Twenty Fourth Edition

Photovoltaics International

THE TECHNOLOGY RESOURCE FOR PV PROFESSIONALS

PICON Solar The state of the art in CIGS production

Fraunhofer ISE All-purpose cell and module architecture for low-irradiance and concentrator applications

Q CELLS State-of-the-art c-Si cell manufacturing: Trends in materials, processes and products identified in the 5th edition of the ITRPV roadmap

Enertis Fundamentals of commissioning large-scale PV power plants

SERIS Large-area solar irradiance mapping

Second Quarter, May 2014 www.pv-tech.org

inter solar
connecting solar business | EUROPE

MUNICH, GERMANY
June 4-6, 2014
Booth A2.630

JA SOLAR
www.jasolar.com

Harvest The Sunshine

Premium Cells, Premium Modules

JA Solar Holdings Co., Ltd.
NO.36, Jiang Chang San Road, ZhaBei, Shanghai 200436, China
Tel: +86 (21) 6095 5888 / 6095 5999 Fax: +86 (21) 6095 5858 / 6095 5959 Email: sales@jasolar.com; market@jasolar.com

Photovoltaics International

Published by:
Solar Media Ltd.,
5 Prescot Street,
London E1 8PA, UK
Tel: +44 (0) 207 871 0122
Fax: +44 (0) 207 871 0101
E-mail: info@pv-tech.org
Web: www.pv-tech.org

Publisher: David Owen

Head of Content: Ben Willis
Deputy Head of Content: John Parnell
Commissioning Editor: Adam Morrison
Sub-Editor: Steve D. Brierley
Senior News Editor: Mark Osborne
Reporters: Andy Colthorpe, Lucy Woods
Design: Tina Davidian
Production: Daniel H Brown, Sarah-Jane Lee

Sales Director: David Evans
Account Managers: Adam Morrison,
Graham Davie, Lili Zhu

While every effort has been made to ensure the accuracy of the contents of this journal, the publisher will accept no responsibility for any errors, or opinion expressed, or omissions, or for any loss or damage, consequential or otherwise, suffered as a result of any material here published.

Cover image: Solibro's CIGS quality inspection system.

Image courtesy of André Forner for Solibro

Printed by Buxton Press
Photovoltaics International
Twenty Third Edition
First Quarter 2014
Photovoltaics International is a quarterly journal published in February, May, August and November.

Distributed in the USA by Mail Right International, 1637 Stelton Road B4, Piscataway, NJ 08854.

ISSN: 1757-1197

The entire contents of this publication are protected by copyright, full details of which are available from the publisher. All rights reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means – electronic, mechanical, photocopying, recording or otherwise – without the prior permission of the copyright owner.

USPS Information
USPS Periodical Code: 025 313

Periodicals Postage Paid at
New Brunswick, NJ
Postmaster: Send changes to:
Photovoltaics International,
Solar Media Ltd., C/o 1637 Stelton
Road, B-4, Piscataway, NJ 08854, USA

Foreword

Signs earlier in the year of the global industry entering a growth phase have now been confirmed beyond any doubt. Almost all the big-name suppliers have now announced some form of manufacturing capacity expansion, a trend that analysts agree will only gather pace as long as the levels of demand predicted over the next few years turn out to be correct.

In this issue of *Photovoltaics International* we bring you a comprehensive analysis of where the capacity expansions will happen. Using data exclusively compiled from our sister website, pv-tech.org, we reveal where and by how much some of the big-name PV equipment suppliers are beginning to expand their operations, and when those expansions will come.

All the signs point to a trend of tentative expansions in the latter part of 2013 gathering pace this year, before being rolled out in earnest in 2015. This will mark a final thaw in the spending freeze by manufacturers on new equipment, at which point the rest of the industry is likely to begin to feel the effects of the upturn. When that time comes, the industry can expect manufacturers to be looking to squeeze out the last drops of value from existing technologies through increased efficiencies and materials savings.

As always, *Photovoltaics International* brings together the most up to date thinking on the state of the art in PV science and engineering. In this issue we present a detailed analysis by scientists at Q Cells of the recently published fifth edition of the International Technology Roadmap for Photovoltaic, an industry blueprint for future equipment trends. Their paper (p.30) explores the potential for further cost savings in c-Si module manufacturing using currently available technologies.

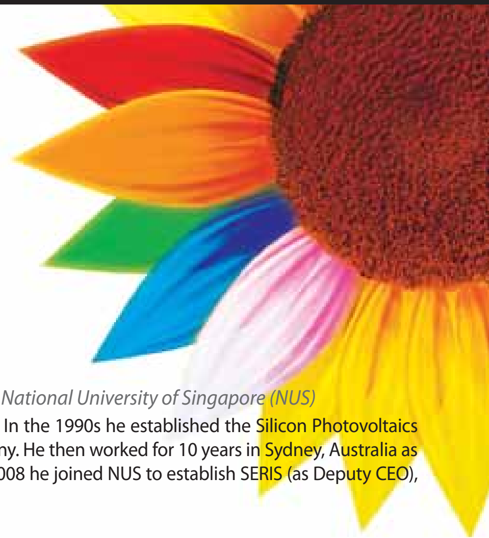
We also look at the other side of the PV coin in the first of a two-part series of papers by PICON Solar exploring the prospects for CIGS thin-film technology. The fact that the production costs for CIGS modules run higher than their c-Si counterparts has long been a thorn in CIGS' side. PICON's paper (p.69) assesses the opportunities for cost reductions in CIGS modules and asks whether a CIGS comeback is on the cards.

And not to ignore the ultimate objective of this industry, which is of course to see more solar PV capacity in the energy mix, researchers the Solar Energy Research Institute of Singapore reveal work they have been doing to improve the forecasting of PV system output. Their paper on p.91 describes a new methodology for more accurately mapping solar irradiance and how this can be used to better plan the integration of variable PV system output into the grid.

I hope you will find this edition of *Photovoltaics International* as informative and valuable as ever.

Ben Willis
Head of Content
Solar Media Ltd

Photovoltaics International



Photovoltaics International's primary focus is on assessing existing and new technologies for "real-world" supply chain solutions. The aim is to help engineers, managers and investors to understand the potential of equipment, materials, processes and services that can help the PV industry achieve grid parity. The Photovoltaics International advisory board has been selected to help guide the editorial direction of the technical journal so that it remains relevant to manufacturers and utility-grade installers of photovoltaic technology. The advisory board is made up of leading personnel currently working first-hand in the PV industry.

Editorial Advisory Board

Our editorial advisory board is made up of senior engineers from PV manufacturers worldwide. Meet some of our board members below:

Prof Armin Aberle, CEO, Solar Energy Research Institute of Singapore (SERIS), National University of Singapore (NUS)

Prof Aberle's research focus is on photovoltaic materials, devices and modules. In the 1990s he established the Silicon Photovoltaics Department at the Institute for Solar Energy Research (ISFH) in Hamelin, Germany. He then worked for 10 years in Sydney, Australia as a professor of photovoltaics at the University of New South Wales (UNSW). In 2008 he joined NUS to establish SERIS (as Deputy CEO), with particular responsibility for the creation of a Silicon PV Department.

Dr. Markus Fischer, Director R&D Processes, Hanwha Q Cells

Dr. Fischer has more than 15 years' experience in the semiconductor and crystalline silicon photovoltaic industry. He joined Q Cells in 2007 after working in different engineering and management positions with Siemens, Infineon, Philips, and NXP. As Director R&D Processes he is responsible for the process and production equipment development of current and future c-Si solar cell concepts. Dr. Fischer received his Ph.D. in Electrical Engineering in 1997 from the University of Stuttgart. Since 2010 he has been a co-chairman of the SEMI International Technology Roadmap for Photovoltaic.

Dr. Thorsten Dullweber, R&D Group Leader at the Institute for Solar Energy Research Hamelin (ISFH)

Dr. Dullweber's research focuses on high efficiency industrial-type PERC silicon solar cells and ultra-fineline screen-printed Ag front contacts. His group has contributed many journal and conference publications as well as industry-wide recognized research results. Before joining ISFH in 2009, Dr. Dullweber worked for nine years in the microelectronics industry at Siemens AG and later Infineon Technologies AG. He received his Ph. D. in 2002 for research on Cu(In,Ga)Se2 thin-film solar cells.

Julia Hamm, president and CEO, Solar Electric Power Association (SEPA)

SEPA is an educational non-profit organization dedicated to helping utilities integrate solar power into their energy portfolios. Prior to leading SEPA, Julia Hamm worked as a senior associate at ICF International where she supported the US Environmental Protection Agency with implementation of its ENERGY STAR programme. She holds a Bachelors of Science in Business Management from Cornell University.

Yong Liu, Chief Operating Officer and Chief Technology Officer, JA Solar

Yong Lui has more than 15 years of operation management experience at semiconductor wafer and solar cell manufacturing facilities. Prior to joining JA Solar, he served as fab director at Semiconductor Manufacturing International Corporation (SMIC), responsible for running three 12-inch wafer foundry fabs, which were the most advanced wafer fabs in China. Mr. Liu received his master's degree in solid state chemistry and bachelor's degree in solid state physics from the University of Science and Technology of China in 1992 and 1990, respectively.

Florian Clement, Head of Group, MWT solar cells/printing technology, Fraunhofer ISE

Dr. Clement received his Ph.D in 2009 from the University of Freiburg. He studied physics at the Ludwigs-Maximilian-University of Munich and the University of Freiburg and obtained his diploma degree in 2005. His research is focused on the development, analysis and characterization of highly efficient, industrially feasible MWT solar cells with rear side passivation, so called HIP-MWT devices, and on new printing technologies for silicon solar cell processing.

Sam Hong, Chief Executive, Neo Solar Power

Dr. Hong has more than 30 years' experience in solar photovoltaic energy. He has served as the Research Division Director of Photovoltaic Solar Energy Division at the Industry Technology Research Institute (ITRI), and Vice President and Plant Director of Sinonar Amorphous Silicon Solar Cell Co., the first amorphous silicon manufacturer in Taiwan. Dr. Hong has published three books and 38 journal and international conference papers, and is a holder of seven patents. In 2011 he took office as Chairman of Taiwan Photovoltaic Industry Association.

Matt Campbell, Senior Director, Power Plant Products, SunPower

Matt Campbell has held a variety of business development and product management roles since joining the SunPower, including the development of the 1.5MW AC Oasis power plant platform, organized SunPower's power plant LCOE reduction programmes, and the acquisition of three power plant technology companies. Campbell helped form a joint venture in Inner Mongolia, China for power plant project development and manufacturing. He holds an MBA from the University of California at Berkeley and a BBA in Marketing, Finance, and Real Estate from the University of Wisconsin at Madison.

Ru Zhong Hou, Director of Product Center, ReneSola

Ru Zhong Hou joined ReneSola as R&D Senior Manager in 2010 before being appointed Director of R&D in 2012. Before joining ReneSola he was a researcher for Microvast Power Systems, a battery manufacturer. His work has been published in numerous scientific journals. He has a Ph.D. from the Institute of Materials Physics & Microstructures, Zhejiang University, China.

