Manufacturing of Large-Area $Cu(In,Ga)Se_2$ Solar Modules
Fast Ramp Up to More than 12% Module Efficiency in Mass Production – Road Map to 14%

A. Neisser et. al., Soltecture, Berlin, Germany

SOLAR CONSTRUCTION
SUSTAINABILITY
TECHNOLOGY

Sulfurcell is now Soltecture

SOLTECTURE

– **Solar**

– **Technology**

– **Architecture**

Soltecture: Passion for CIS since 1991 and more than 200 years of combined CIS experience

SOLTECTURE

1991 **2003** **2010**

Research
Preparation of Mini-Modules

Pilot Production
3 MW/a

Mass Production
35 MW/a

Lab at Helmholtz Center

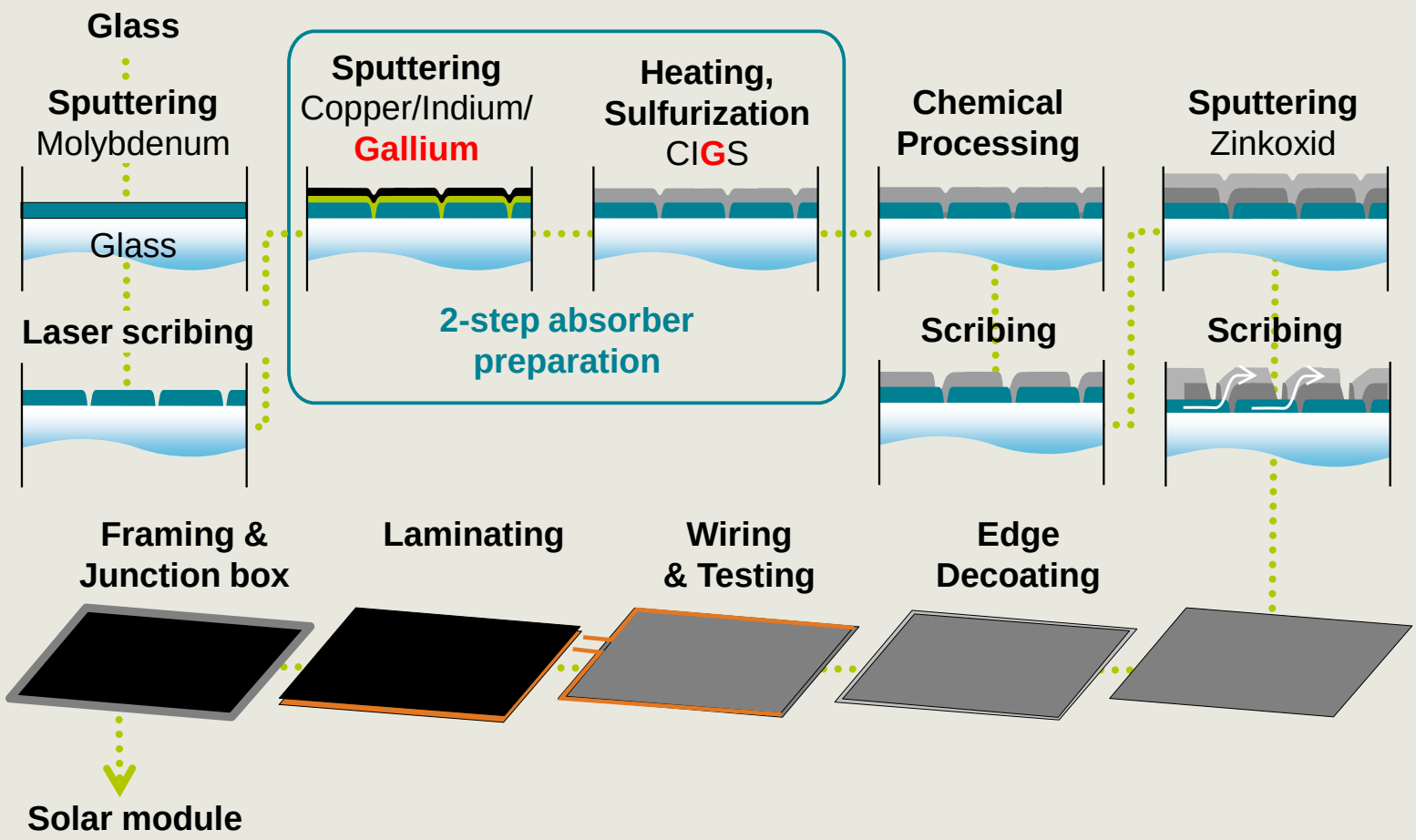
Soltecture's pilot production

Soltecture's 35 MW facility

1991 – 2001	Helmholtz-Center Berlin (HZB) takes lead in thin-film technology based on CIGS
2001	Founding of Sulfurcell Solartechnik GmbH
2004	Pilot production facility ready for production
Dec 2005	Market entry
Apr 2010	35 MW facility ready for production

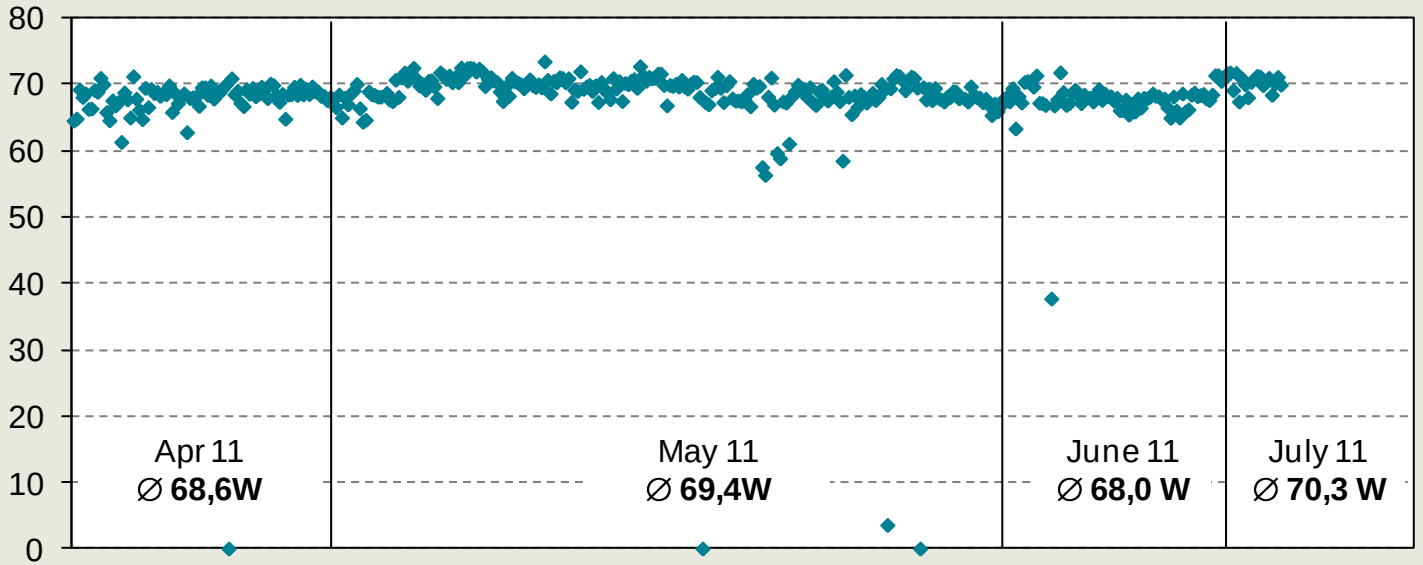
More than 200 years of combined CIS experience in Soltecture's staff of 50 highly qualified engineers

Latest result: Incorporation of Gallium into Soltectures sequential technology



Soltecture's has successfully qualified an improved Gen1 process enhancing module power from 60 W to 70 W in average

