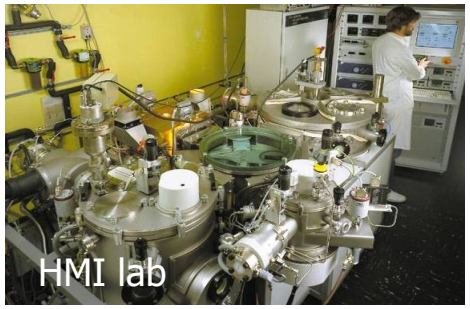
MANUFACTURING OF LARGE-AREA $CuInS_2$ SOLAR MODULES – FROM PILOT TO MASS PRODUCTION

Axel Neisser
Sulfurcell Solartechnik GmbH
Groß-Berliner Damm 149, D-12487 Berlin, Germany

SULFURCELL

Sulfurcell's history: Passion for CIS since 1991

1991 RESEARCH **2003** PILOT PRODUCTION **2008** MASS PRODUCTION



1991 – 2001	Hahn-Meitner-Institut Berlin takes lead in thin-film technology based on Copper-Indium-Sulfide (CIS)
April 2003	Launch of HMI spin-off Sulfurcell (EUR 16m financing closed)
July 2004	Plant begins operation
July 2005	Scale-up of CIS technology completed (5 x 5 ⇒ 125 x 65 cm²), prototype presented to public
Dec 2005	Market entry
2005 – 2008	Continuous improvement of key performance indicators up to a run rate of 2.5 MW/a / 80 % yield
Jul 2008	75 MW expansion started (EUR 85m of equity raised)
Nov 2009	First CIS modules from 75 MW line

SULFURCELL

Sulfurcell's 75 MW production facility CIS-Line

Dimension

- 16.000 m² production
- 3.000 m² offices

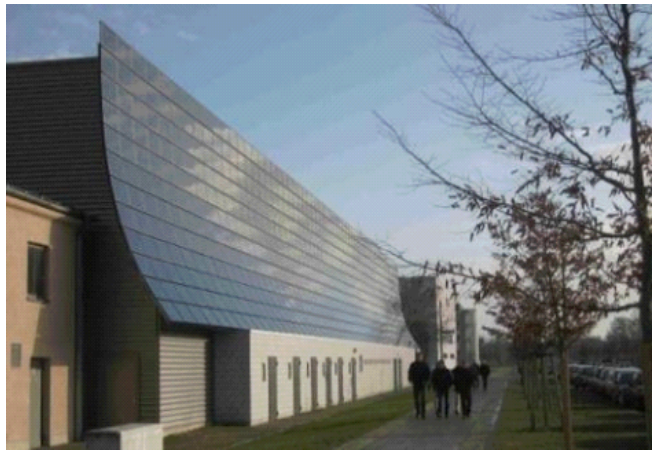
BIPV

- 700 facade-integrated CIS modules
- PV test field + 300 kW PV power plant on roof

SULFURCELL

Sulfurcell serves the market with high-quality products with a focus on building integrated photovoltaics (BIPV)

SULFURCELL'S PRODUCT PORTFOLIO



Framed modules

- Max. mechanical load (4800 kPa/m²)
- Applicable as cladding element

Frameless modules

- Optimized for minimum costs
- Excellent self-cleaning

Modules for roof integration

- Aesthetic excellence
- Replacing roof tile (rainproof)

QUALITY

All products passed accelerated life-time tests (IEC 61646) and are certified by German TÜV

www.tuv.com TÜVRheinland ID: 0000023251

CONTRACTED WHOLESALER

IBC SOLAR

krannich Solar

energiebau solarstromsysteme gmbh

SULFURCELL

Sulfurcell's technology roadmap towards high-efficiencies and lowest costs

GOAL
- **Grid-parity**, manufacturing costs lower than 0.7 €/W.

STRATEGY
- **Specialisation on technologies based on CIS/CIGSe**
- **Technology evolution**

→ Driven by Sulfurcell's technology team (50 engineers and PhDs in engineering, R&D and product development)

→ Continuous improvement of production technology

→ Mid-term projects targeting on advanced processes (Keeping 80%, improving 20%)

→ Test of new methods/materials within the CIS/CIGSe family

→ Modification of Indium-to-Gallium and Sulfur-to-Selenium ratio

→ Deep cooperation with Helmholtz-Zentrum Berlin (HMI) and other research groups

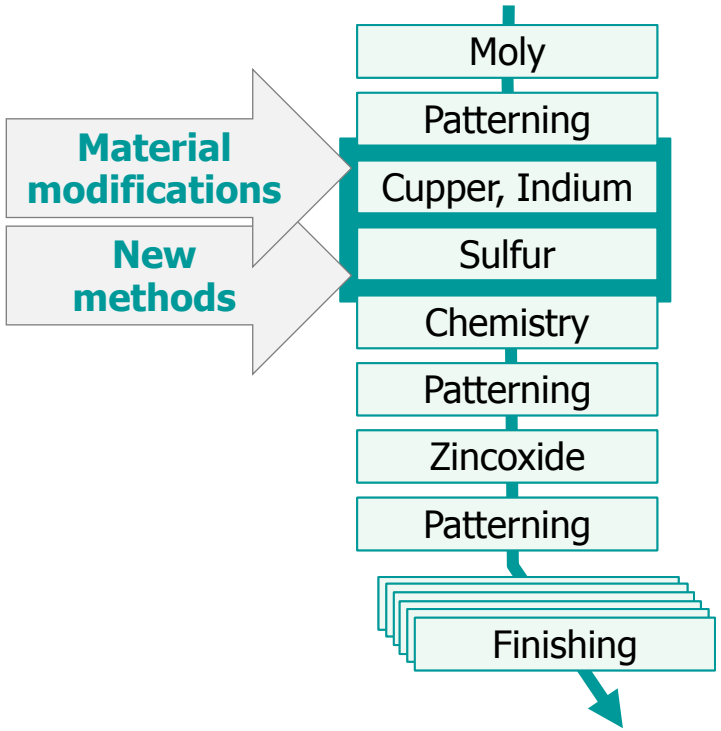
- **Orientation towards manufacturing**

→ Fast transfer of innovations into production

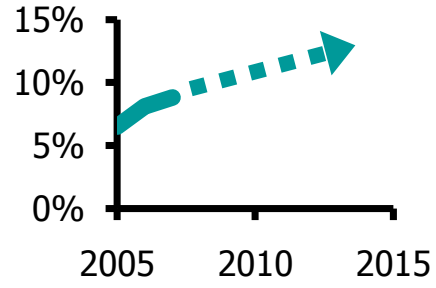
→ Test & optimisation of new techniques in pilot production environment parallel to production

