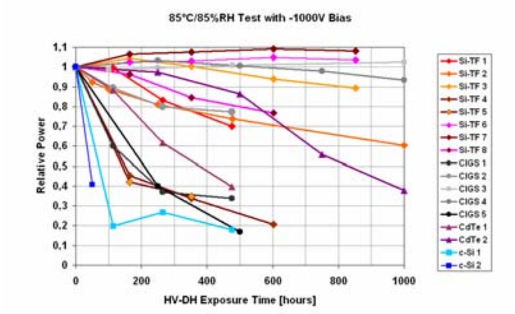


Estimation of Time to PID Failure

Time to PID Failure

Module Type	Q _ HV-DH for P90 [C/m²]	Daily* Qd from Outdoor [mC/m²]	Time* to P90 t [a]
c-Si 2	0,6	2	0,8
CIGS 1	1,4	1,6	2,5
Si-TF 2	33	35	2,6
CdTe 2	23	7,8	7,9
Si-TF 6	> 300	1,4	> 5*E2
CIGS 3	> 37	0,19	> 5*E2
CIGS 4	> 87	0,5	> 5*E2

*** Average values fall/winter at Widderstall**



„PID-Failure“
90 % of initial power (P90)

- **Time to PID Failure depends on climate**

Summary

- Methods for evaluation of characteristic module parameters from field data have been presented
- Self referencing uses the module itself as a best matched irradiance sensor
- Module power is a unique function of effective irradiance, → transformation to laboratory measurements under reference conditions
- From long term measurements stability trends can be extracted with high accuracy
- Time to PID Failure can be estimated

Thank you for your attention!

ZSW Testfeld WIdderstall