Power distribution of Gen1 modules made by the new Gallium-containing process



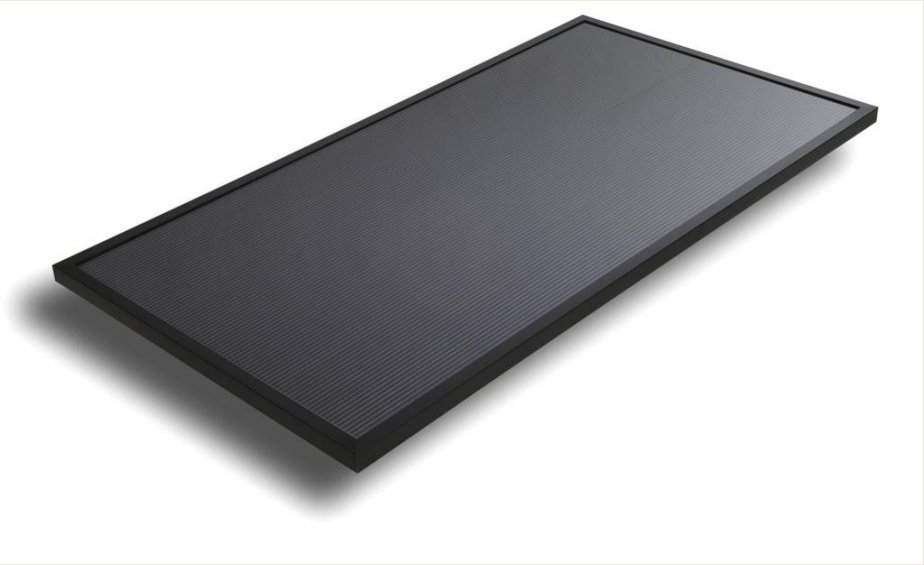
Average: 70 W
= 9.4% aperture area efficiency
= 8.6% total area efficiency

Champion: 74.6 W
= 10.0% aperture area efficiency
= 9.2% total area efficiency

New world record for Selenium free modules in production

Incorporation of Gallium

- Soltecture has introduced Gallium in its sequential technology, hereby increasing module power to more than 70W in production
- Best modules reach 10.0% aperture area efficiency
- Highest value for selenium free large area module



PV parameters of $Cu(In,Ga)S_2$ champion module

Pmp	eta	Voc	Isc	ff
74.6 W	10.0 %	60.1V	1.76 A	70.5 %
		732mV/cell	19.4mA/cm2	

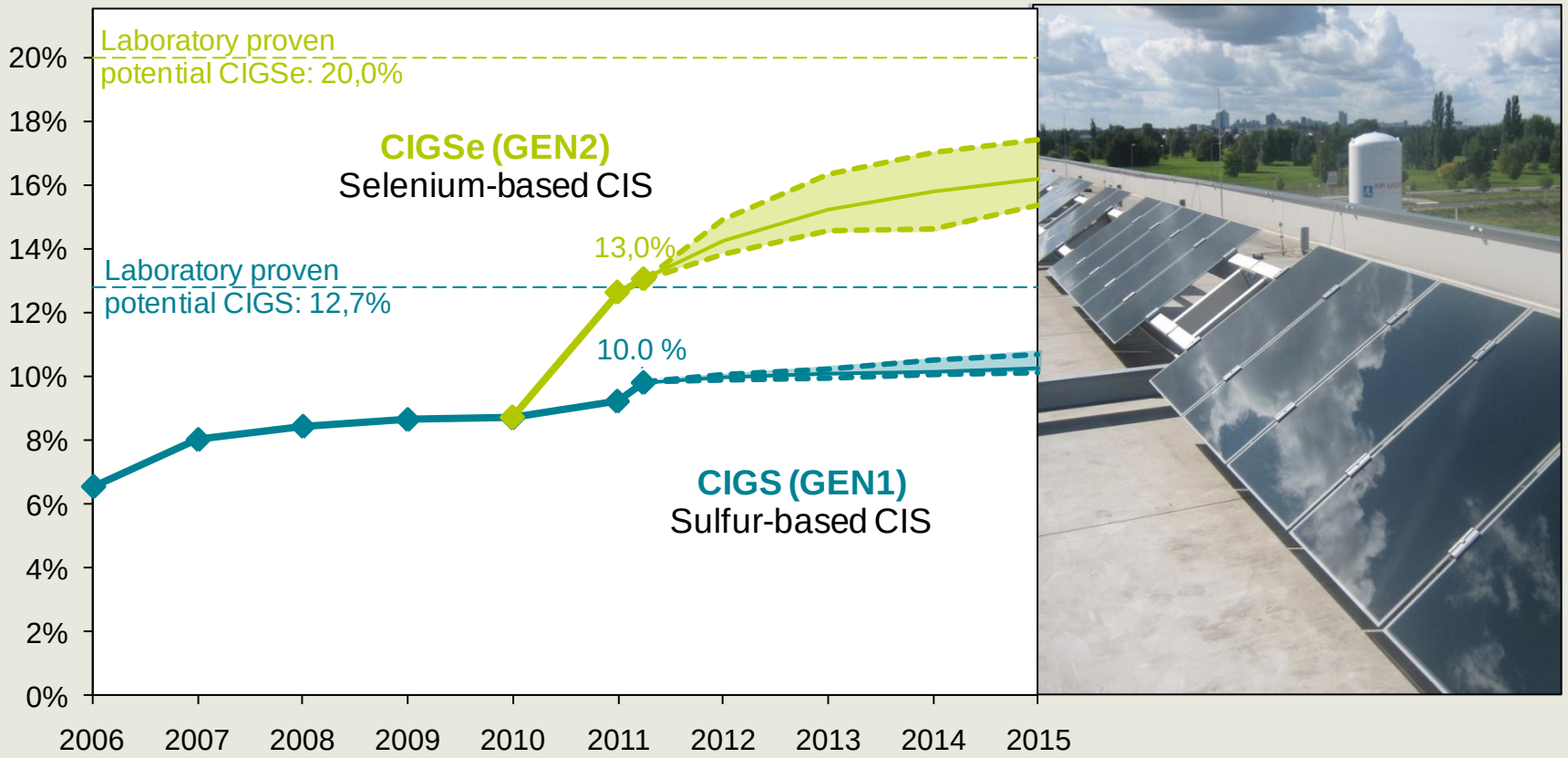
Aperture area: 1.215 x 0.615m^2

Soltecture's efficiency roadmap continues the company's historic achievements

SOLTECTURE

Champion efficiencies: Milestones and roadmap

Module aperture area: 1.215 x 0.615 m²



Soltecture's technology platform for CIGS & CIGSe: Modules with premium performance and top efficiency

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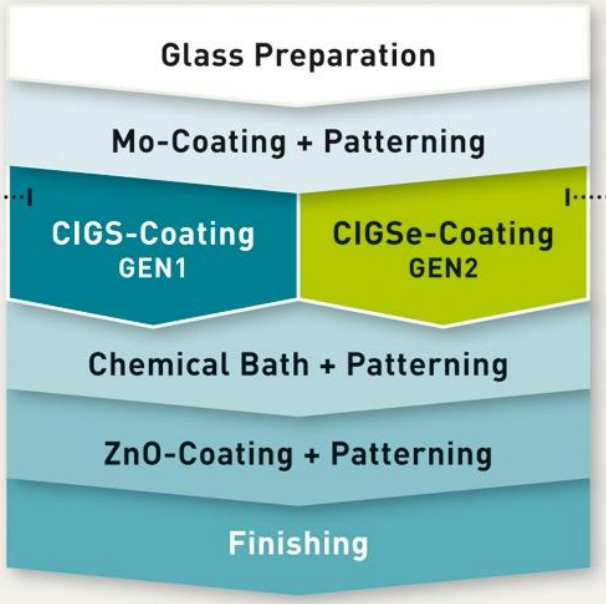
Manufacturing process in Sulfurcell's Berlin production