→ Focus on fast, highly-productive processes

INNOVATION FOCUS



EFFICIENCY GOALS



Sulfurcell's Technology

Sulfurcell takes advantages from a sequential preparation process for $CuInS_2$

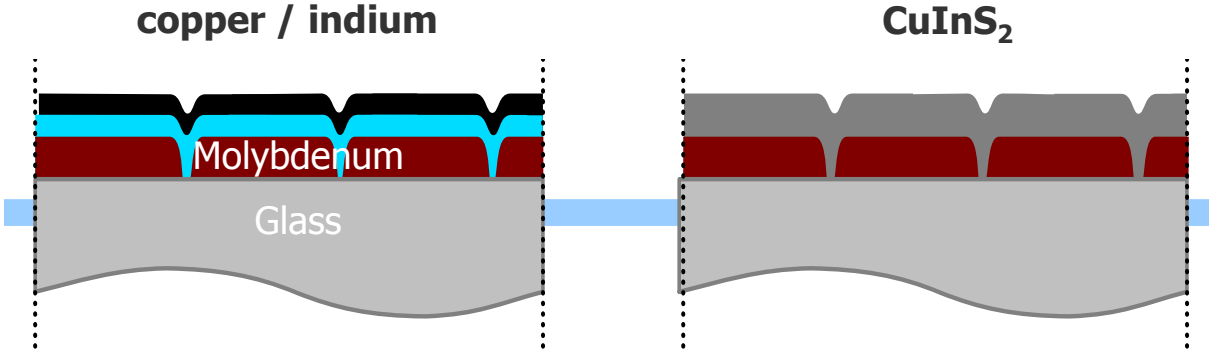
Formation of $CuInS_2$

Needs

- Deposit of copper, indium and sulfur
- Compound copper, indium and sulfur (activated at 500 °C)
- Build polycrystalline layer

Sulfurcell's approach

- Sputtering of copper and indium (precursor)
  → to avoid high-temperature processes for metal deposition
  → to achieve reasonable machine costs
- Rapid thermal annealing of copper and indium under sulfur atmosphere
  → to benefit from high reactivity of sulfur
  → to achieve short cycle-time
- Use Cu-rich precursor (Cu:In > 1)
  → to benefit from copper accelerating growth and enhancing crystal quality