Contents

A new day has dawned,
The future is bright.
Suntech – Be Unlimited!
Learn more at: ***www.suntech-power.com***

SUNTECH
BE UNLIMITED

Fab & Facilities

SunPower's PV project pipeline tops 7.5GW as demand exceeds supply

Major PV energy provider SunPower has said that demand for its PV modules has exceeded supply and that its PV project pipeline has topped 7.5GW, boosted by around 300MW of secured projects through its majority shareholder, the oil giant Total.

Significantly, management noted that Fab 4 technology and processes would not only produce its highest cell efficiencies but would also enable module production costs to be reduced by up to 35%. Capital expenditures in the second quarter of 2014 were expected to be in the range of US$30 million to US$40 million mainly related to the ramp in construction of Fab 4, according to the company.

SunPower also noted that its project pipeline included 4GW in the Americas, 1.7GW in the MENA region, 1.45GW in the APAC region, notably Japan and China, and 500MW across Europe. SunPower's project pipeline has increased by 1.5GW since May, 2013.

The company noted that its global distributed generation (DG) business deployments in the first quarter of 2014 totalled 108MW, and that demand continued to exceed supply.

Source: SunPower

SunPower is ramping production capacity after demand for its modules exceeded supply.

Expansion

Trina Solar guides over 1GW of PV module shipment increase in 2014

Trina Solar reached PV module shipments in 2013 of approximately 2.58GW, over 1GW above shipment levels achieved in 2012.

Source: Trina Solar

Trina Solar is to expand capacity on the back of increase shipments.

Due to expected strong demand in 2014, the company guided shipments to increase a further 1GW to between 3.6GW to 3.8GW. Trina Solar reported full-year net revenue of US$1.77 billion, an increase of 36.9% from US$1.30 billion in 2012.

With Trina Solar guiding over 1GW of increased shipments in 2014, manufacturing capacity is expected to keep pace. Ingot/wafer production stood at 1.4GW at the end of 2013, with plans to expand capacity slightly to approximately 1.7GW by the end of the year.

The company noted that in-house solar cell capacity stood at 2.5GW at the end of 2013, while PV module production stood at 2.8GW. However, the recent Hongyuan acquisition will result in solar cell capacity to around 3GW and module capacity to 3.8GW by the end of 2014.

Expansion and manufacturing line upgrades will result in capital expenditures reaching between US$230 million to US$250 million in 2014.

negative 20.6% in 2012.

Wuxi Suntech upgrading and adding PV production capacity

Wuxi Suntech is currently upgrading cell and module production lines in China ahead of plans to increase in-house module capacity in 2014, according to its recently appointed CEO, Eric Luo.

In an interview at PV Tech's headquarters in London, England, Luo said that Wuxi Suntech was upgrading lines to improve conversion efficiencies and expand module production to between 2.4GW to 2.5GW, a 20% increase from official production levels at the end of 2011.

Luo said that the intention was to expand in-house capacity by the end of 2014 to between 3GW and 3.5GW. According to the last published annual report of Suntech Power Holdings in 2011, Wuxi Suntech's wafer and ingot production capacity stood at 1.6GW, while its cell and module capacity stood at 2.4GW.

The Wuxi Suntech CEO highlighted that the increased production and capacity expansions were required to support parent company Shunfeng's drive to further its downstream PV project business, which currently has a 3GW pipeline.

Powerway partners with Sungrow and InnoVent on major collaboration plans in Africa

Powerway Renewable Energy is building a major stake in local manufacturing in South Africa and using the base to expand business opportunities across the African continent.

Having already announced a JV partnership with tier one PV manufacturer, JA Solar, to establish a PV module assembly plant in Port Elizabeth with an initial nameplate capacity of 150MW, Powerway has attracted Sungrow Power, the third largest PV inverter manufacturer in the world, to establish inverter manufacturing at the same facility.

Powerway has been operating as a PV project developer and PV systems integrator in South Africa for two years, one of a

Source: REC Solar

REC Solar is planning a US$70 million capacity expansion.

number of China-based PV manufacturers that have successfully won major supply orders under the South African Renewable Energy Independent Power Producer Procurement Programme (REIPPPP).

The programme has attracted major international project developers as well as leading component suppliers to establish satellite manufacturing operations in the country as over 1GW of PV projects were sanctioned under the first two REIPPPP rounds and several utility-scale projects were completed in 2013.

JA Solar beats guidance on increased outsourcing demand; adding 1GW module capacity

Major tier-one PV manufacturer JA Solar reported better than guided shipments for the fourth quarter of 2013, while ending two years of quarterly losses on revenue of US$357.3 million.

The company experienced increased demand for solar cells and PV modules, notably in Asia Pacific due to continued outsourcing from Japan-based PV suppliers. JA Solar is planning to expand solar cell production capacity to 2.8GW, a 300MW increase and expand PV module capacity to match cell capacity with a significant 1GW expansion.

JA Solar said the cell and module expansions would be completed during the second quarter of 2014.

REC Solar spending US$70 million on planned 300MW capacity expansion

Running at full-capacity and benefiting from the weakness of remaining European module manufacturing competitors in Europe, REC Solar ASA is planning to expand capacity 1GW in 2014 and a further 300MW in 2015 to meet demand.

The company expects to undertake module assembly line de-bottlenecking in the first quarter of 2014 at its fab in Singapore to provide a full-year PV module capacity of 940MW and a nameplate capacity of 1GW, up from 820MW at the end of 2013.

Milestones

SunEdison touts module outsourcing model after hitting 1GW milestone

Photovoltaics energy provider, SunEdison, has claimed to have reached a new milestone by hitting 1GW of outsourced PV module production in under three years.

The company announced in January 2013 that it had previously hit the millionth module production mark with its branded 'Silvantis' series modules with major outsourcing partner, Flextronics at its facility in Johor, Malaysia.

SunEdison has been leveraging its in-house polysilicon and solar wafer production capacity to ink outsourcing deals in solar cell production through to module assembly.

Solargiga expects PV outsourcing business with Sharp to rise over 30% in 2014

Solargiga Energy Holdings, the largest solar PV outsourcing supplier to Sharp Corporation in China, expects business with the Japanese electronics giant to expand by more than 30% in Sharp's 2014 financial year.

Solargiga noted that in 2013, shipment volume of PV modules increased by approximately 299.5% from the previous year and was predominantly attributable to its major OEM deal with Sharp. PV module shipments in 2012 had only been 55.7MW, according to the company.

The company noted that it had an annual capacity of approximately 1.2GW of monocrystalline silicon ingot production and 900MW for solar wafer production, as well as an annual capacity of approximately 300MW and 400MW for multicrystalline cells and modules production, respectively.

However, its module production capacity has not kept pace with the growing outsourcing demands of Sharp. The Japanese firm has benefited from being the major supplier in the second largest global PV market in 2013, while negating capacity expansions and instead outsourcing an increasing amount of module production to meet domestic demand.

To meet the expected increase in outsourcing from Sharp in 2014, Solargiga noted that it had attracted Kinmac Holding and Sunvision Capital to invest a further RMB100 million (US$15.9 million approx) in module manufacturing subsidiary, Jinzhou Yangguang to expand capacity.

However, Solargiga noted that Jinzhou Yangguang was being force to outsource module production to third-party subcontractors to meet "surging demand" from Sharp.

Financial Trouble

Chaori Solar closes Shanghai plant as de-listing looms

Bankrupt PV module manufacturer Shanghai Chaori Solar has stopped production at its Shanghai headquarters as customers cancel orders and it struggles to generate cash flow.

The company was the first in China to default on a bond and has posted two years of losses, with the result that its shares and bonds are expected to be de-listed on the Shenzhen Stock Market when it issues 2013 annual report at the end of April. The company has already warned about expected losses for last year and de-listing.

The company said it was collaborating with other firms to keep several other plants open, including four solar cell production lines (Jiujiang) with Dragon Optical, and was seeking similar arrangements for its Shanghai production lines.

Bosch providing €50 million in aleo solar liquidation

Plans have been agreed at the aleo solar EGM for the company to wind down through a liquidation, with as much as €50 million (US$69.1 million) of support provided by parent company Robert Bosch in order to avoid bankruptcy proceedings.

The decision clears the way for SCP Solar the JV company established by

Source: aleo solar

Aleo solar has seen revenues fall by 55%.

Sunrise Global Solar Energy and Japanese manufacturing machinery producer, CHOSHU Industry to own and operate aleo solar's module manufacturing plant in Germany, saving around 200 jobs.

The aleo brand will be used by the JV, which will operate the plant under the name, AS Abwicklung und Solar-Service AG.

Wuxi Suntech requires US$1.26 billion in working capital

Shunfeng Photovoltaics is expected to need US$1.26 billion in working capital requirements for the next 12 months once its takeover of Wuxi Suntech is finalised, financial filings reveal.

Shunfeng reported that the expanded company, which would include Wuxi Suntech needed the working capital primarily for the funding of 35 existing PV power projects (890MW) currently under EPC contracts.

The acquisition of Wuxi Suntech via the Wuxi bankruptcy court will enable Shunfeng to initially shed a significant tranche of Wuxi Suntech's debt, which was documented to be around US$2.75 billion.

Aleo solar 2013 report shows revenues fell by over 50%

Aleo solar has reported negative operational earnings of almost 74% in its full-year report for 2013 while revenues have fallen by over 55%, as the company prepares to enter liquidation.

Full-year figures published by the company revealed operational earnings stood at €-92 million (US$127 million) for the year. In 2012 the figure had been €-77 million (US$106 million).

These results are marginally better than preliminary figures for the year, released by the company earlier in the month, which stated that aleo solar expected losses for 2013 to total as much as €100 million (US$136.7 million).

Full-year revenue stood at €124.9 million (US$172.64 million) for the year, while in 2012 the full-year revenue was €279.9 million (US$386.9 million).

Indosolar looks to restructure debt as profits feel the pinch

Indian PV manufacturer Indosolar has asked to have its debt restructured because it says low equipment prices mean it is unable to make a profit.

In a stock exchange filing last week, the Indian company said one of its plants, a 160MW plant in Greater Noida, Uttar Pradesh, had been idled because the high cost of production against the low prices for PV cells "did not yield margins".

This is the second time Indosolar has asked to have its debt restructured; in January 2012 the company was granted approval to restructure around US$31 million of its debt.

Fab & Facilities

Materials

Cell Processing

Thin Film

PV Modules

Power Generation

Overview of challenges in ultrathin substrate handling

Tim Giesen, **Raphael Adamietz**, **Guido Kreck**, **Tobias Iseringhausen** & **Roland Wertz**, Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Stuttgart, Germany

ABSTRACT

The positive expectations for the global PV market are driven by state-of-the-art PV products which have become economically attractive because of technical optimization. Nonetheless, scientists and engineers face the next generation of wafer-based PV technologies in terms of processing recipes and automation techniques. In this paper, motivations, challenges and advances relating to the handling of ultrathin PV substrates are identified for future application. A brief look out of the PV box at neighbouring disciplines in high-tech sectors will also be taken. The differences and advances in the automated handling of ultrathin substrates will be highlighted as well as the difficulties for transportation. The advanced production challenges of a gripper-based substrate movement will be accompanied by increased cleanliness requirements, as test results from the Fraunhofer IPA automation lab show.