GEN1

- CIGS = $Cu(In, Ga)S_2$
- 2-step process: Sputtering + Annealing
- Capacity: 20 MW
- Average efficiency: 8%
- **Champion efficiency: 10.0 %**
- Technology roadmap to 10%

↓

High-quality modules with excellent heat tolerance



GEN2

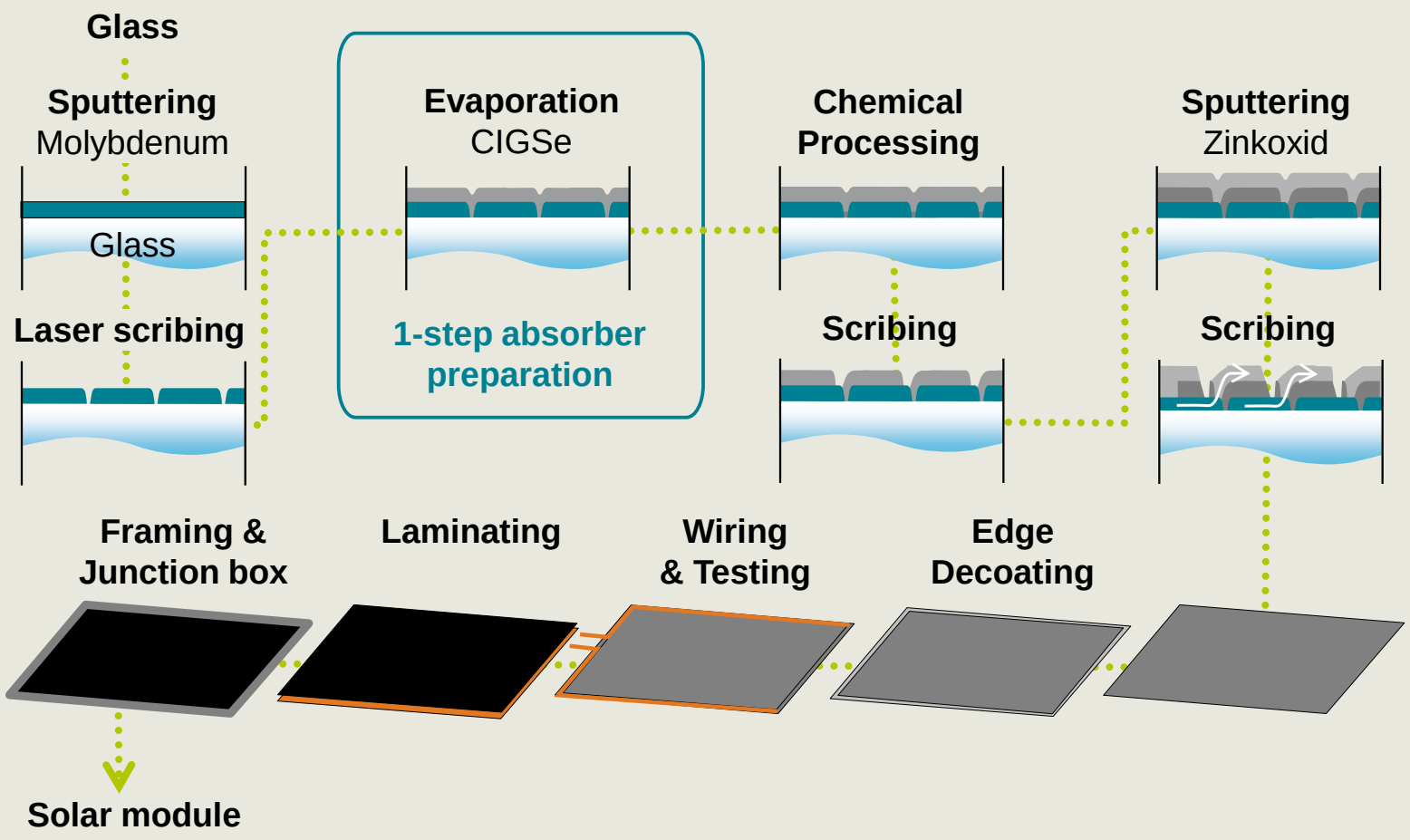
- CIGSe = $Cu(In, Ga)Se_2$
- 1-step process: Coevaporation
- Capacity: 15 MW
- Average efficiency: 11%
- **Champion efficiency: 13.1 %**
- Technology roadmap to >14%

↓

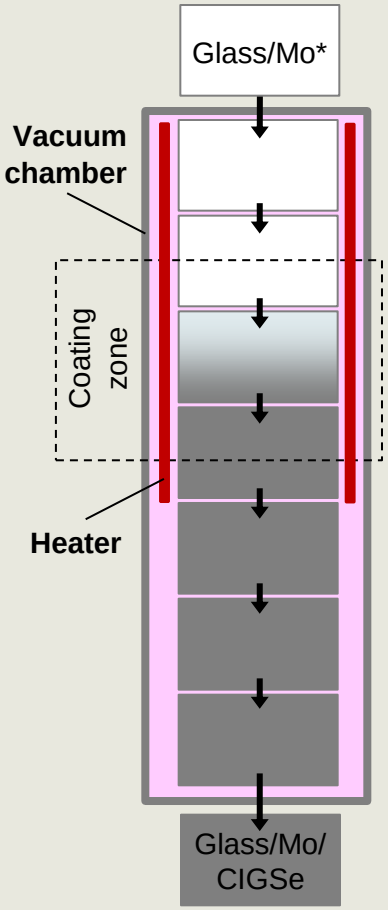
Premium modules with very high efficiency

All efficiency numbers related to aperture area of full-sized modules of 1.25 m x 0.65 m.

Sulfurcell´s manufacturing process for CIGSe PV modules (Gen2)



The coevaporation technology



*Molybdenum-coated glass (1.25 x 0.65 m²)

Technique

- Simultaneous evaporation of the elements Cupper, Indium, Gallium and Selenium
  ⇒ Formation of CIGSe on glass substrates passing the evaporation sources
- Optimisation of film composition by adjusting evaporation rates and temperature

Features of the machine design

- Material usage rate as high as for sputtering (> 40%)
- Stable operation over several days (no drift, no glass breakage, total yield > 80%)
- Excellent homogeneity of film composition: Cu:(In+Ga): ± 2.5%
- Excellent CIGSe quality: 15% efficiency of solar cells cut out of full-scale modules
- High productivity (4 min cycle-time, roadmap to < 2 min)

RAMP UP

Project Plan for Introduction of GEN 2 technology fulfilled

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Apr 10 — **Process definition**

Targets

- ✓ Module efficiency >10%
- ✓ Industrial feasibility
  - ✓ Cycle-time 5 min
  - ✓ No glass damage
  - ✓ Reproducibility
  - ✓ Good adhesion

Aug 10 — **Product qualification**

Targets

- ✓ Product design
- ✓ Production: Multi-day runs
- ✓ Accelerated lifetime tests

Oct 10 — **Pilot production**

Targets

- ✓ Uptime > 50%
- ✓ Yield > 70%
- ✓ Output: > 2,000 per month
- ✓ Outdoor-testing
- ✓ Shipping to pilot customers