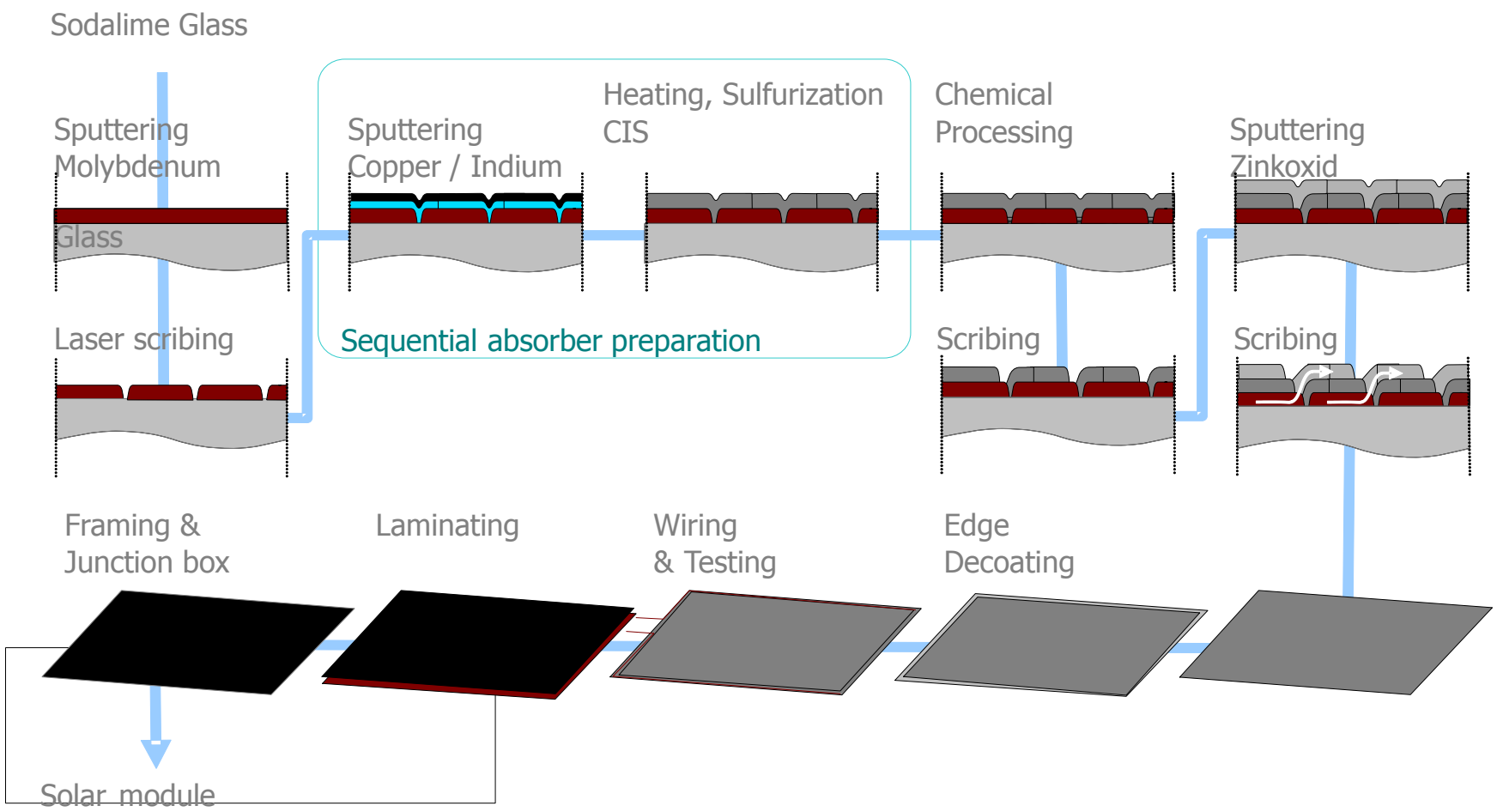


SULFURCELL

Sulfurcell's technology

Sulfurcell has a lean production process involving five deposition steps

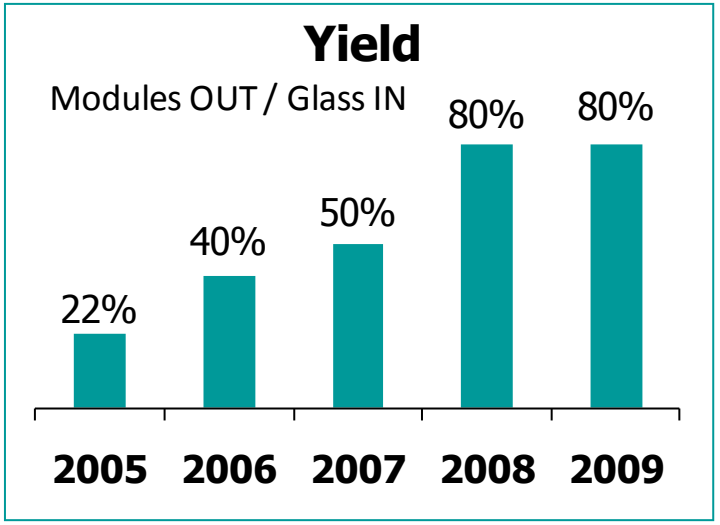
Sulfurcell's production process

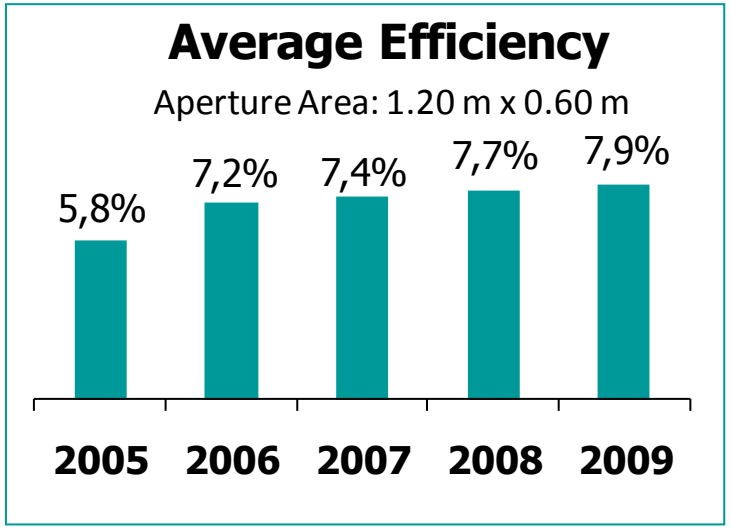


Learning curves of key performance indicators

Key performance indicators

- start of 24/7 operation in Oct 07
- run rate since Jul 08 of 2.5 MW/a
- yield stabilized in Q1/08 at 80%
- continuous improvement of module power



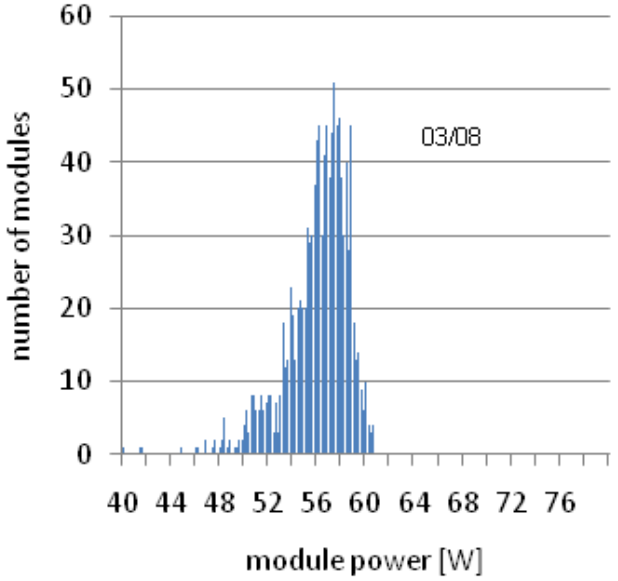


SULFURCELL

CIS module development

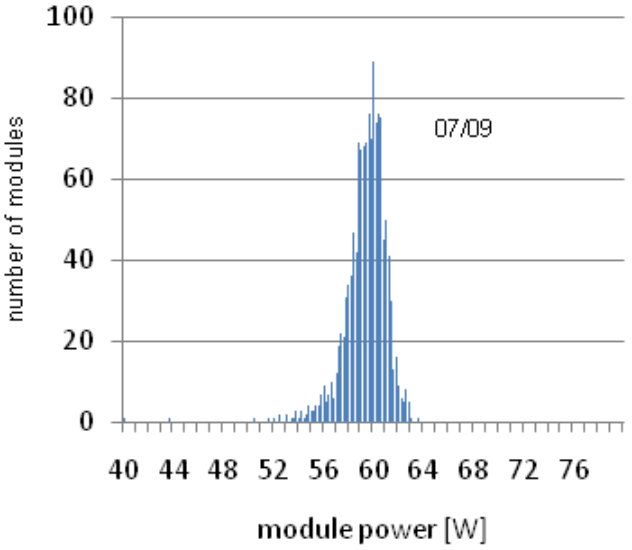
R&D top four in 2008/2009:

- production-line stability issues
- bulk absorber properties
- CIS/CdS/ZnO interface issues
- active area / patterning



Module power development

- best CIS modules reach 9% active area efficiencies.
- average quarterly module power reached 60Wp (=8,2%) in Q4/09
- narrowed power distribution down to a FWHM of only 2,2 W