Motivation of the PV industry for technology development

If we were to examine the path of the PV industry in relation to Gartner's Hype Cycle we could find ourselves somewhere after the 'trough of disillusionment' and on the 'slope of enlightenment'. Enlightenment? Yes, the global PV market seems to be on its way to stabilizing and recovering from the sector's self-made crisis. Regardless of the damaged confidence and the weak stability, the PV industry is being reanimated by market growth in Asia. For 2014, analysts expect the markets in China, Japan and the USA (with a new capacity between 8 and 12GW) to play the most important role. Europe is about to install up to 8GW, while new markets in South America, Southeast Asia and Oceania may contribute to further growth of the global market [1]. The positive developments in the PV markets will also have positive effects on the research and development of new crystalline PV technologies. As a consequence, the technological progress of PV products is reclaiming attraction. Initiatives for crystalline PV technology development and improvement will inevitably start to decrease the wafer thickness again: the silicon wafer still represents one-third of the cell's manufacturing costs [2].

Although the silicon bulk price is at a low level, the use of thin and ultrathin wafers is becoming more and more interesting. The material-saving argument is no longer the dominant research driver, as there are promising benefits expected from ultrathin substrates. The integration of PV cells on thinner substrates reduces the weight and broadens the area of their application. The reported increased versatility of ultrathin crystalline silicon substrates [3] facilitates a higher grade of customizability and may, for example, enable aesthetic issues with PV product designs to be addressed. Further opportunities for application are accompanied by the quest for increased cell efficiencies.

> "Although the silicon bulk price is at a low level, the use of thin and ultrathin wafers is becoming more and more interesting."

Overview of ultrathin cell technologies

Kerr et al. [4] reported a theoretical maximum efficiency of 29% for single-junction silicon PV cells in relation to the substrate thickness; a substrate thickness in the range 55–90µm was calculated, depending on the dopant density and type as well as the silicon quality. Sakata et al. [5] realized a conversion efficiency of 22.8% with a 98µm-thick HIT cell; according to those authors the fabrication of a 58µm-thick HIT cell will become more lucrative when the I_{sc} transmission losses can be reduced by the cell's design. Kray & McIntosh [6] demonstrated constant high cell efficiencies for 75µm float-zone substrates with a PERC structure. The motivation for further reductions in cell thickness is also reported in the International Technology Roadmap for Photovoltaic [7].

While wire-sawing technology is limited to the wafering of certain thicknesses, new approaches to fabricating an ultrathin silicon substrate are being researched. Brendel et al. [8] provide an overview of recent progress in kerf-less wafering techniques and differentiate the wafering from liquid, solid and gaseous silicon. R&D pursuits in the fabrication of ultrathin wafers entail the conversion of the solid substrate from discs into foils and finally into silicon layers.

Returning now to industrial reality, while the state-of-the-art PV production of crystalline PV cells has the know-how to benefit from continuous optimization processes, the emerging wafer-based technologies have yet to enter this process, although the market entry already begins at a higher point on the PV manufacturing learning curve. This will be significantly assisted by appropriate automation solutions for processes and transportation.

Challenges for the handling of ultrathin wafers

The manufacture of cells from ultrathin substrates is somewhat challenging, both for the handling during processes and for the transportation between processes. The success of a handling or transportation method for thin wafers is directly linked to the mechanical strength of the substrate. Maintaining the mechanical integrity of the wafer at the required standard is one of the most important issues that must be considered in the development of automated handling [9].

The challenges for wafer handling in terms of the mechanical strength of silicon wafers have been widely researched, and have been reported by Brun et al. [10] and Koeppge et al. [11], among others. The results of Popovich [12] demonstrate that a certain surface roughness has an enormous effect on

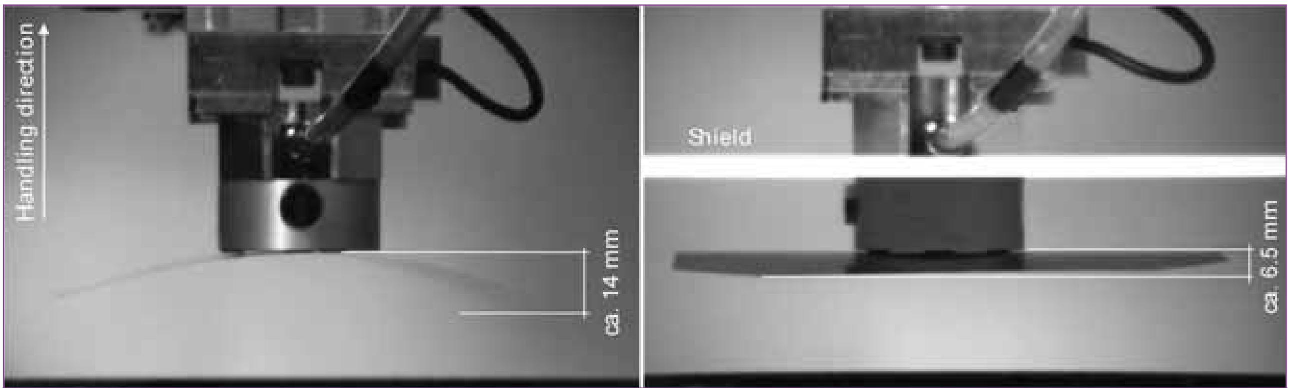


Figure 1. Deformation of thinned 125mm × 125mm ultrathin wafers during high-speed handling with a Bernoulli gripper (vertical acceleration 25m/s^2, travel velocity 3m/s). Aerodynamic issues become a more important factor in meeting future production throughput requirements.

the bending strength of 200µm silicon substrates. The strength of textured and polished samples is significantly higher than that of as-sawn samples. The same characteristic may be assumed for wafers with a reduced thickness. As reported in Schoenfelder et al. [13], a reduction in the substrate thickness leads to an enhancement in strength of small-area substrates: the fracture stress increases considerably in the 50–100µm thickness range. However, the increased fracture stress detected in multiple lab tests with homogeneous loads can not be directly assumed for the actual challenges in an industrial production environment where inhomogeneous loads frequently occur. Here, the reduced stability and stiffness of ultrathin substrates, paired with demands for a high production throughput [7], are facing yet-unresolved challenges.

Some of the automation solutions developed for thin PV wafers [14] may be directly adaptable to ultrathin wafer handling. Since temporary bonding techniques are not likely to be economically attractive to PV producers, an adaptation of pick-and-place methods from thin to ultrathin handling objects may be feasible. However, a general statement cannot be given, as investigations in automated handling have identified significant differences in the behaviour of large-format ultrathin (~50µm) PV wafers and thin (~160µm) PV wafers [15].

The potential benefits offered by ultrathin cells do not yet outweigh the production advantages of standard cells. But the usual technology life cycle is most likely not making an exception for PV products. Even if producers decide to leapfrog certain cell technologies, the appropriate automation concepts need to be identified more quickly than in the past in order to shorten the time taken to put the next-generation PV on the market. The big quest for competitiveness for new PV technologies based on ultrathin cells is enabling a fast improvable production by using capable equipment. By projecting this picture onto the handling automation, the gripper-based transportation of ultrathin substrates will fade in the spotlight.

In general, the goal of modern industrial production is to develop manufacturing methods which keep the working piece always positioned and in contact with a carrying device; the latter acts as a targeted permanent access for the collection of evolutionary data regarding the working piece.

In any case, relocation by pick-and-place operations will remain a necessary handling step in the manufacturing and processing of next-generation PV cells. Carrying devices such as the temporary carrier used in ultrathin semiconductor production are currently not suitable for PV throughputs. The pick-and-place of ultrathin PV wafers can be achieved by appropriate gripping methods, though the specified cycle times remain challenging. The handling and transportation of ultrathin wafers by using established gripping principles has revealed some differences in comparison with state-of-the-art wafers. Three types of gripper have recently been investigated in the Test and Demonstration Center of Fraunhofer IPA: these pneumatic end-effectors can be grouped into Bernoulli grippers, vacuum cup grippers and area vacuum grippers. A repeatable breakage-free transportation of thinned (50–70µm) 125mm × 125mm CZ wafers is possible if attention is paid to some interactions.

The gripping of flat ultrathin wafers by vacuum suction cups evokes selective stresses and strains, accompanied by relatively strong vibrations in the crystalline substrate. The detected vibrations not only result from the transportation/movement but also originate from an ordinary asynchronous compression of the activated suction cups. Such uncontrollable movements are typical for a vacuum cup application on flexible substrates. A certain amount of time is necessary to identify the suitable parameter settings for a workable pick-and-place application while not punching holes in the substrate. The employment of vacuum gripping for a high-volume wafer handling requires a more detailed study, especially for precise assembly tasks. It is therefore doubtful that vacuum cup-based handling has a future in ultrathin wafer handling automation.

> “Tests demonstrated that the direct handling of flat and ultrathin wafers by standard Bernoulli grippers causes strong deformations during pick-up and placement.”

Tests performed with a variety of settings demonstrated that the direct handling of such flat and ultrathin wafers by standard Bernoulli grippers causes strong deformations during pick-up and placement of the handled object. The implications of strong yet smooth deformations are unknown, as are universally valid absolute numbers for the limit of mechanical loads on wafers in general. The results of previous investigations were inconclusive. Deviations in the integrity of standard wafers have been found to be somehow gripper dependent: the investigation by Koeppge et al. [11] stated that an effect of handling by grippers can be characterized by deviations in the wafer's mechanical strength. The fact that the wafer oscillations were responsible for a change in wafer strength could not be confirmed.

At any rate, Bernoulli grippers are suitable for ultrathin wafer-handling operations, although the implications on throughput have to be considered. An increased throughput requires faster handling cycles, whereas the effect of air drag on the unstable substrates is considerable. The abilities of Bernoulli grippers in combination with optimized parameter tuning are convincing – it is possible to achieve precise positioning of substrates where necessary and fast handling where required. In the high-speed handling of ultrathin substrates a wind shield assists even more (see Fig. 1).

In a third test batch the area gripping of flat thin wafers produced acceptable results in all categories. Area grippers comprise a substrate-covering gripper body and model-dependent gripping-force activation. Bearing in mind that certain ultrathin substrates sporadically tend to form a bow, the limitation of the handling capability is reached when it comes to manipulating ultrathin handling objects with uneven or non-plate-like surfaces. For high-speed PV handling, the potential slip of tensioned wafers is contrary to the requirement of reliable positioning accuracy.

A large area support of the substrate offers handling benefits: deformations during the gripping phase are kept to a minimum, even in comparison with a shielded Bernoulli gripper. The full-area gripping of light pieces, however, also has a certain side effect. Waiting times for the wafer placement after handling may prolong the cycle time (up to 600ms) because of a sticking effect of the light and smooth substrate. An irritation of the ultrathin wafer during the release can result in breakage, chipped edges or other losses in quality of the working pieces when being blown off onto carriers, ring belts or rollers. Electrostatic gripping may offer an acceptable alternative, although the risk of polarization of the thin substrate requires slightly more complex solutions for multiple repetitive grippings of the same substrate. Most electrostatic gripping solutions make use of a full-area contact for ultrathin wafer support and blow-off functions, so the same side effects as for pneumatic area gripping will have to be taken into account in terms of particulate contamination on substrate and gripper surfaces.