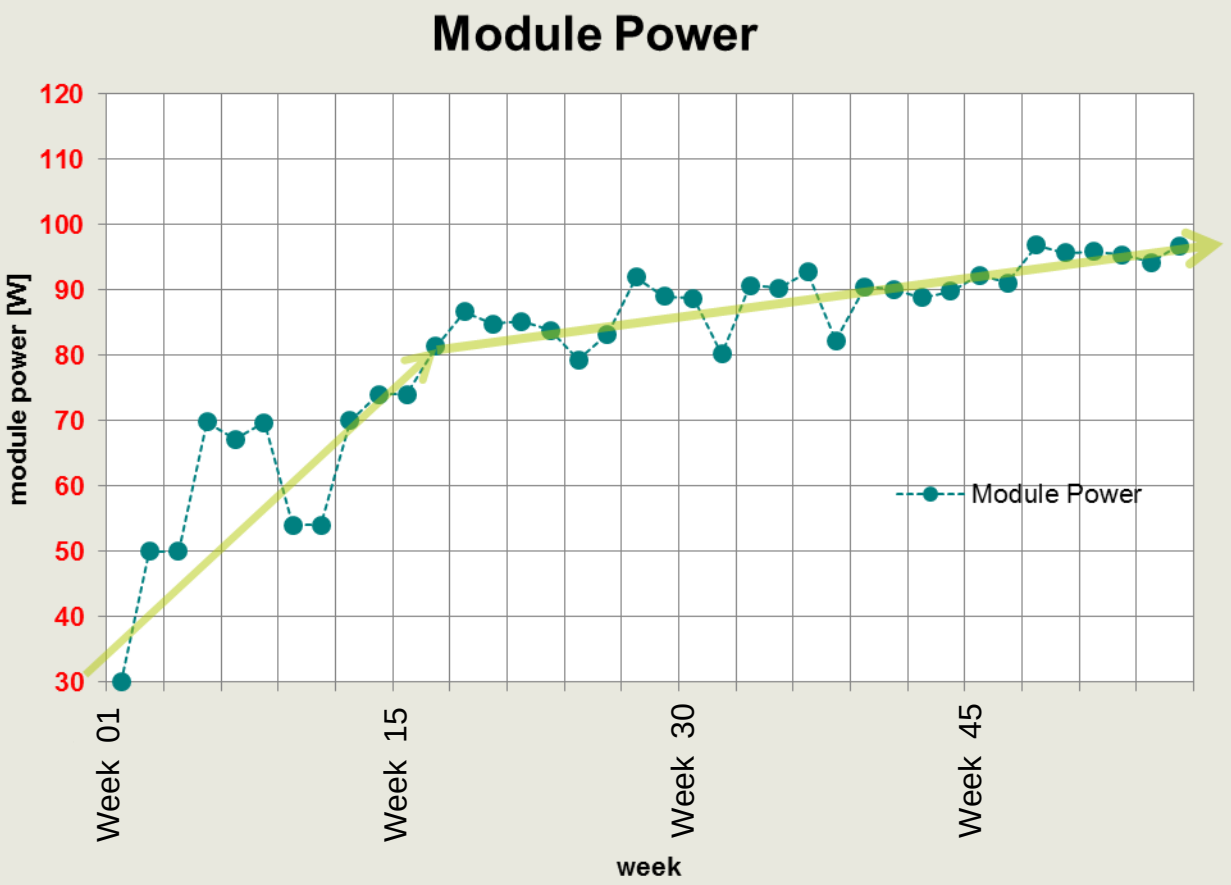
Jan11 — **Production & Sales** (Continuous Improvement)

Rapid learning curve demonstrates good process understanding and control

Evolution of module power

> 80W (>10.7%) after 4 month of process development

Continous steady progress towards 100W (13.4%)



Soltecture technology allows for very tight control of layer composition – key for further performance improvements

CIGSe composition optimisation

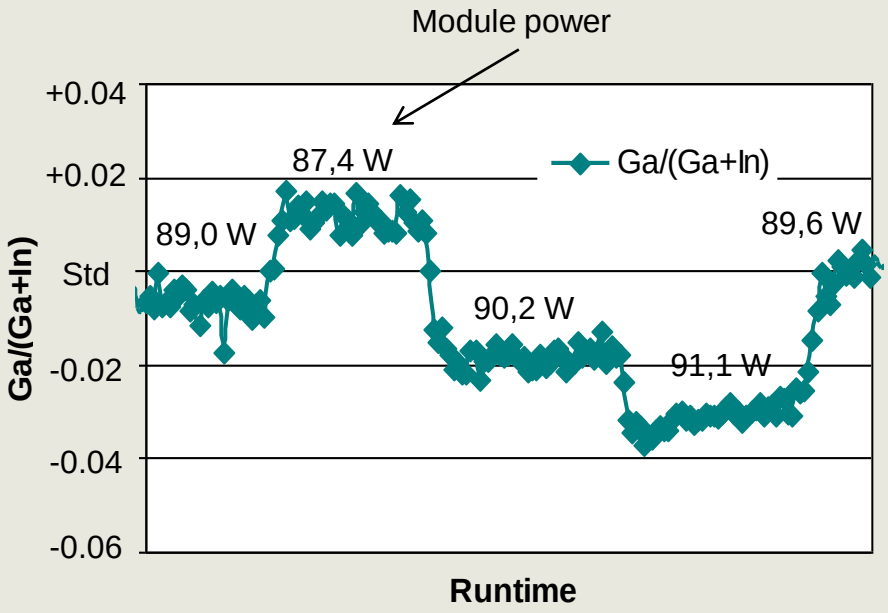
Topic:

Dependence of module power on elemental ratios Cu/(Ga+In) & Ga/(Ga+In)

Solution:

Optimisation of source parameters to define optimum setpoints for CIGSe runs:

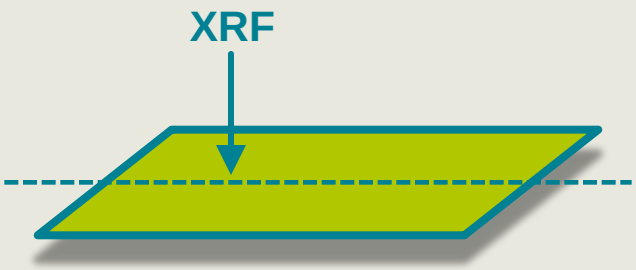
- Precise source control and stability allow straight-forward optimisation
- Setpoints for Cu/(Ga+In) & Ga/(Ga+In) defined