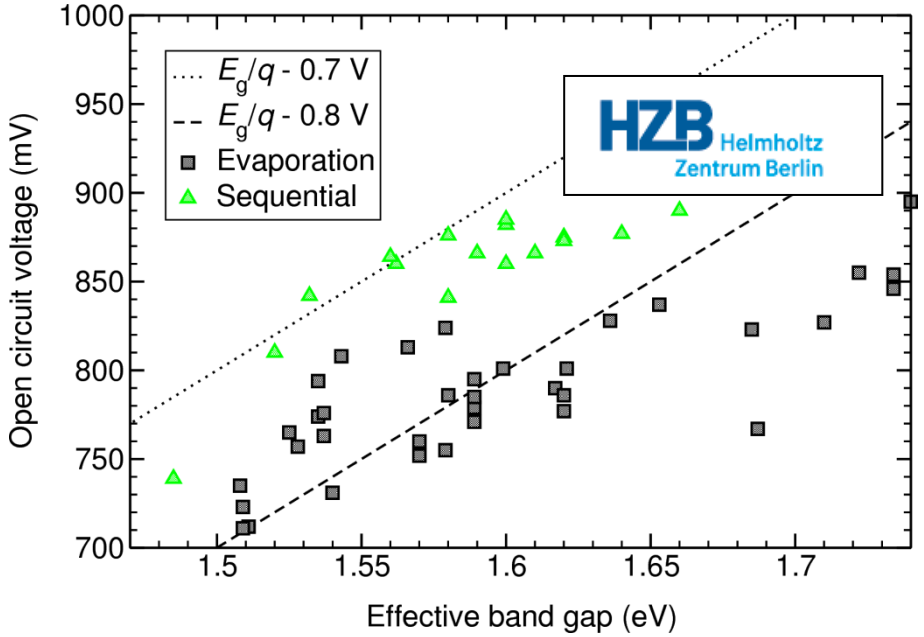
SULFURCELL

CIGS technology integration

Integration of Gallium

Incorporation of Gallium has been shown to be a successful way in increasing the efficiency of small area laboratory cells

	Eg [eV]	**Eff [%]**	Voc [mV/cell]	FF [%]	Jsc [mA/cm^2]	
CIS	1.5	**11.4**	730	71.7	21.8	Ga-free reference
CIGS	1.56	**13.0**	864	64.0	23.4	active area, w AR
CIGS	1.60	**12.7**	885	71	20.2	active area, w/o AR
CIGS	1.60	**12.0**	865	69	20.0	total area, w AR, NREL certified
CIGS	1.65	**11.5**	890	64	20.0	active area, w AR



Source: Reiner Klenk, **Helmholtz-Zentrum Berlin für Materialien und Energie**

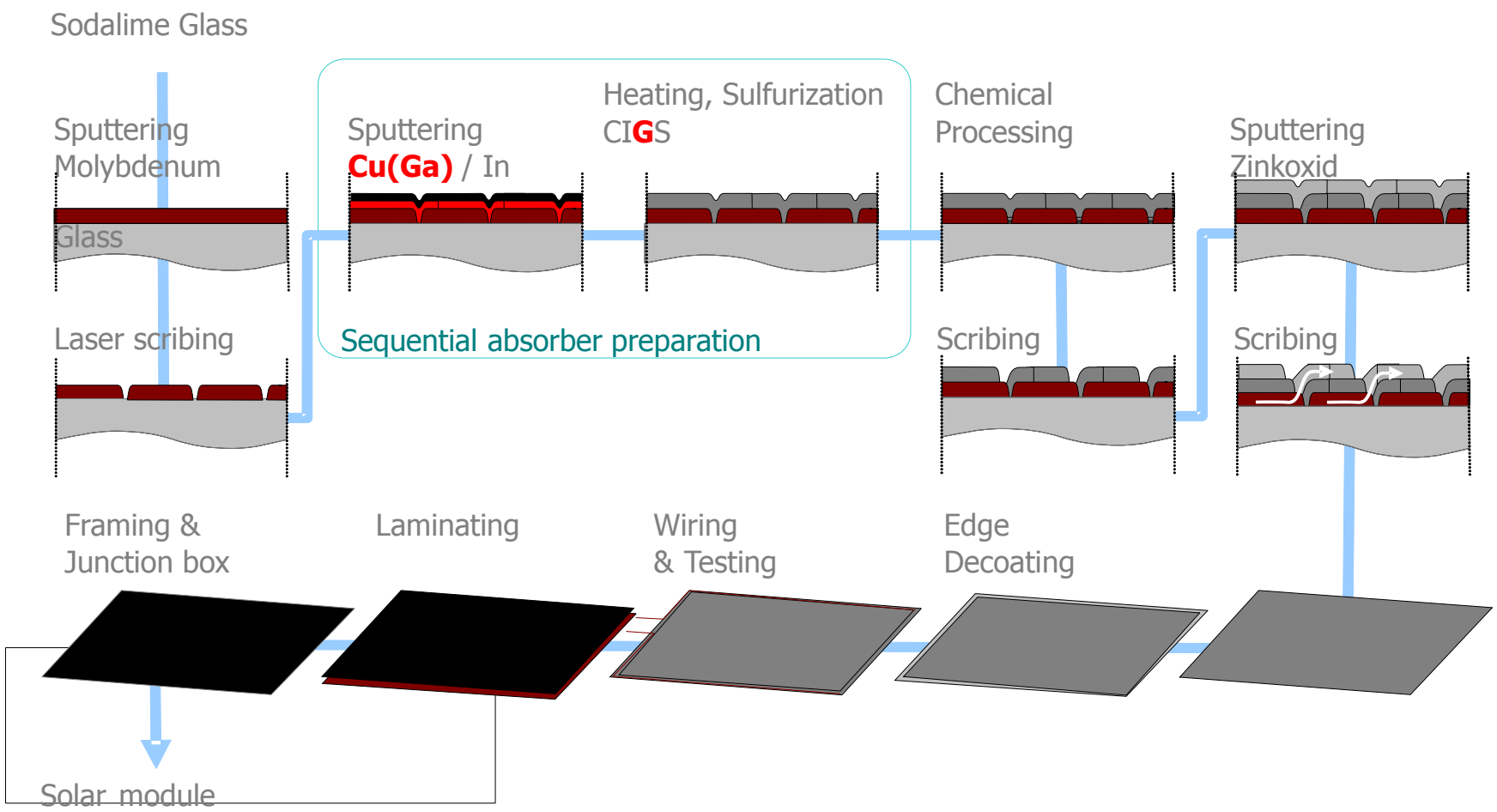
E_g derived from external quantum efficiency measurements

S.Merdes , R.Kaigawa J.Klaer R.Klenk, R.Mainz A.Meeder N.Papathanasiou D.Abou-Ras S.Schmid, Proc. 23rd EU-PVSEC, Valencia, 1-5 September 2008 (2008)
S.Merdes, B.Johnson R. Saez-Araoz A.Ennaoui J.Klaer I.Lauermann R.Mainz A.Meeder R.Klenk, Mater. Res. Soc. Symp. Proc. Vol. 1165 1165-M05-15 (2009)
S.Merdes , R.Saez-Araoz A.Ennaoui J.Klaer M.Ch.Lux-Steiner R.Klenk, Appl. Phys. Lett. 95 p.213502 (2009)
S. Merdes, R. Mainz, J. Klaer, A. Meeder, H. Rodriguez-Alvarez, H. W. Schock, M. Ch. Lux-Steiner and R. Klenk, Sol. En. Mat. Sol. Cells, submitted