Contamination challenges of gripping processes for cleanliness-critical products

Another point that should be addressed is the implication of the contact area. For example, area grippers distribute the gripping force on larger surfaces by using large contact areas between the gripper material and the wafer. While Bernoulli grippers are designed for so-called contactless handling, a vacuum suction gripper will patently 'print' the suction cup material on the substrate, as found in the laboratory investigation presented here (see Fig. 2). This is contrary to the trend whereby PV producers and equipment designers strive for a minimum of contact between devices and substrates.

For the investigation, different kinds of suction cup with a diameter of 9mm were tested for stain production on standard CZ wafers. First, all suction cups were run in by performing more than 2000 handling cycles. In a second step, the untouched as-cut wafers were gripped and released 20 times. Subsequently, the handled wafers (not pretreated) were slowly passed through an alkaline solution to evoke visible cup imprints.

As the results demonstrate in Fig. 2, the different contact materials have different implications for the surface condition. All wafer charges of silicone (SIT) cups and nitrile butadiene rubber (NBR) cups left significant imprints. The suction cup with a polyether ether ketone (PEEK) inlet, however, produced very slight imprints on one wafer, while other wafers in the PEEK batch had no marks.

It is assumed that a certain material deposition on the wafer's surface is caused by the abrasive contact during suction cup contraction in the vacuum gripping phase. As a consequence, the cup material at the contact point causes a different wettability of the solution in comparison to the untouched silicon surface. As producers have stated, there is no implication for the cell's electrical quality and only the aesthetic drawback remains, apart from the fact that an unknown and uncontrollable

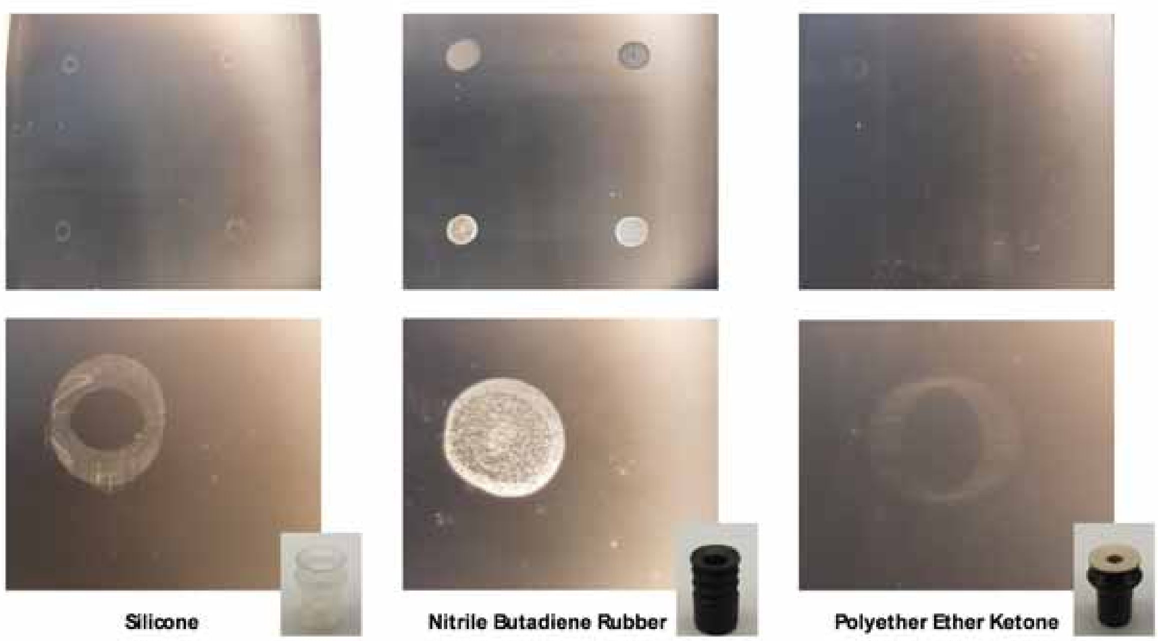


Figure 2. Visible imprints of different suction cup materials produced on as-cut wafers.

event occurs in the production chain. This appearance is negligible for thick wafers but may become an issue for ultrathin wafers: for the latter, surface homogeneity may be an even more important requirement, such as for new light-trapping techniques. Without a doubt, contact materials do have an increasing significance for the handling of thin substrates and have therefore been investigated in another experiment.

As substrates and functional layers become thinner, contact materials become more critical. Particles in the size range of a few microns may be generated from a touched material because of contact. In general, different contamination scenarios of a substrate are possible:

Generated particles caused by friction between the gripper and the handled substrate.

- Particles transferred from the gripper to the substrate.
- Particles transferred from supply media, such as compressed dry air.

To avoid, or at least diminish, these contamination factors, some counteractive measures are possible. Since friction between the gripper and the substrate is possible during gripping processes, it is important to consider more precisely the effect of frictional processes as a critical source of particles. In order to reduce particle generation to a minimum, it makes sense to take this aspect into consideration when selecting suitable materials. To do this, the emission of particles from tribologically stressed materials can be determined: airborne particles generated by the frictional process are detected by a particle counter and correlated with air cleanliness classifications in accordance with ISO 14644-1 (1999). This enables material pairings tested under the same stress parameters to be compared with one another, and the results obtained to be used to select the most suitable material combinations for the gripper system (see Fig. 3).

It is unlikely that contact between the gripper and the substrate can be avoided during a gripping process (even for so-called 'non-contact grippers'), so it is important to consider the *cleanability* of materials, as a contaminated gripper material could lead to contact transfer contamination. Cleanability describes the extent to which various forms of contamination (particulate, filmy, etc.) can be removed from a material surface under defined general test conditions (cleaning procedures, contamination quantities, roughness, etc.). Such a test ascertains the amount of contamination present on the surface before and after cleaning. In conjunction with the chemical resistance that determines the compatibility of materials with certain cleaning agents, the cleanability of

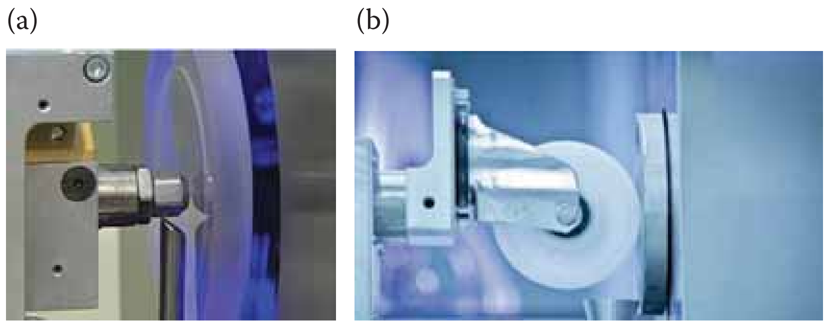


Figure 3. (a) Ball-disk test to simulate sliding friction; (b) roll-disk test to simulate rolling friction.

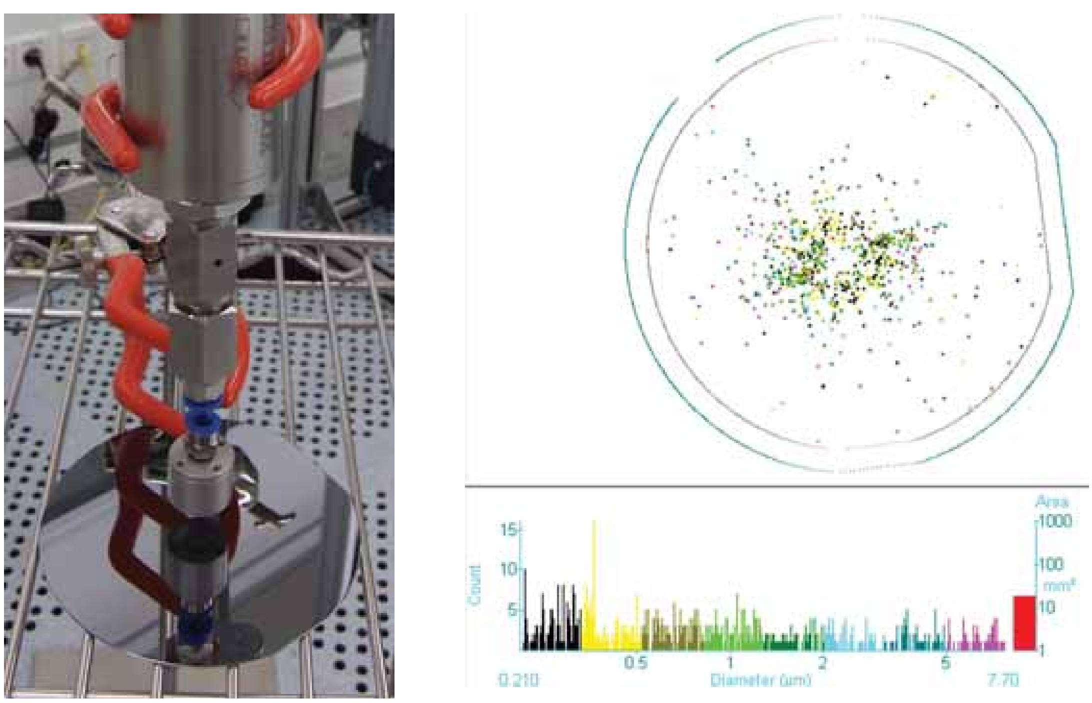


Figure 4. (a) Set-up of the ISO class 1 cleanroom handling experiment with a Bernoulli gripper above a clean and polished 4" silicon wafer. (b) Surface inspection result of one handled wafer after seven gripping cycles – 1.5 bar supply pressure, 7-sec activated gripping each cycle. Gain value 0.21–7.7µm: twenty times more particles.

a material may become an important assessment and selection criterion for a gripper system. Even if wafers are handled with a minimum of direct material contact, such as during Bernoulli gripping, a contamination of the substrate is possible.

> "The cleanability of a material may become an important assessment and selection criterion for a gripper system."

Fig. 4(a) shows the handling of a polished 4" wafer with a Bernoulli gripper; Fig. 4(b) shows the contamination assessment performed using a surface scanner (type: KLA Tencor Surfscan 6200) after Bernoulli handling of the previously clean substrate. Bearing in mind the general advantages of the minimum contact points of Bernoulli grippers, the implication of an activated Bernoulli gripper for the substrate's surface cleanliness was not clear. The necessity of using filtered compressed air for pneumatic grippers was investigated in a cleanroom experiment.

The test demonstrated the potential implications of automated handling using a Bernoulli gripper. In order to obtain a visible result, the test set-up was designed as a worst-case scenario, in which the wafer had to clear a gap of 5mm during picking up. Consequently, the wafer impacted on the gripper's end-stops, with parameter values being used that were not optimized but were realistic in relation to industrial applications. This material contact, along with the contamination of the compressed dry air (CDA) used, provoked the detected contamination shown in Fig. 4(b). To reduce this contamination factor, the additional use of filtration for receiving ultra-high purity CDA, as well as the use of abrasion-resistant contact materials, could be helpful. Moreover, all surfaces in direct contact with the CDA, for example pipes, have to be clean with regard to the considered critical contaminants. This will apply in particular to PV substrates when new cell technologies become more sensitive to contamination.