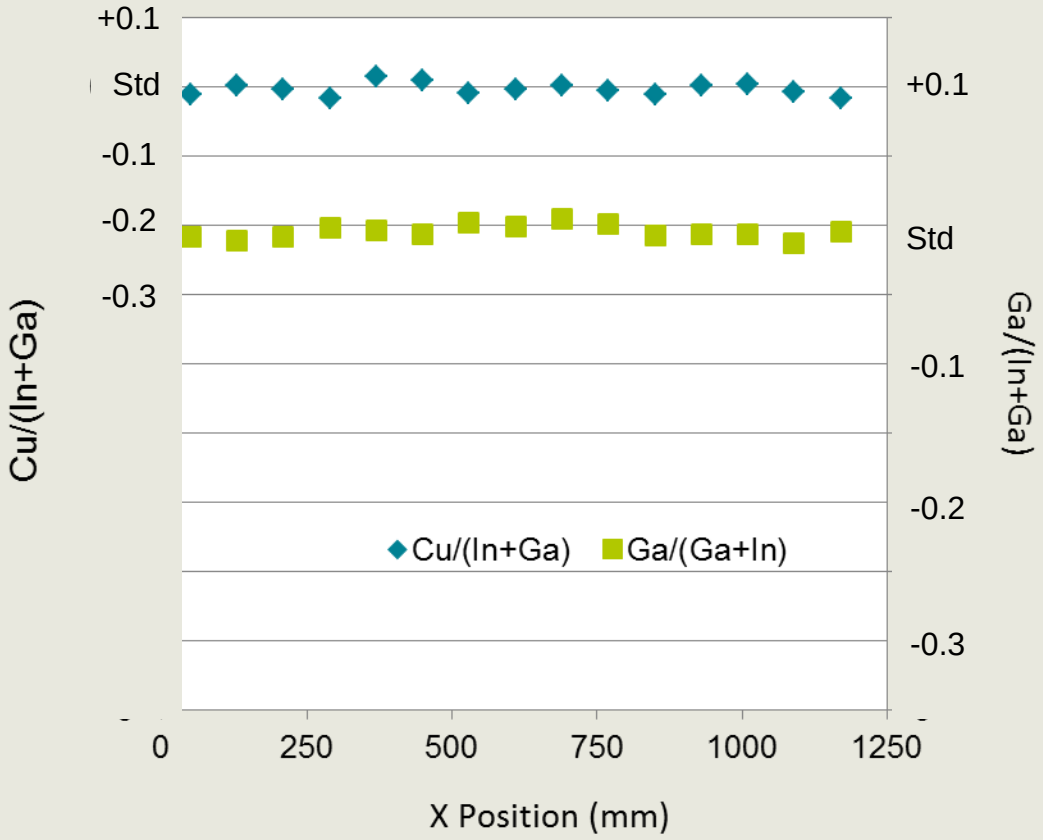


CIGSe-coater (Gen2) achieves excellent uniformity of +/- 2% across individual substrates

Results: Homogeneity of metal ratios along substrate length (measured by XRF)

Uniformity across substrate +/- 2%

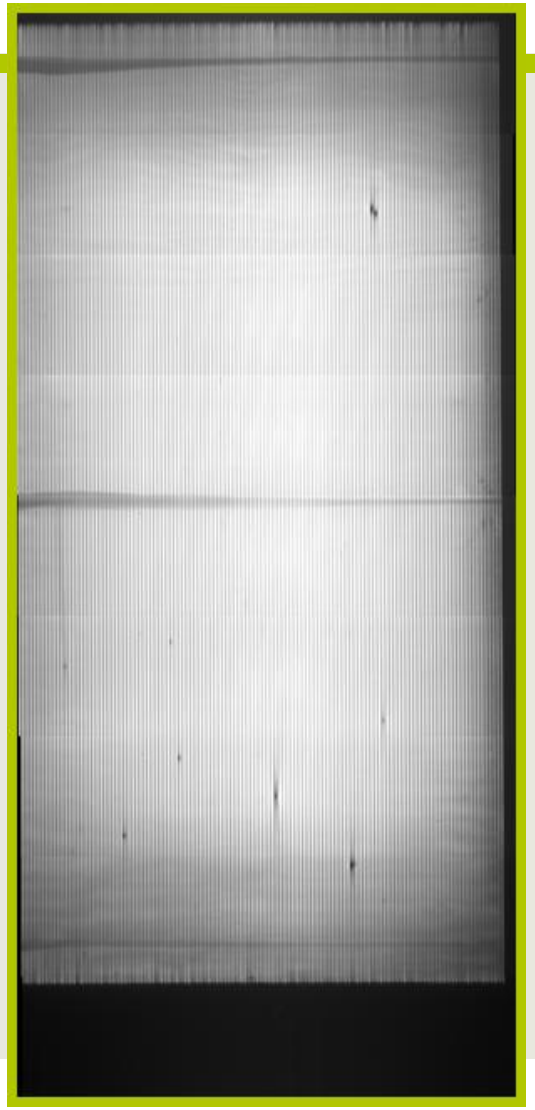




Good uniformity in composition leads to good uniformity in electrical performance

Homogeneity of metal ratios along substrate length

- measured by XRF
- Uniformity across substrate +/- 2%
- Very homogeneous electroluminescence image of large area modules



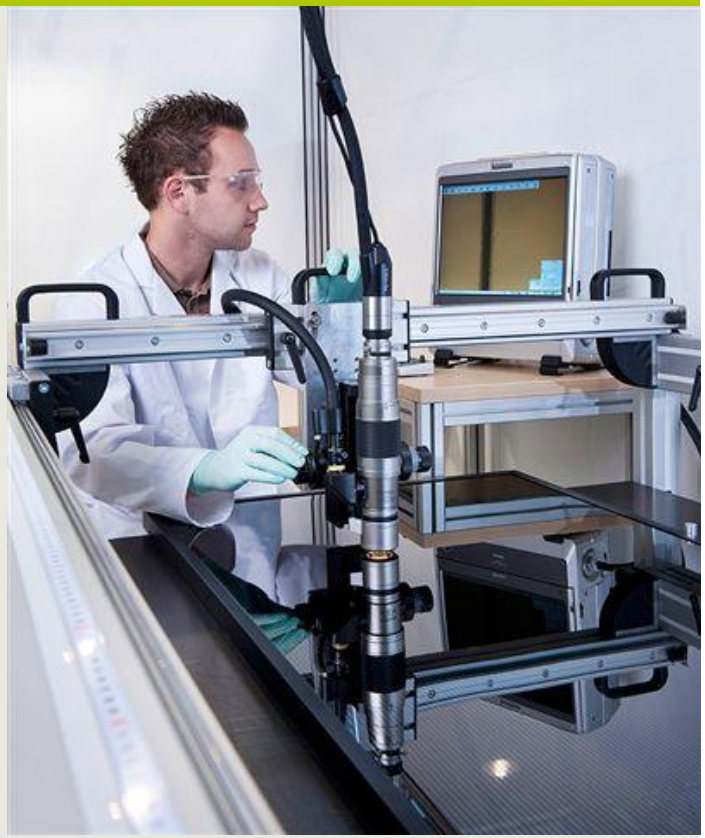
Best module from Soltecture production line generates 98W = 13.1 % app. area efficiency

PV data of best module

- taken from Soltecture production line
- aperture area = 0.75m^2
- number of cells = 123

- 12.6 % externally confirmed (different module)