CIGS technology integration

Straight forward integration of Gallium in Sulfurcell's production process

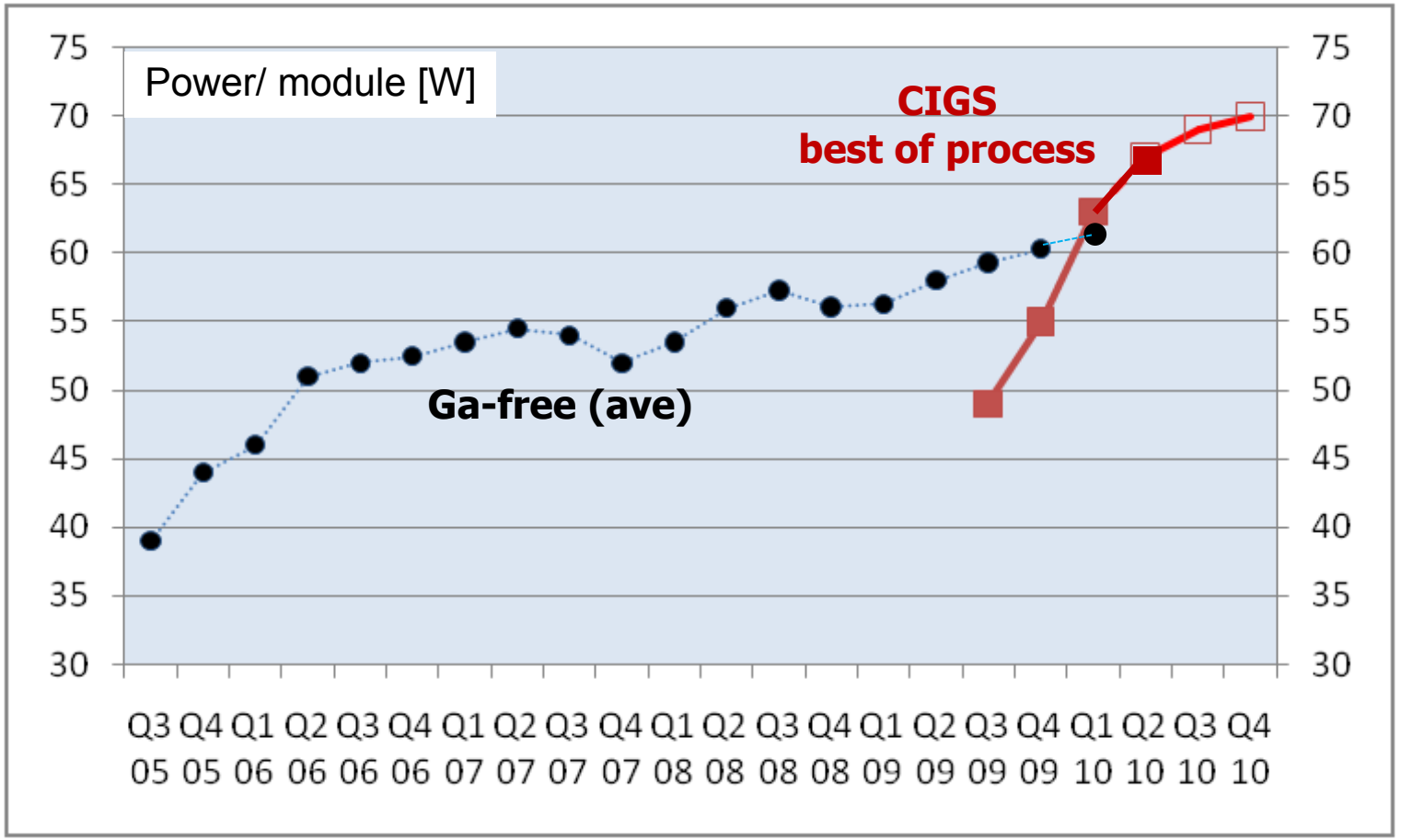
Integration of Gallium



Sulfurcell's Gallium-technology

Status of Gallium project

- Steady increase in module power since start of process development on large area
- Latest results 3W better than standard Ga-free process



SULFURCELL

Sulfurcell's Gallium-technology

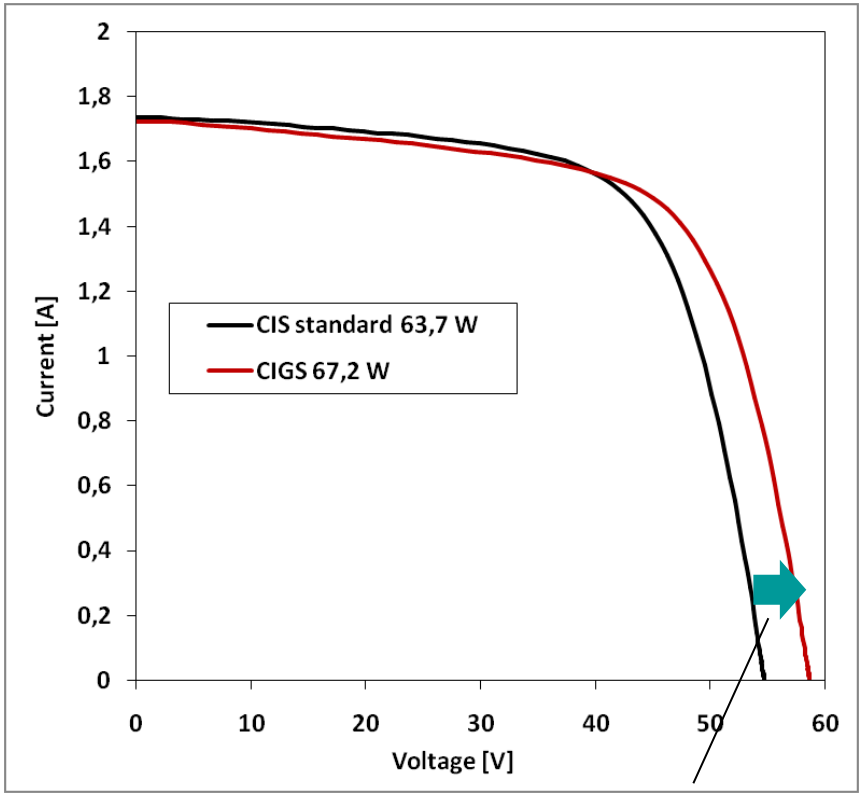
Current project status

- Process will be ready for production in June
- Best modules show 67W module power