Challenges and solutions in other sectors

It is not just the PV industry that is steering towards thinner and contamination-sensitive substrates. The EC-funded project SMARTLAM aims at building complex three-dimensional components from stacks of structured and functionalized polymer films for microelectronics. Different additive and subtractive technologies are combined to cover a wide range of applications. Furthermore, polymer films with functional properties, such as anisotropic conductive properties, are applied (see Fig. 5). An overview of the technological approach has been recently published [16].

Besides the individual processing technologies, the handling of polymer films is an important aspect of the technological approach. Flexible materials are manipulated not only in industrial applications in the field of electronics, but also in, for example, the textile and automotive industries [17]. In particular the mechanical flexibility of the applied films and the sensitivity of the films pose numerous, as yet unresolved, challenges.

The size of the applied sheets is 150mm × 150mm with thicknesses down to 100µm. Different polymer materials (e.g. PI, PMMA, COC and PE) are applied, partly with structured or functionalized surfaces.

In contrast to rigid parts, the application of stresses leads to a change in the shape of thin, flexible parts. The influence of stresses caused by physical, thermal or chemical interaction therefore needs to be reduced to a minimum. Additionally, the manufacturing of the sheets leaves them with internal stresses, which causes them to bend without any further external influences. Generally the internal stresses need to be reduced beforehand, in order to decrease this bending effect. Furthermore, any deformation of a flexible part needs to be counteracted by the handling process itself.

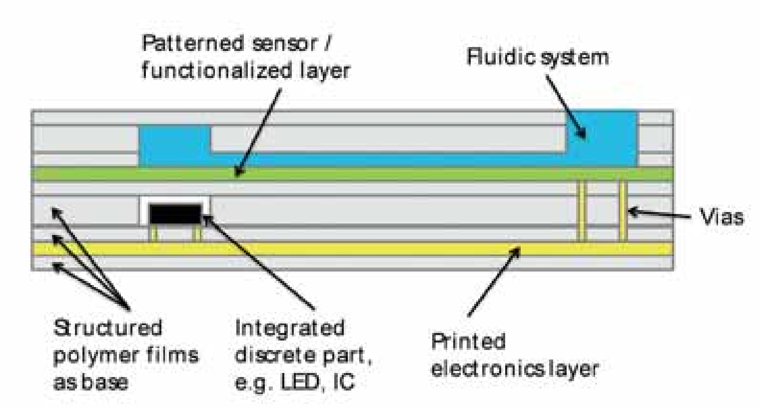


Figure 5. Example of a complex layer-based component.

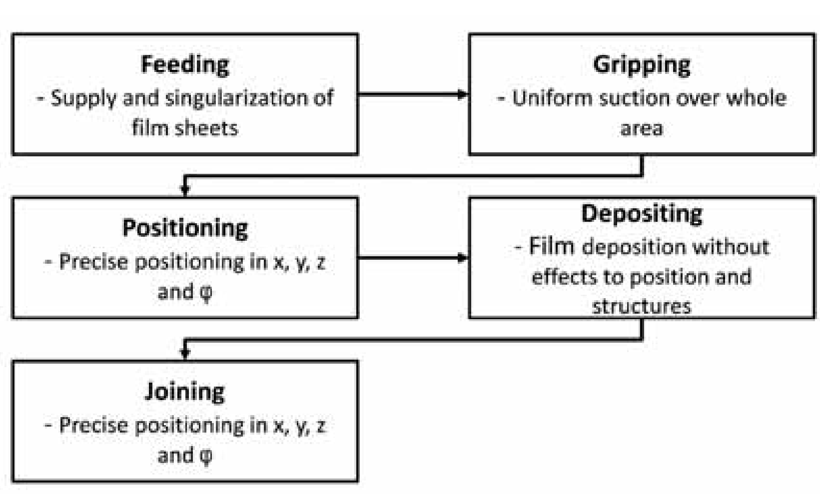
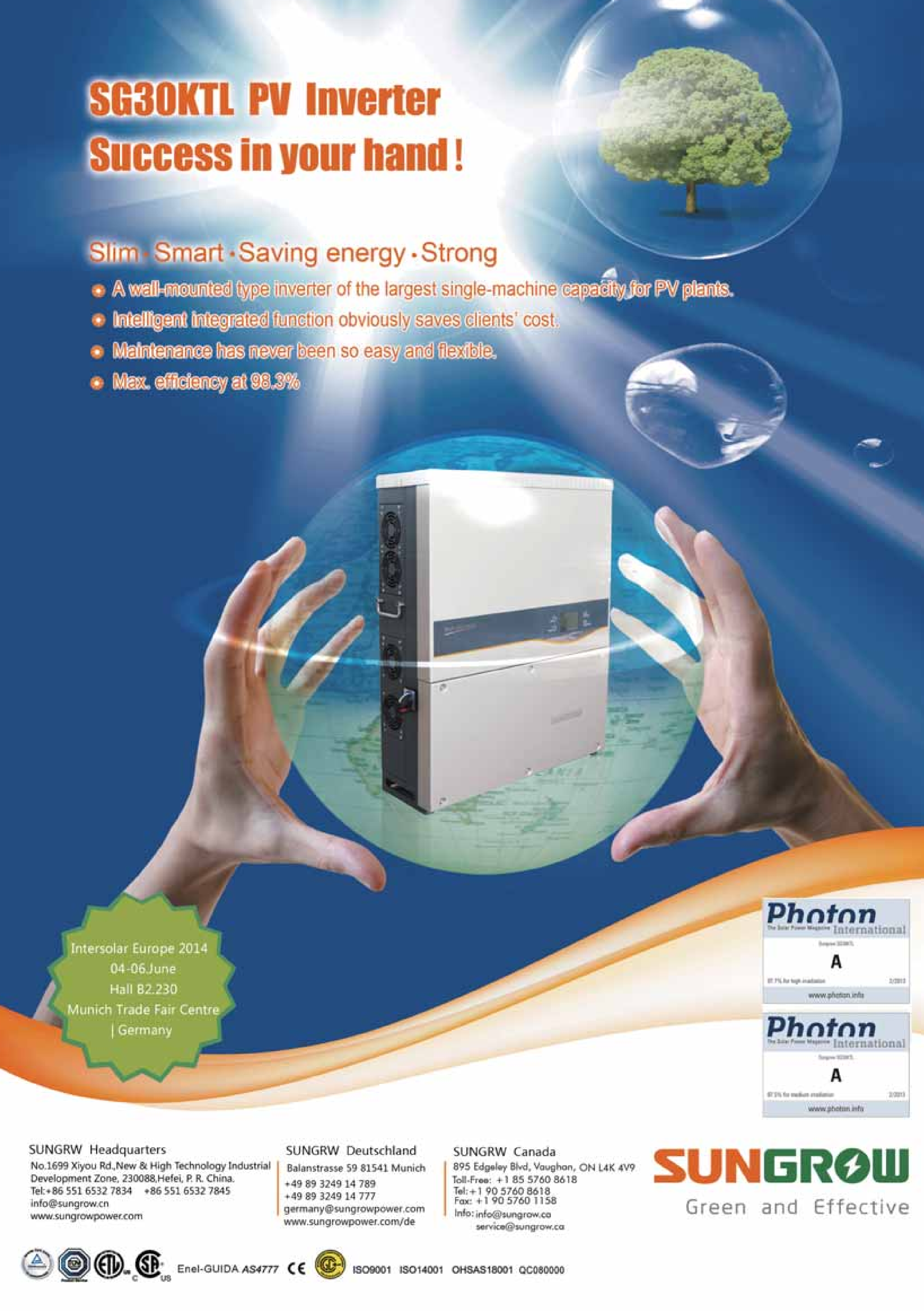


Figure 6. Handling steps for SMARTLAM foil handling.



SG30KTL PV Inverter
Success in your hand !
Slim · Smart · Saving energy · Strong
A wall-mounted type inverter of the largest single-machine capacity for PV plants.
Intelligent integrated function obviously saves clients' cost.
Maintenance has never been so easy and flexible.
Max. efficiency at 98.3%
Intersolar Europe 2014
04-06.June
Hall B2.230
Munich Trade Fair Centre
| Germany
Photon International
A
www.photon.info
Photon International
A
www.photon.info
SUNGRW Headquarters
No.1699 Xiyou Rd.,New & High Technology Industrial Development Zone, 230088,Hefei, P. R. China.
Tel:+86 551 6532 7834 +86 551 6532 7845
info@sungrow.cn
www.sungrowpower.com
SUNGRW Deutschland
Balanstrasse 59 81541 Munich
+49 89 3249 14 789
+49 89 3249 14 777
germany@sungrowpower.com
www.sungrowpower.com/de
SUNGRW Canada
895 Edgeley Blvd, Vaughan, ON L4K 4V9
Toll-Free: +1 85 5760 8618
Tel:+1 90 5760 8618
Fax: +1 90 5760 1158
Info: info@sungrow.ca
service@sungrow.ca
SUNGROW
Green and Effective
Enel-GUIDA AS4777 CE
ISO9001 ISO14001 OHSAS18001 QC080000

"Any deformation of a flexible part needs to be counteracted by the handling process itself."

The overall handling process in SMARTLAM has been subdivided into feeding, gripping, positioning, depositing and joining, as depicted in Fig. 6. Single film sheets in an approximate known position and orientation are provided in the first step – the feeding step. The flexibility of the sheets is an important factor that needs to be taken into account: to flatten and to clamp the sheets for the following processing steps in a standardized way, a work-piece carrier is therefore provided (see Fig. 7). This is equipped, on the one hand, with a removable porous vacuum chuck for a uniform gripping action with clamping forces that are only perpendicular to the sheet surface so as to avoid deformation by, for example, stretching. On the other hand, the carrier has an additional mechanical clamping means for transport purposes or for processes requiring an aperture. Sheet distortion is reduced by vertical clamping after the sheet is flattened on the vacuum chuck.

The next step in the handling sequence is the gripping of the sheet. During this process the work-piece carrier suction must still be activated to avoid deformation of the sheet. In this state a gripping device should pick it up, again without deforming the sheet. In addition, the sensitivity of the structures, particularly the additive ones, has to be considered. A flat gripper based on porous material and providing a uniform vacuum over the whole surface, similar to the work-piece carrier, is proposed for this task. The structures on the sheets require precise relative positioning and orientation of the sheet relative to the substrate: the required positioning accuracy is less than 10µm. The specific approach to achieving the alignment is based on fiducial markers on each sheet and the work-piece carrier, which are measured by a highly precise vision system. As in the case of the gripping process, the deposition should again avoid any sheet deformation or loss of position. Here an appropriate deposition strategy is required which does not affect the position or shape of the sheet during or after the deposition as a prerequisite for the joining process.

During the whole handling process, particle contamination is to be controlled and aggressively avoided. Appropriate cleaning procedures for the equipment involved between process steps are therefore called for. Furthermore, in-process inspection steps of each layer are being considered in order to detect potential sources of failure as early as possible. A number of preliminary tests of the handling process have been made with promising results. A modular automated manufacturing system is currently being set up as a basis for further development of the process chain and detailed investigations.