Pmp	eta	Voc	Isc	ff
98.2 W	13.14 %	72.8V	1.89 A	71.3 %
		592mV/cell	31,3mA/cm2	



CIGSe-coater (Gen2) achieves excellent long term stability of coating conditions

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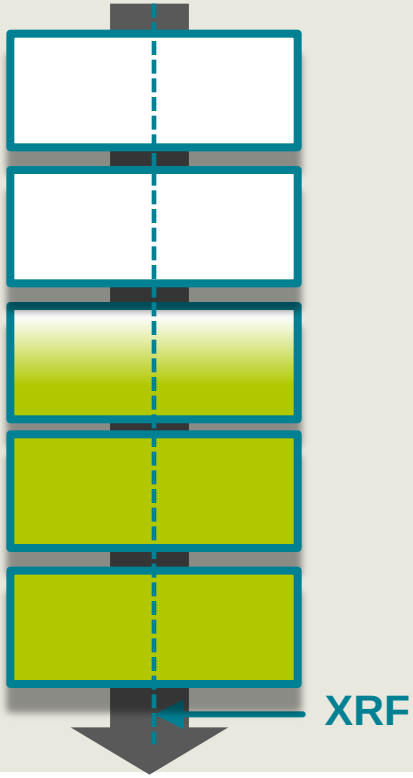
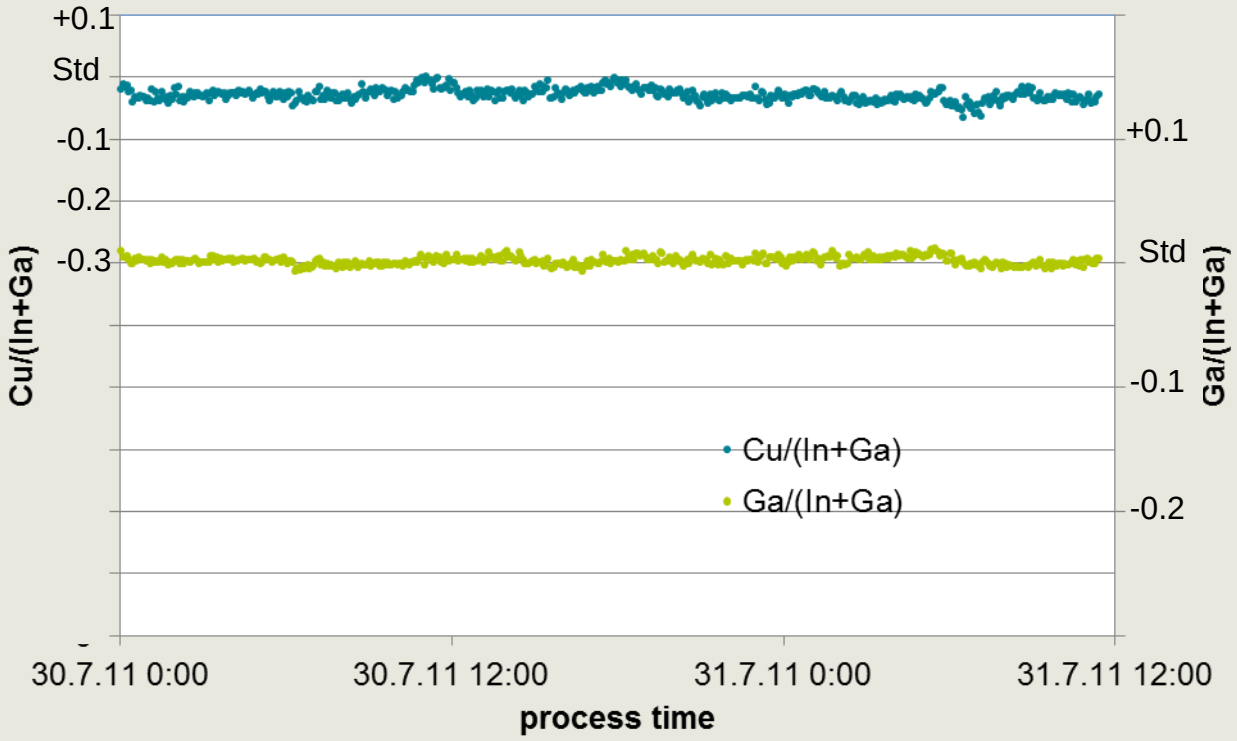
Composition of CIGSe layers on 125 cm x 65 cm sized substrates during 36 h of continuous operation run (measured by XRF) → Excellent substrate to substrate uniformity – key to successful scale up

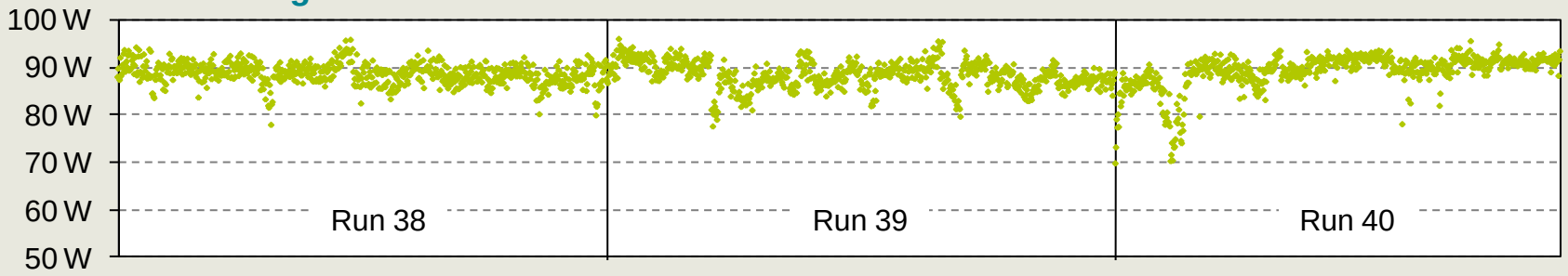




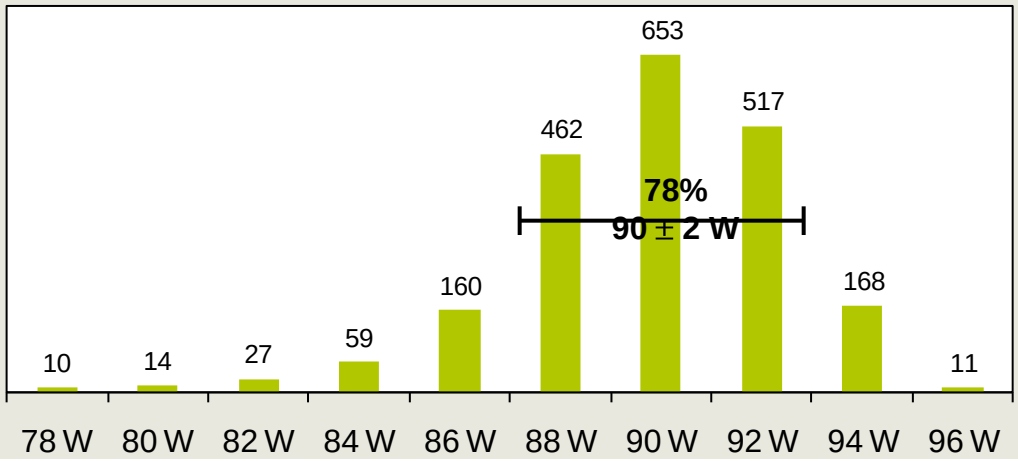
Soltecture's gen2 process has proven excellent process stability and narrow power distribution

POWER DISTRIBUTION OF 2.100 SEQUENTIALLY PROCESSED MODULES (FEB 11)