Comparison of small area reference cells

technology	CIS		CIGS	
process	lab	prod	lab	prod
area [sqcm]	0.5			
Eff [%]	11,4[1]	10,4	> 13	> 11,5
Voc [mV/cell]	730	700	> 860	> 780
FF [%]	71,7	71	69	71
Jsc [mA/cm²]	21,8	21	22	21

Comparison of Ga to Ga-free module



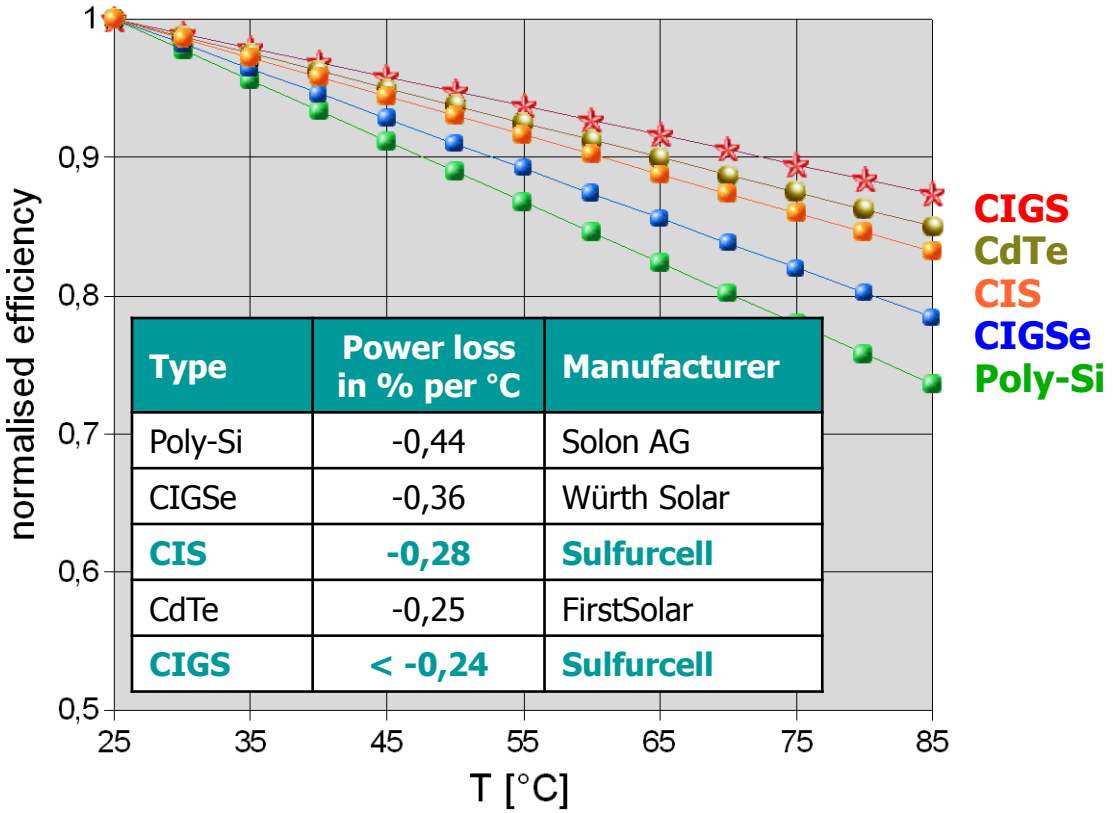
Higher voltage per module due to Gallium incorporation

Sulfurcell's Gallium-technology shows very low temperature coefficient

Comparison of T-coefficient of various PV technologies

Very low temperature coefficient

- Observation of lowest temperature coefficient of all PV technologies besides amorphous
- Low temperature coefficient promises high performance on a kWh per kW basis in warm-weather regions (e.g. 8 % more than poly-Si at 65 °C)



Type	Power loss in % per °C	Manufacturer
Poly-Si	-0,44	Solon AG
CIGSe	-0,36	Würth Solar
CIS	**-0,28**	**Sulfurcell**
CdTe	-0,25	FirstSolar
CIGS	**< -0,24**	**Sulfurcell**

Continuous quality control – a daily in-house

Accelerated life-time test – Sulfurcell resources

- Damp heat test
- Dry heat test
- UV test
- Mechanical load and deformation test
- Light-soaking test

System test

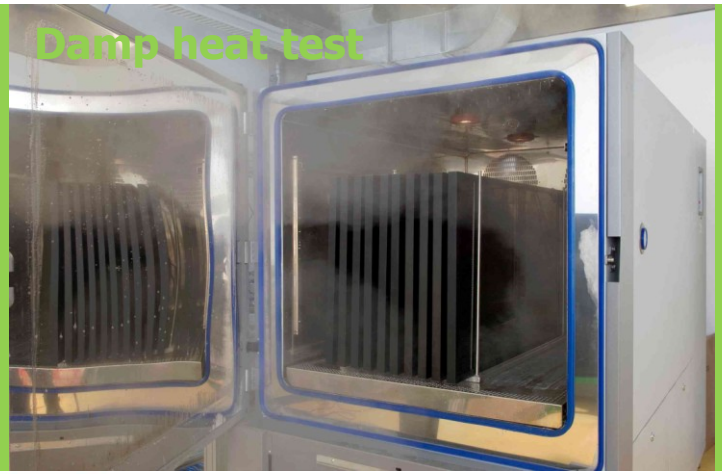
- Monitoring of PV-test systems
- Qualification of inverters and mounting systems

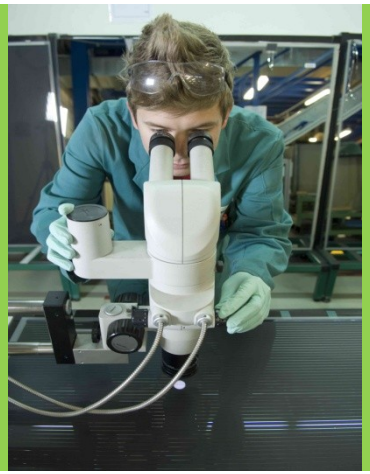
Extended in-house testing program at Sulfurcell:

- 3000 h damp heat
- 30 cycles humidity freeze
- damp heat under bias,
- mechanical load under torsion