As well as the development of polymer film handling, along with other applications, the semiconductor industry has been reducing the thickness of semiconductor dies for many years now. As is widely known, the trend for compact and portable electronic devices drives the semiconductor industry towards thinner substrates, which enable the packaging of integrated circuits on a smaller footprint. The gain in flexibility of ultrathin silicon substrates is being increasingly taken advantage of in new applications. Various techniques for manufacturing ultrathin chips for solid-state devices have been researched and solutions published [18,19].

Advances in ultrathin substrate handling

In PV the challenge of transporting ultrathin wafers with considerably larger areas than those of the dies of integrated circuits, while aiming to achieve anticipated PV wafer throughputs, still remains. One particular advance in PV manufacturing is module-level processing [20]. Here, a certain number of pre-processed ultrathin wafers are bonded on a glass superstrate, which allows a more rigid handling object to be transported between processes. The monolithic back-side processing of back-contact cells is performed at the module level and could be performed on thinner wafers. Rationalizing effects are further gained by an integrated cell and module metallization of back-contacted cells. This requires a very sensitive and accurate assembly of the wafers on the common glass substrate.

An automated prototype for the placement of front-side processed ultrathin wafers on a glass substrate

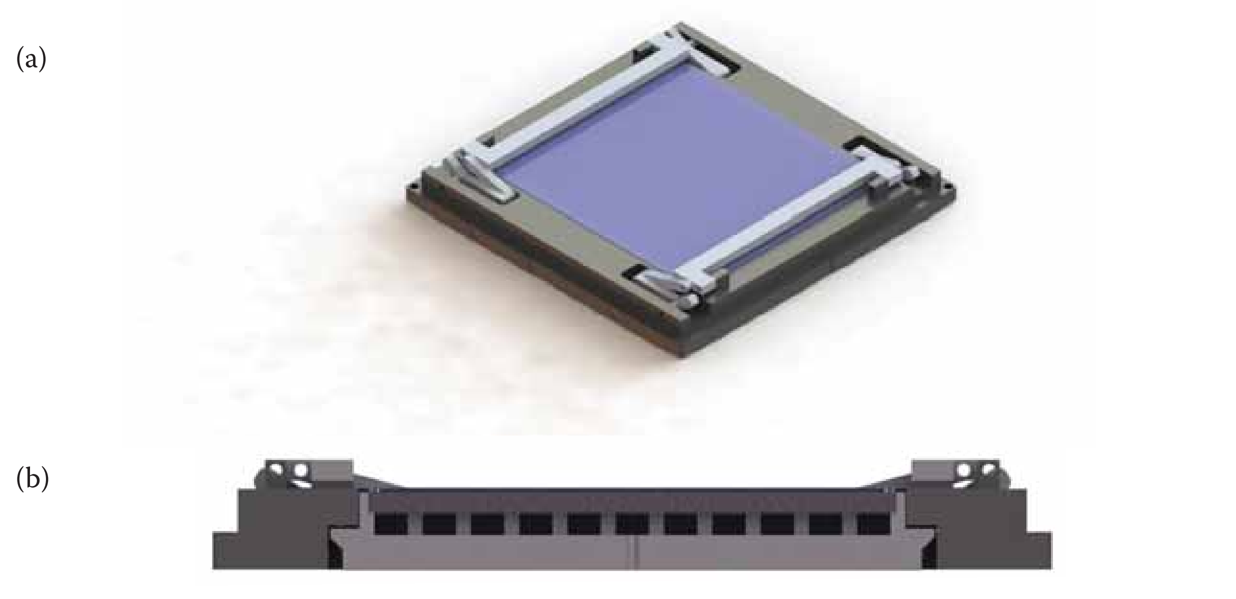


Figure 7. (a) Work-piece carrier solution for 100µm polymer film handling; (b) section view of the work-piece carrier.

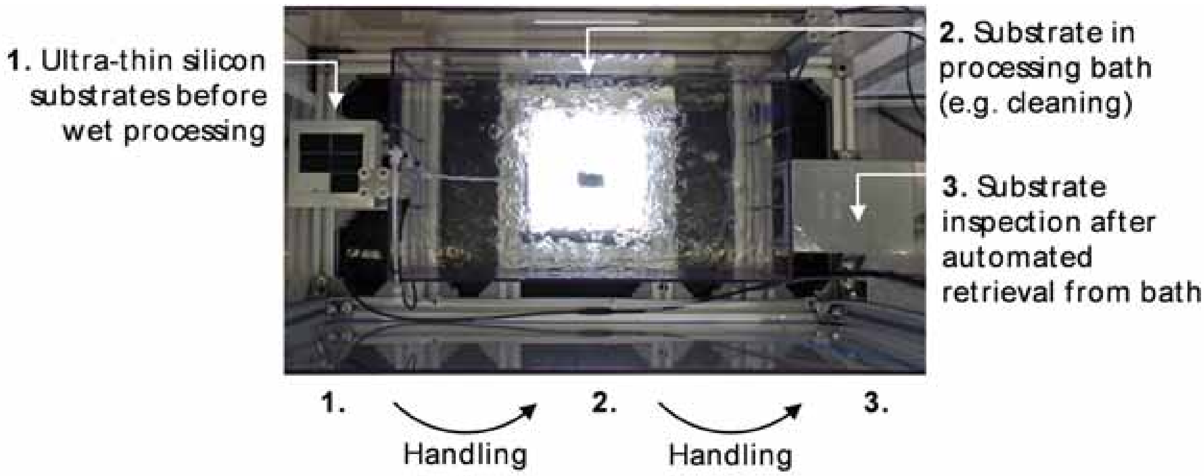


Figure 8. Top view of the test equipment for the automated handling of ultrathin substrates within wet processes. The correlation is determined between the achievable accuracy of substrate detection and a reliable, gentle gripping for retrieving the ultrathin substrate from the cleaning bath.

for the bonding-on-glass step has been developed and is presented in Mayer et al. [21]. The requirements for the accuracy of the ultrathin wafer placement are in the range ±50μm, defined by the module-level processing conditions. Because of the silicone-coated glass, only one attempt for the wafer placement is possible, as adjustments after placement are impracticable. Extensive investigation of the handling characteristics of different grippers has led to a feasible automated process for the bonding-on-glass method. The appropriate gripper settings are essential for thinner wafers, because wafer deformations due to gripping (e.g. strong suction) will cause deviations in the position accuracy during the placing procedure. The in-house team at IPA has demonstrated repeatable results for automated handling and assembly of ultrathin wafers, and the procedures are ready for industrial exploitation and scale-up.

Furthermore, when the manufacture of products from ultrathin wafers is envisaged there will also appear new challenges for processes that are already under full control in a state-of-the-art cell production. For example, the batch processing of ultrathin substrates may limit the current capabilities of carrier solutions, as the unstable substrates will tend to sag in carrier slots. As a consequence, the breakage rate, which has been stringently reduced in PV productions by optimization efforts in the past, will once again become critical.

The primary handling methods for thin substrates will have to be reviewed for their use with ultrathin substrates. Some state-of-the-art solutions may be adaptable, but some uncertainties are obvious. A higher risk of crashes among the substrates because of their vibrations in the carrier slots caused by the carrier movement, or because of the interacting forces in processes such as the dipping in wet benches, may occur. In addition, inline processing will need to address the interaction of substrate edges with lateral guides during roller transportation, as well as the accurate and sensitive substrate hold-down mechanisms during forwarding in wet processes. Critical edge loads have already been minimized in previous automation approaches because of the crucial disadvantages of contact between transporting device and silicon substrate. There is also an increase in equipment component wear as the substrates get thinner and the edges sharper [22].

One advance for ultrathin substrate handling is the gripping-in-liquid method, which consists of ultrathin substrate handling in different liquid environments for cleaning purposes (see Fig. 8). Beyond the point at which a batch or an inline processing capability is stretched to its limits, the gripping-in-liquid process provides an addition to the available capacities and manufacturing skills. Thus, with the implementation of the process feed-through of ultrathin substrates in cleaning solutions or rinsing baths, the gripping-in-liquid method allows flexible interaction within dry and wet environments where other approaches risk partial damage or breakage and therefore process interruptions. The gripping-in-liquid method facilitates the processing of substrates which undergo a geometrical transformation, such as a substrate that is bowed before liquid (e.g. a solution) contact and flat after retrieval from the liquid – or conversely. Such geometric transformations can be caused by intrinsic tensions in ultrathin substrates, by deposited material on ultrathin wafers, or by future surface structuring for light trapping. As a result of an applied advanced process control method and the accessibility of multiple sensor data, the new handling process is adequately prepared for the requirements of the factory of the future.

> "The use of smart equipment will optimize interdependencies of processing and automation."

Conclusion

In general, developers face new challenges for the manufacturing of ultrathin silicon or other versatile substrates for high-volume production. However, modern production methods – such as the implementation of smart equipment for PV – can assist in reducing the obstacles to the accelerated manufacturing of new PV cell concepts. Such smart equipment may be represented in several ways. For example, a control for the wear and tear of drives and the determined placement inaccuracies in the handling of wafers or cells will help to plan maintenance intervals and reduce equipment downtimes. The use of smart equipment will lead to even more transparent production steps and will optimize interdependencies of processing and automation and the corresponding implication for the product's quality. Smart equipment in production will allow a faster optimization and therefore a faster profitability of processing for the production of the next PV technology developments. But there may be many ways leading to a 'plateau of productivity'.

Acknowledgements
Part of this work is co-funded by the European Commission within the 7th Framework Programme. Thanks to all partners of the SUGAR and SMARTLAM projects for their contributed work and input. Special thanks to all partners of the Industry Alliance for PV substrate handling.

References

[1] Meza, E. 2014, "Deutsche Bank expects solar gold rush in 2014", *pv magazine* (January) [http://www.pv-magazine.com/news/details/beitrag/deutsche-bank-expects-solar-gold-rush-in-2014_100013889/#axzz2wsHzvhKa].

[2] Werner, J.H. 2014, "Braucht man eigentlich noch Photovoltaik-Forschung?", Univ. Stuttgart: Elektrotechnisches Kolloquium (January) [http://www.ipv.uni-stuttgart.de/news/2014_01_14_Braucht_PV-Forschung_final.pdf].

[3] Teixeira, R.C. et al. 2008, "Stress analysis on ultra thin ground wafers", *J. Int. Circ. Syst.*, Vol. 3, No. 2, pp. 83–89.

[4] Kerr, M.J. et al. 2003, "Limiting efficiency of crystalline silicon solar cells due to Coulomb-enhanced Auger recombination", *Prog. Photovolt.: Res. Appl.*, Vol. 11, pp. 97–104.

[5] Sakata et al. 2010, "R&D progress of next-generation very thin HIT™ solar cells", *Proc. 25th EU PVSEC*, Valencia, Spain, pp. 1102–1105.

[6] Kray, D. & McIntosh, K.R. 2009, "Analysis of ultrathin high-efficiency silicon solar cells", *physica status solidi (a)*, Vol. 206, No. 7, pp. 1647–1654.

[7] SEMI PV Group Europe 2014, "International technology roadmap for photovoltaic (ITRVP): Results 2013", 5th edn (March) [available online at http://www.itrpv.net/Reports/Downloads/].

[8] Brendel, R. et al. 2013, "Recent progress and options for future crystalline silicon solar cells", *Proc. 28th EU PVSEC*, Paris, France, pp. 676–690.