Scatter diagram



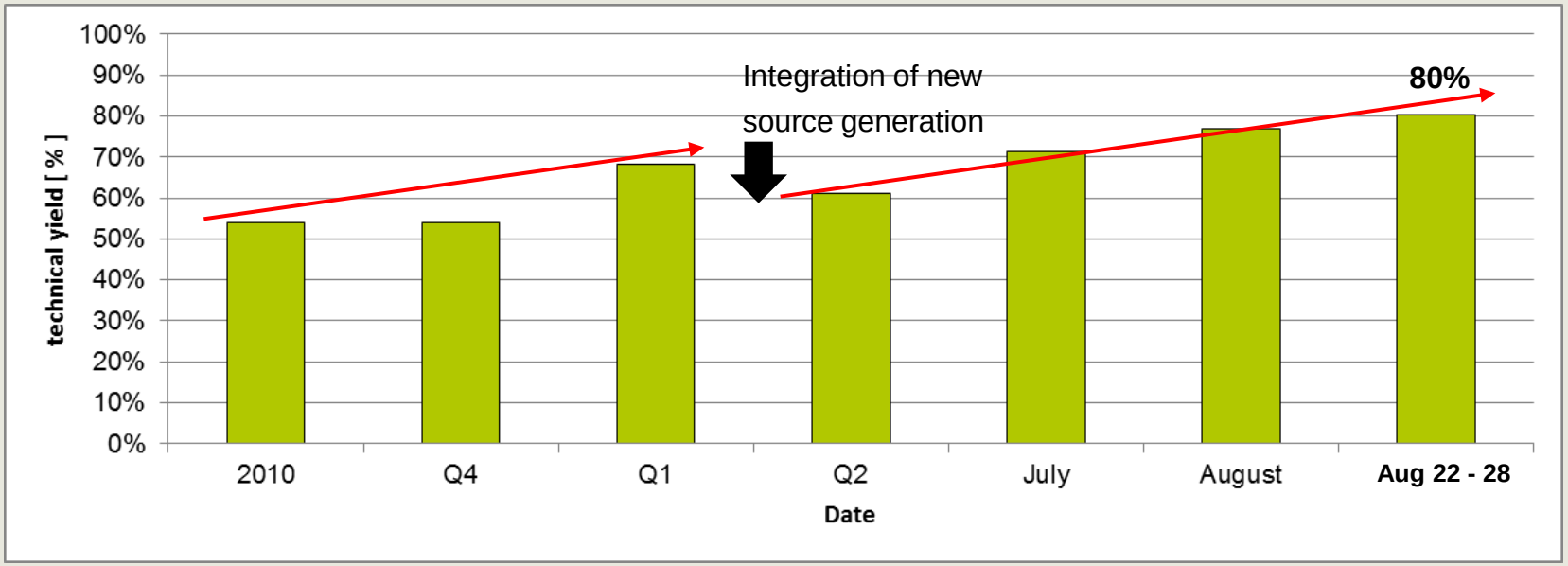
Histogram



90 W
= 12% aperture area efficiency
= 11% total area efficiency

Yield level of 80% proven
40% scrap reduction in less than one year

Evolution of Yield during ramp up of first coevaporation tool



First pass yield > 80%
Minimizing absorber related yield issues will lead to > 95%

Current Yield analysis sorted by production line section

- Total first pass yield > 80% level
- Electrical yield higher than 97%
- Back end yield constantly in the 97-98% range
- Front end yield P2/ZnO/P3: half of rejects due to CIGSe absorber issues
- By minimizing the number of rejects at coevaporation tool alone yield will improve by 7%
- By minimizing all other absorber related detractors, yield will improve to >95% level

Section	Yield
Front End w/o CIGSe	95%
CIGSe	93%
IV out of spec	98%
Back End	97%
Total	**84%**

Lessons learned during ramp up

Conclusions

- Ramp up of our new absorber technology to > 10% modules in less than 20 weeks
- Ramp up of yield to more than 80% in less than a year
- **due to high synergy effects between Gen01 and Gen02 technology**

- Production stability and quality assurance in CIS manufacturing require:
  - CIS related expertise of the manufacturer's technology team
  - Production experience with CIS-based technology
  - Scientific support
  - Industrial knowledge
- → there is no turn key CIS technology yet, Soltecture and it's team combines more the 200 person years of CIS experience and more than 5 years in continuous production –> prerequisite for fast ramp up

PRODUCT QUALIFICATION

All relevant IEC test can be performed in soltecture's in-house module test center

Accelerated life-time test

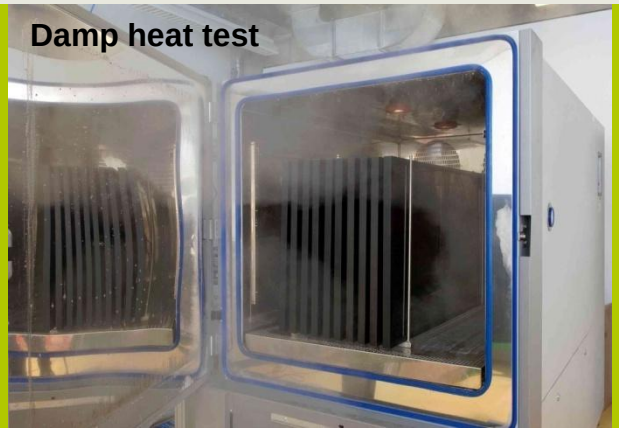
- Damp heat test
- Dry heat test
- Thermal cycling test
- Humidity-Freeze test
- UV irradiation
- Mechanical load and deformation test
- Light-soaking test

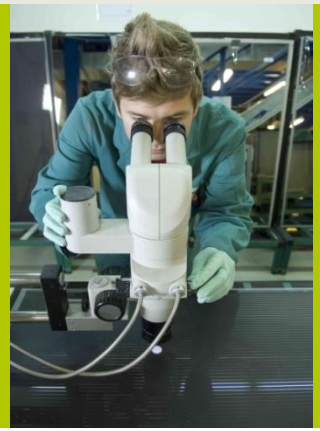
Thin-film analysis

- Electrical and optical analysis (a.o. Raman, PL)
- Microscopic analysis of layer structure (SEM)
- Homogeneity analysis
- X-ray analysis (XRF)

System test

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





Product qualification and certification
SCG-GEN2-HV-F (CIGSe) product

Test	Internal pass criteria		External pass criteria acc. IEC61646 / IEC6173
Mechanical load	P_{MPP} > **95%** after MLT **10 modules**	✓	P_{MPP} > 90% after final lightsoaking 2 modules
Humidity freeze test	**40 cycles** P_{MPP} > **95%** after 40 cycles **10 modules**	✓	10 cycles P_{MPP} > 90% after final lightsoaking 2 modules
Damp heat test	**2000h** P_{MPP} > **95%** after 2000h **10 modules**	✓	1000h P_{MPP} > 90% after final lightsoaking 2 modules
UV preconditioning	P_{MPP} > **95%** after UV test 2 modules	✓	P_{MPP} > 90% after final lightsoaking 2 modules
Reverse current overload test	P_{MPP} > 95% after test acccording to EN50380 **5 modules**	✓	P_{MPP} > 95% after test acccording to EN50380 1 module
Hot-spot test	no evidence of major visual defects insulation resistance >50MΩ **5 modules**	✓	no evidence of major visual defects insulation resistance >50MΩ 1 module

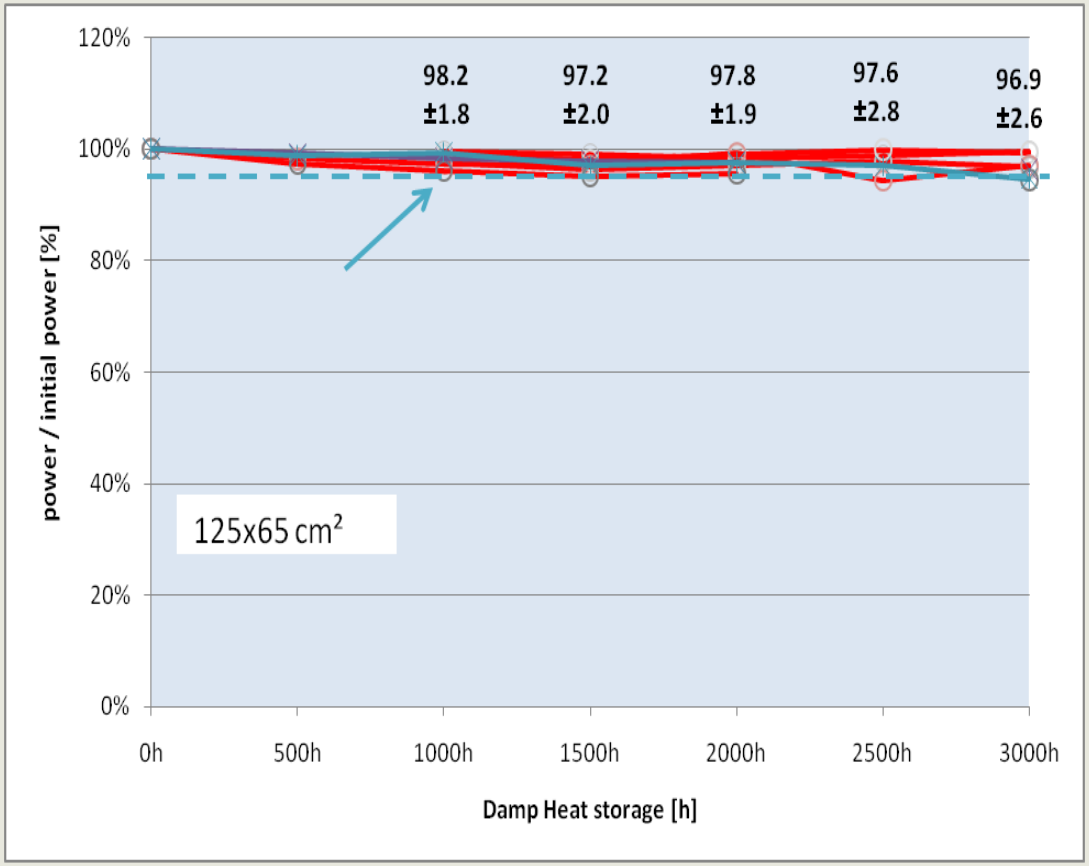
→ SCG-GEN2-HV-F modules are qualified according to IEC61646 and IEC61730 and passed the internal higher requirements