Extended testing program in coop. with externals:

- 500ppm NH3-atmosphere according to DIN50916:1985,
- Salt-mist corrosion test according to IEC61701:1995
- Hail impact test



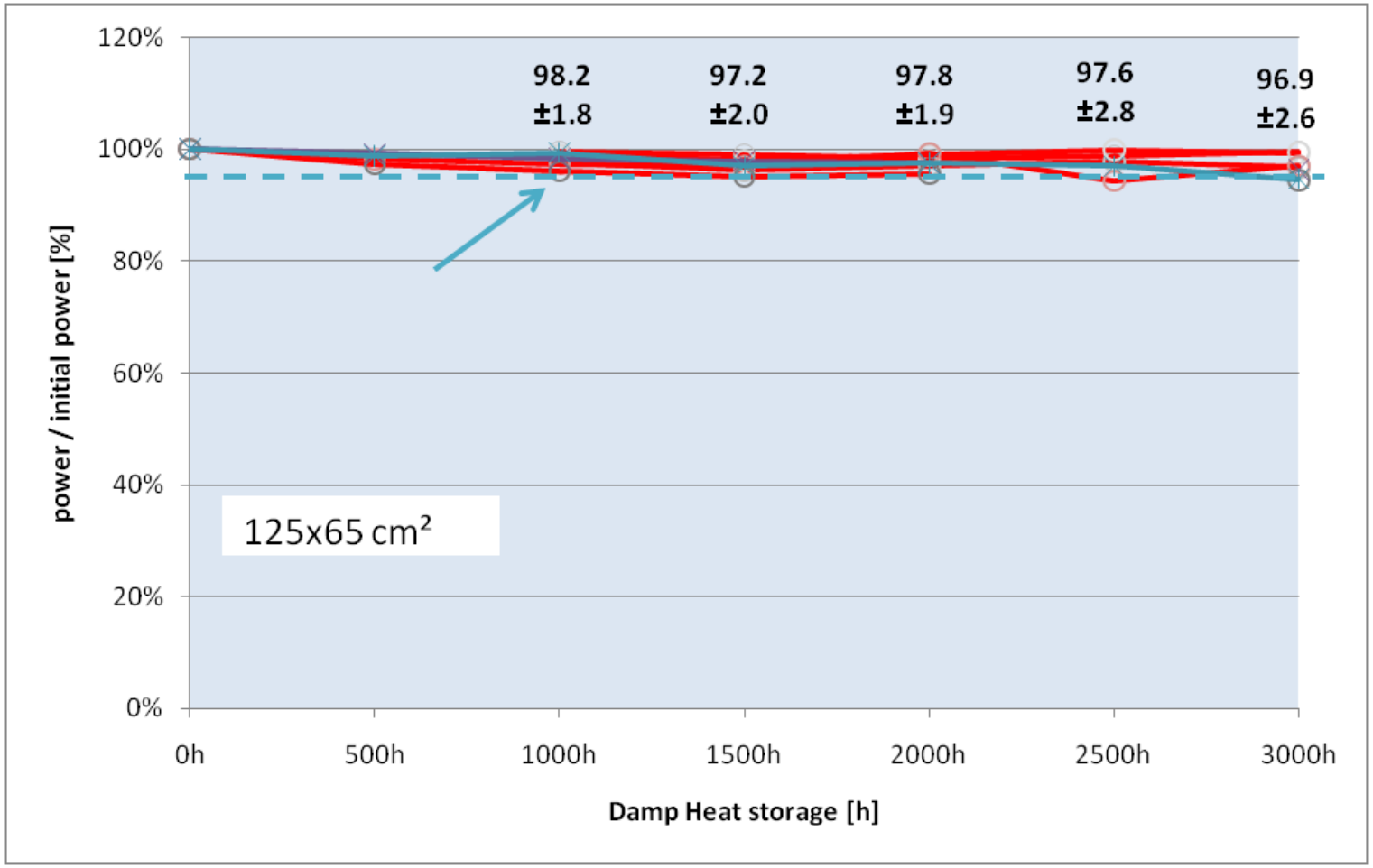


SULFURCELL

Product stability

Encapsulation of $CuInS_2$ modules

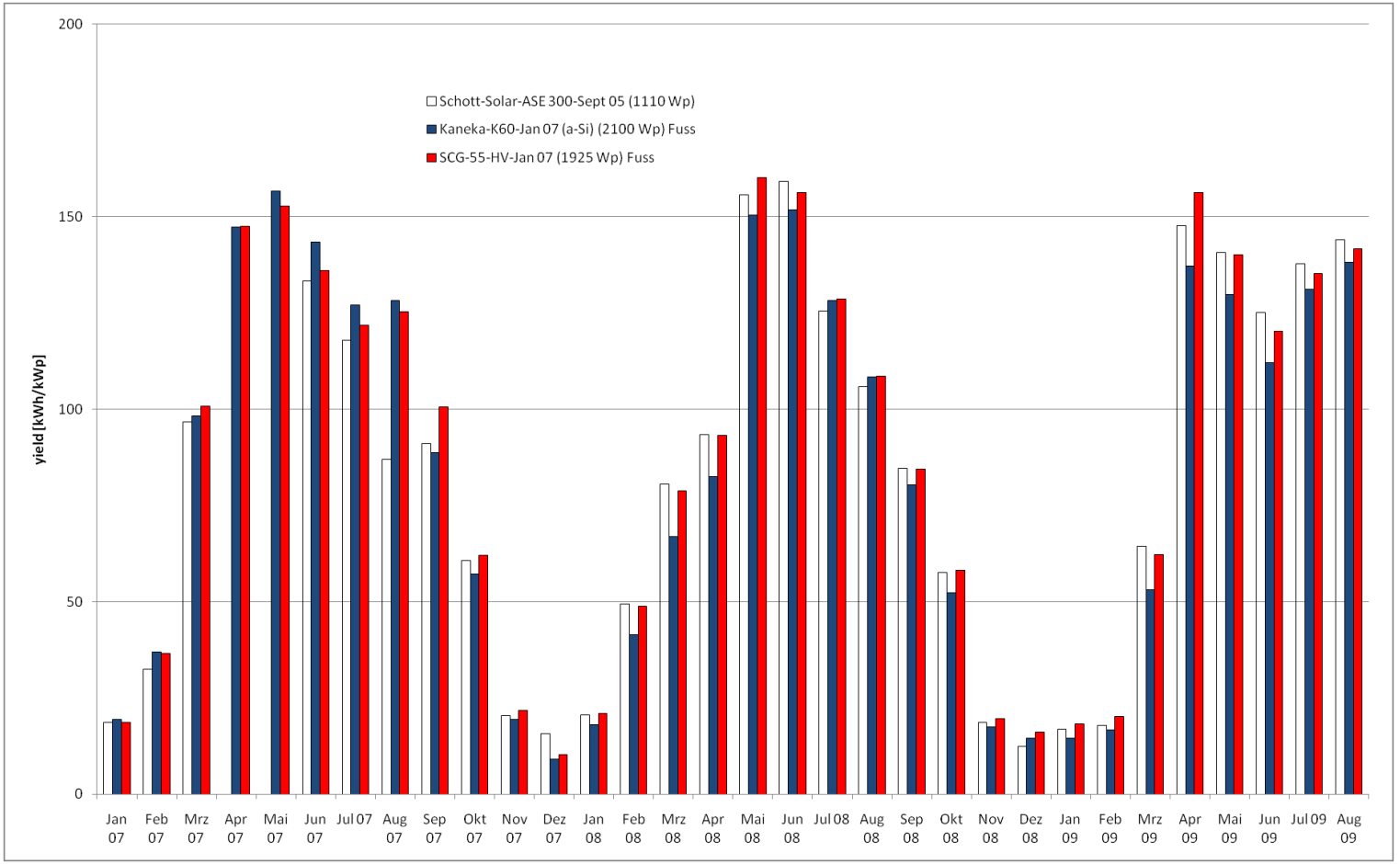
- Improvement of encapsulation has lead to an outstanding damp heat stability of Sulfurcell's products
- Today damp heat stability exceeds the IEC standard by three times
- Sulfurcell products have passed the IEC61646 certification procedure at TÜV Rheinland