[9] Giesen, T. et al. 2013, "Advanced gripper development and tests for automated photovoltaic wafer handling", *Assembly Automation*, Vol. 33, No. 4, pp. 334–344.

[10] Brun, X.F. et al. 2009, "Analysis of stresses and breakage of crystalline silicon wafers during handling and transport", *Solar Energy Mater. & Solar Cells*, Vol. 93, No. 8, pp. 1238–1247.

[11] Koeppge, R. et al. 2011, "The influence of transport operations on the wafer strength and breakage rate", *Proc. 26th EU PVSEC*, Hamburg, Germany, pp. 2072–2077.

[12] Popovich, V.A. 2011, "Breakage issues in silicon solar wafers and cells", *Photovoltaics International*, 12th edn, pp. 49–57.

[13] Schoenfelder, S. et al. 2006, "Influence of the thickness of silicon dies on strength", *Proc. 7th Int. Conf. Therm., Mech. & Multiphys. Sim. Exp. in Micro-Electr. & Micro-Sys.*, EuroSimE, Como, Italy.

[14] Reddig, K. 2009, "Overview of automation in the photovoltaic industry", *Photovoltaics International*, 4th edn, pp. 18–29.

[15] Giesen, T. et al. 2012, "Advanced production challenges for automated ultra-thin wafer handling", *Proc. 27th EU PVSEC*, Frankfurt, Germany, pp. 1165–1170.

[16] Dickerhof, M. et al. 2013, "An additive manufacturing and eprinting based approach for flexible scalable manufacturing of microsystems", *Proc. 10th Int. Conf. Multi-Mater. Micro Manufac.*, San Sebastián, Spain.

[17] Saadat, M. & Nan P. 2002, "Industrial applications of automatic manipulation of flexible materials", *Industr. Robot: An Internat. J.*, Vol. 29, No. 5, pp. 434–442.

[18] Burghartz, J. (Ed.) 2011, *Ultra-thin Chip Technology and Applications*, Berlin: Springer.

[19] Angelopoulos, E.A. et al. 2012, "Manufacturing aspects of an ultra-thin chip technology", *Proc. 42nd Europ. Solid-State Dev. Res. Conf. (ESSDERC0)*, Bordeaux, France, pp. 141–144.

[20] Govaerts, J. et al. 2013, "I-module technology: Evaluation and evolution", *Proc. 28th EU PVSEC*, Paris, France, pp. 59–62.

[21] Mayer, P. et al. 2013, "Development and evaluation of a prototypic automated high precision assembly of ultra-thin miniaturized silicon wafers", *Proc. 28th EU PVSEC*, Paris, France, pp. 1752–1756.

[22] Wertz, R. et al. 2012, "Passive alignment of wafers – Design and impact", *Proc. 27th EU PVSEC*, Frankfurt, Germany, pp. 1175–1178.

About the Authors

Tim Giesen joined Fraunhofer IPA as a project manager for national and international research projects in 2008. He holds degrees in industrial engineering and logistics management. Tim is currently working in the group for planning and control of productions critical to contamination; his expertise comprises automation for material handling, clean assembly and automation equipment prototyping.

Raphael Adamietz has been a project manager at Fraunhofer IPA since 2009. He has a diploma degree in mechanical engineering and is currently pursuing a Ph.D. at the University of Stuttgart. Raphael works on several national and international research projects, including the SMARTLAM project, and his research focuses on modular assembly platforms and micro-assembly.

Guido Kreck studied aviation and aerospace engineering at the University of Stuttgart and has been with Fraunhofer IPA since 2006. His main research interests are particle sampling and measurement technologies, cleanroom equipment design, and the qualification and optimization of components regarding cleanroom suitability and cleaning technologies.

Tobias Iseringhausen studied manufacturing technology for microsystems at the RWTH Aachen University, Germany, and holds a diploma in mechanical engineering. He is a project manager at Fraunhofer IPA, where he specializes in micromanufacturing. His research activities include micro-assembly automation and related equipment.

Roland Wertz is the manager of the Fraunhofer IPA group involved with the planning and control of productions critical to contamination. He received a Dipl.-Ing. degree in applied cybernetics from the University of Stuttgart and currently works in the field of factory automation, including equipment automation, material-handling solutions, logistics and data modelling/processing.

Enquiries

Dipl.-Wirtsch.-Ing. (FH) Tim Giesen MBE
Project Manager
Fraunhofer IPA
Ultraclean Technology and
Micromanufacturing Department
Nobelstrasse 12
D-70569 Stuttgart, Germany

Tel: +49 (0) 711-970-1500
Email: tim.giesen@ipa.fraunhofer.de
Website: http://www.ipa.fraunhofer.de

The next PV capacity expansion phase is under way

Mark Osborne, senior news editor, Photovoltaics International

ABSTRACT
Two years of overcapacity in the global PV supply chain have led to investment in new manufacturing capacity grinding to a halt. However, booming global end-market demand has brought the supply–demand imbalance under control and as a result the world's leading equipment suppliers have begun looking at serious capacity expenditure. On the basis of recent announcements and annual report publications by some of the leading manufacturers, this article examines where, when and by whom capacity expansions are now planned.

Introduction

It is hard to believe that after more than two years of chronic overcapacity up and down the supply chain, the PV industry has entered a new capacity expansion phase. The industry became burdened with a nameplate capacity of over 60GW by 2011, while global end-market demand was just over 30GW in that year, according to European Photovoltaics Industry Association data.

Saddled with such a significant level of overcapacity, and end-market demand that barely expanded (to just 31GW) in 2012, the industry suffered dramatic consequences: plummeting prices across the supply chain resulted in very low production utilization rates at best, and closures, bankruptcies and exits from the industry at worst. Since then the industry has experienced over two years of profitless prosperity, and capital expenditure (capex) budgets were slashed to facility and equipment maintenance levels only.

Strong growth recovery in global end markets in 2013, however, meant installations topped over 36GW, according to NPD Solarbuzz. The market research firm's latest PV Equipment Quarterly predicts that the freeze in spending by equipment suppliers over the past two years will finally thaw by early 2015 as a rebalancing of supply and demand took effect. Solarbuzz has said that the overcapacity in the sector led to PV equipment spending falling to an eight-year low of US$1.73bn in 2013, down from US$13bn in 2011. This means equipment suppliers in 2013 saw bookings of less than US$1bn.

But Solarbuzz predicts that over the next six months PV end-market demand will catch up with the 45GW of 'effective capacity' within the industry. The market research firm expects that 49GW of end-market demand in 2014 will push production utilization rates well above 90% for Tier 1 manufacturers, while prompting many to increase production outsourcing, from wafers and cells through to modules.

Source: Solibro

PV manufacturers have begun announcing plans to expand production capacity later this year and into 2015. Source: Applied Materials.

The new real growth phase for equipment manufacturers, however, will be driven primarily by a small number of Tier 1 manufacturers – a reflection of how the recent shakeout has consolidated the supply chain. But a key will be technology-driven spending, as China-based manufacturers are being pressured by government polices to push cell/module efficiencies beyond 20%.

Market research firm IHS recently tweaked its capex forecast up US$430m in 2014 to a total of US$3.8bn. The firm had previously said that spending would increase by 42% from the lows of 2013 and reach US$3.37bn in 2014.

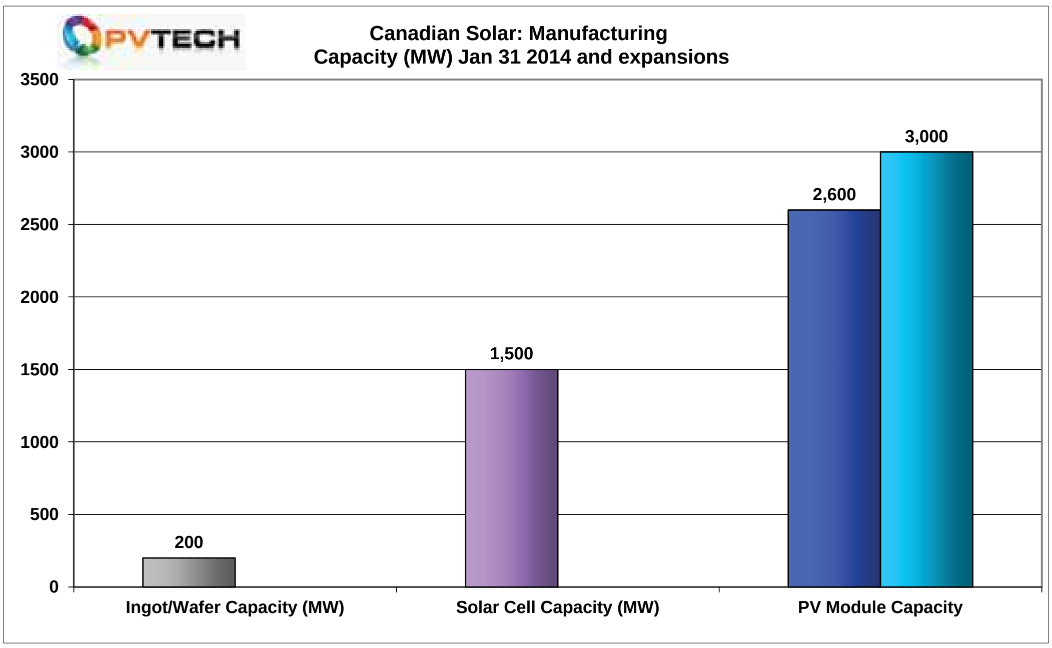
"The new real growth phase for equipment manufacturers will be driven primarily by a small number of Tier 1 manufacturers."

Major c-Si capacity expansion plans

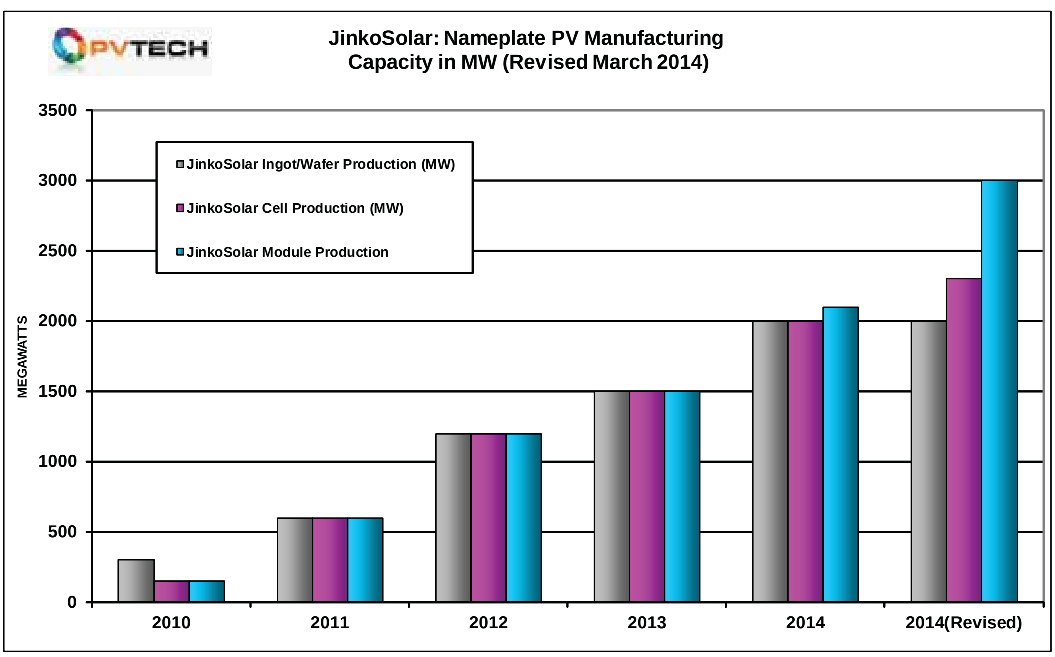
Since the fourth quarter of 2013, there has been a growing number of planned capacity expansions, some which are at the gigawatt level.