→ confirmation by TÜV Rheinland received in June 2011

Damp heat stability of Soltecture modules exceeds the IEC standard by three times

Encapsulation of CuInS2 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



IEC 61646 received after less than a year of process and product development

TÜVRheinland

Certificate

Registration No.: PV 60040123 Page 1 Report No.: 21171690.001

License Holder:
Soltecture GmbH
Groß-Berliner Damm 149
12487 Berlin
Germany

Manufacturing Plant:
Soltecture GmbH
Groß-Berliner Damm 149
12487 Berlin
Germany

Product:
PV Module
Type:
Linion 75 F
Linion 80 F
Linion 85 F
Linion 90 F
(power range: 74.7 to 91.3 Wp) [1]

Basis:

☒ IEC 61646: 2008
EN 61646: 2008
"Thin-film terrestrial photovoltaic (PV) modules - Design qualification and type approval"

• Qualified, IEC 61646
• Periodic inspection

☒ Factory inspection
To document the consistent quality of the product factory inspections are performed periodically.

Remarks:
- The details of the factory inspection are documented in report no. 21215425.
[1] The specified power class includes the tolerance which is mentioned on the type label.

Conditions:
The product test is voluntarily according to technical regulations. Any change of the design, materials, components or processing may require the repetition of some of the qualification tests in order to retain type approval.
The certificate has a validity of 5 years counting from date of issue.

Certification body

Cologne, 20 July 2011

Dipl.-Ing. M. Adrian

TÜV Rheinland LGA Products GmbH, Tillystrasse 2, D-90431 Nürnberg / Contact: + 49 221 806 2477 email: enertest@de.tuv.com

- Total module size: 1.25 m x 0.65 m (aperture area: 1.215 m x 0.615 m)

UNIQUE SYSTEM SOLUTIONS

Soltecture‘s unique flatroof solution

Fast and easy installation

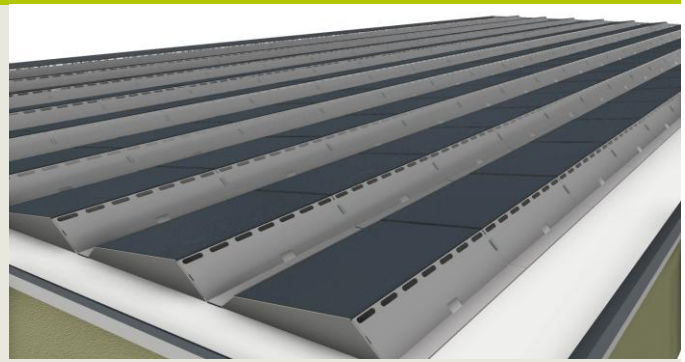
- Module carries its mounting system
  ⇒ Plug and Play, tool-free installation
- No roof penetration
- No or very low requirements for additional loads

Applicable on large commercial roof-tops

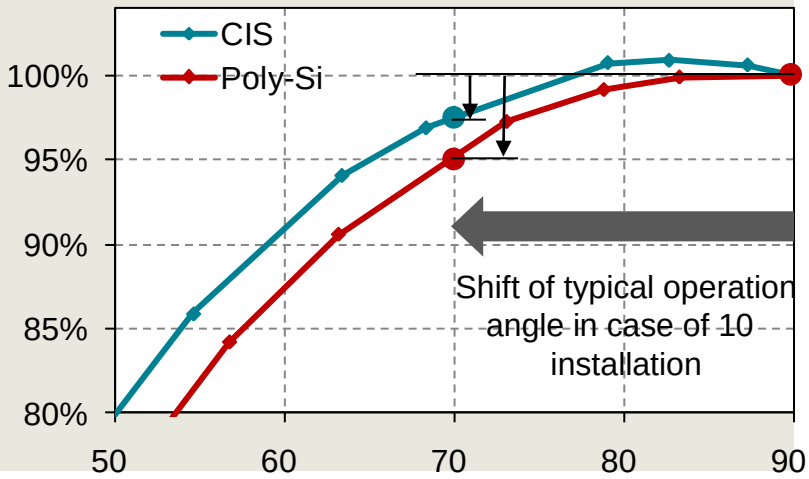
- System weight and wind load at least 30% lower than for standard solutions on the market
- Unique solution for building with very low load tolerance

High energy yield

- On-roof power density comparable to c-Si solutions due to 10° slope allowing low distance between modules lines
- Very low output reduction by flat installation due to excellent performance under low insolation angles

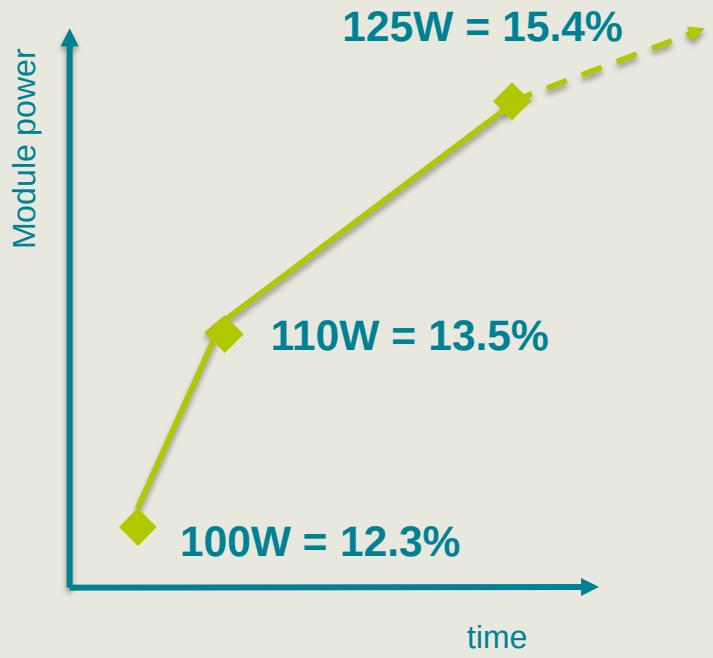


Dependence of the power output on the insolation angle



Outlook / road mapping

loss	improvement area
Scale up losses	Improvement of uniformity and temporal fluctuations
CIGSe	Reduction of defect density of absorber
CIGSe/CdS	Heterojunction / Contact layers
Scale up losses	Improved module design
CIGSe/CdS	Alternative buffer layer
CIGSe	High-temperature CIGSe coating



Summary / Conclusions

– The company has introduced a new one-step deposition process for high efficiency Cu(In,Ga)Se2 absorber layers based on coevaporation

– Ramp up of our new absorber technology took place in less than one year to 12.0% module efficiency, yield levels > 80% and including external certification

– Technology road map to >15% module efficiency defined and in progress

→ Coevaporation is very well compatable with mass production

Acknowledgement

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Cooperation partners:

and others

Thank you for your attention