CIS outdoor performance experience

Comparison of outdoor performance of c-Si, a-Si and CIS

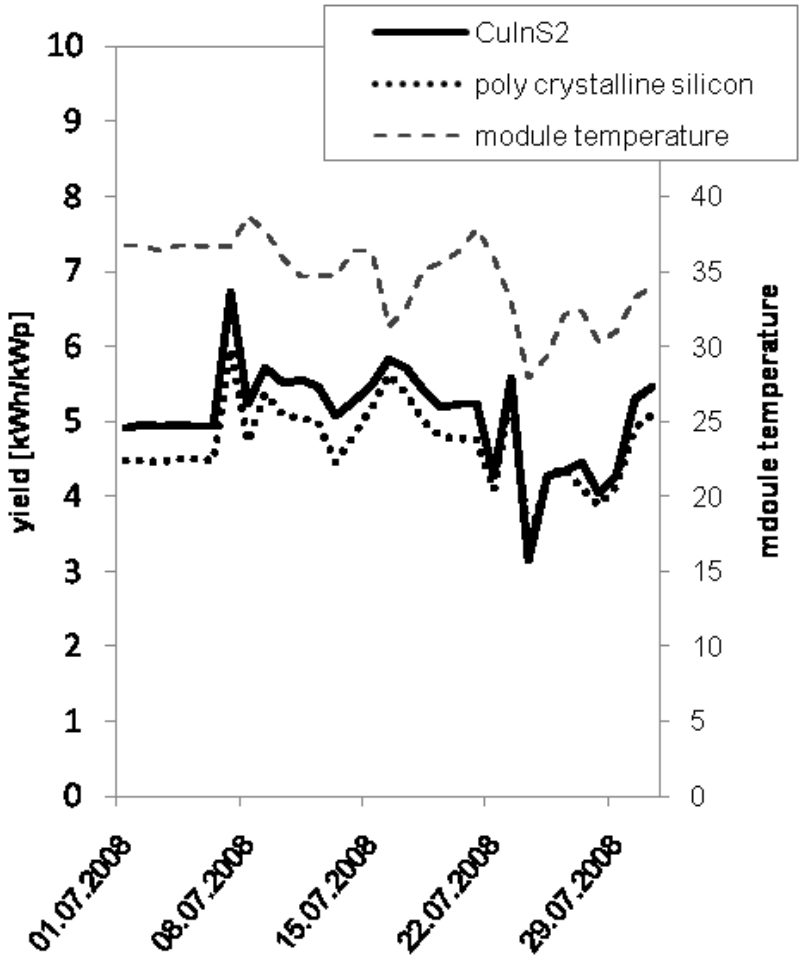
- stable and reliable performance over 3 years of outdoor experience.
- energy yield of c-Si and CIS comparable.
- CIS does not show any light-induced degradation effects.
- oudoor results have been confirmed by numerical simulations using the PV-Sol software



(location of 3 x 1 kWp pv installation: Berlin, Germany)

SULFURCELL

CIS outdoor performance experience



systems are installed on the same site in Rizoma near Trikala, Greece

Comparison of c-Si and CIS in hot climates

numerical simulations using the PV-Sol software confirm our oudoor results:

Simulated specific energy yield [kWh/kW_p a] of a $CuInS_2$ PV system and a c-Si system.

	$CuInS_2$	**c-Si**
Temperature coeff.	**0.28%/K**	**0.48%/K**
Spec. energy yield		
Berlin, Germany	925	891
Rome, Italy	1478	1396
Madrid, Spain	1492	1401
Cairo, Egyt	1772	1652

SULFURCELL

Summary

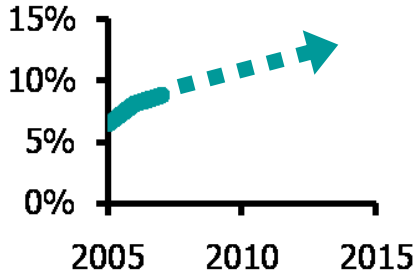
TECHNOLOGY

- Application of proprietary CIS-based technology.
- Long-years track record in industrial application of CIS: Sulfurcell modules shipped and sold, 2.5 MW/a manufacturing rate.
- 220 staff with 30 in-house CIS-specialists. Alliance with Europe's leading research institute on thin-film PV (Helmholtz Centre Berlin).
- 75MW line has been installed in 2009, will reach stage one capacity of 35MW in mid 2010

PRODUCTS

- Sulfurcell products are designed and equipped for building integration.
- The high quality standard is certified by TÜV Rheinland (IEC 61646).

EFFICIENCY ROADMAP




Sulfurcell's facade-integrated modules


Sulfurcell modules replacing roof-tile


View into Sulfurcell's production

SULFURCELL