Canadian Solar

Canadian Solar has already increased module assembly capacity at its plant in Ontario, Canada, from 330MW at the end of 2013 to 530MW as of January 31st 2014. Total nameplate capacity at module production plants in China and



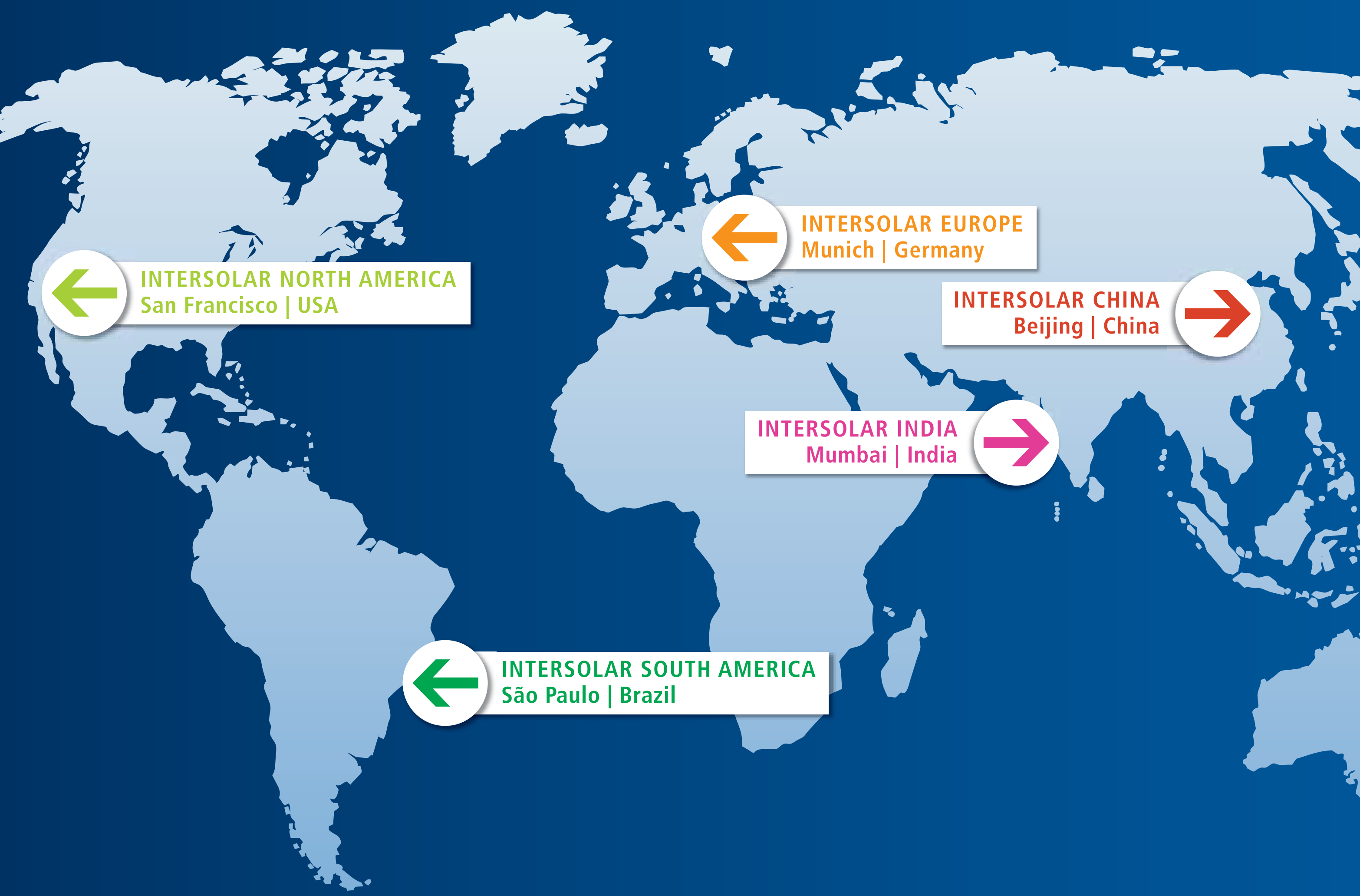
Canadian Solar's ingot, wafer and cell capacities remain modest, but it is planning to expand module output to 3GW.



JinkoSolar is planning further capacity expansions in 2014, which will take its nameplate capacity to 2GW.

inter
solar
connecting solar business

The World's Leading Exhibition Series for the Solar Industry



5 exhibitions | 4 continents | Most international solar event series with b2b focus | Meet the decision makers who are shaping the solar market | Stay informed about the latest technological innovations | Get connected at exclusive networking events | Meet renowned speakers at the world-class conferences | Benefit from the events in the world's key solar markets

MAR 26–28 2014
www.intersolarchina.com

JUNE 04–06 2014
www.intersolar.de

JULY 08–10 2014
www.intersolar.us

AUG 26–28 2014
www.intersolar.net.br

NOV 18–20 2014
www.intersolar.in


INTERSOLAR CHINA


INTERSOLAR EUROPE


INTERSOLAR NORTH AMERICA


INTERSOLAR SOUTH AMERICA


INTERSOLAR INDIA

Canada currently stands at 2.6GW, up from 2.4GW in 2013.

Canadian Solar has typically used a flexible, vertically integrated manufacturing model but has significantly smaller capacity in ingot/wafers (200MW) and solar cells (1500MW) than in module assembly (2.6GW). However, the company recently raised around US$200m for further expansion of manufacturing capacity to 3GW in order to meet growing demand.

JinkoSolar

JinkoSolar added several hundred megawatts of module capacity in 2013. The company had 1.5GW of annual nameplate capacity for silicon ingots, wafers and solar cells, and approximately 2.0GW for solar modules.

This year, however, JinkoSolar recently announced it was acquiring Topoint, which would provide the company with 500MW of cell and 500MW of wafer capacity as well as 100MW of module capacity, bringing its total nameplate module capacity to 2GW-plus.

Trina Solar

Trina Solar has also followed the acquisition route to gaining new capacity with the purchase of a majority shareholding in Hubei Hongyuan PV Science and Technology, a small solar cell producer, as well as taking over operations of Tier 2 module manufacturer NESL Solartech.

The operations takeover deal was struck with Chinese conglomerate Yabang Investment Holding Group, owners of NESL Solartech. The new joint venture will be called Changzhou Trina Yabang Solar Energy Co., Ltd., with Trina Solar holding a 51% stake and Yabang Group having a 49% interest. The facility will be managed by Trina Solar management, according to a statement. Trina Solar said that the total investment by both companies would be approximately US$45m, a sum that will be used for capital expenditure and working capital requirements. NESL Solartech had a PV module nameplate capacity of 400MW, which under the JV investment is expected to be increased to 500MW before the end of 2014.

Trina Solar will also form a joint venture with Shenzhen S.C. New Energy Technology Corporation, the owner of Hubei Hongyuan PV Science and Technology, taking a 51% stake in the solar cell producer; the operations will be renamed Hubei Trina Solar Co., Ltd. The partners said that the existing production facilities would be expanded to a capacity of 420MW by mid-2014.

Having recently detailed its module capacity levels after line upgrades and throughput improvements that effectively took annual nameplate capacity from 2.4GW to 2.8GW, Trina Solar now has a module capacity standing at 3.3GW, or 900MW higher than mid-2013. Solar cell nameplate capacity increased to 2.6GW, providing the potential need for 600MW of outsourced cell production in 2014.

Trina Solar is expecting capital expenditure to reach US$213m in 2014 as it targets expansion of capacity from ingot/wafer through to 1GW of extra module capacity.

SunPower

SunPower has guided capex plans for 2014 that are nearly double the spending in 2013. The company reported in its 2013 annual report that its capex would be in the range US$150m to US$170m in 2014, a possible increase of 88.8% from its 2013 guidance range of US$70m to US$90m.

The company had noted in its recent fourth quarter 2013 conference call that spending in the first quarter of 2014 would be in the range US$25m to US$30m as it started to ramp the construction of its 350MW facility in the Philippines, Fab 4.

The company is expected to be capacity constrained throughout 2014, unless further expansion is made at its JV Fab 3 in Malaysia, which was reported to have a production capacity of 800MW but a nameplate capacity over 1GW. No plans have been announced to expand Fab 3 production in 2014, and no further clues were revealed by SunPower on any planned expansion in its recent management conference call with analysts.

SunPower has revealed it is prepping plans for its next-generation 'Fab 5' manufacturing facility, which would be on a larger scale than existing facilities. The plant will be built as part of a major capacity expansion planned for 2015, once the new plant in the Philippines has been completed.

Hanwha Q CELLS

In December 2013 Hanwha Q CELLS started building a new solar cell plant at its manufacturing complex in Cyberjaya, Malaysia, which will house a 204MW solar cell production line. The new line will focus on producing high-efficiency solar cells for its Q.PRO G3 multicrystalline PV modules, which will be in production by early autumn 2014.

With the addition of the 204MW solar cell production line, Hanwha Q CELLS said the nameplate capacity of its Malaysian facilities would surpass 1GW, with 1.1GW of integrated production capacity and a total production capacity of 1.3GW.

Wuxi Suntech

Wuxi Suntech is currently upgrading cell and module production lines in China ahead of plans to increase in-house module capacity in 2014. Line upgrades relate to improved conversion efficiencies and take module production to between 2.4GW and 2.5GW, a 20% increase from official production levels at the end of 2011. The intention is to expand in-house capacity by the end of 2014 to between 3GW and 3.5GW.

According to the last published annual report of Suntech Power Holdings in 2011, Wuxi Suntech's wafer and ingot production capacity stood at 1.6GW, while its cell and module capacity was 2.4GW.

SunEdison

Potentially the biggest planned expansion relates to SunEdison. The company said a few months ago that it was undertaking a feasibility study on establishing a fully integrated PV manufacturing complex, including FBR polysilicon production in partnership with the Saudi Arabian government. The plans call for an investment of US$6.4bn in a major complex that could potentially be commenced later in 2014. As yet the company has not publicly provided further details.

JA Solar

JA Solar has plans to add capacity at existing production plants but has also ventured outside China for the first time, with a recent announcement to join forces in operating a module assembly plant in South Africa.

JA Solar and Powerway have formed a joint venture to establish a PV module assembly plant in Port Elizabeth, South Africa, with an initial nameplate capacity of 150MW. The JV partners said that production would start as early as the second quarter of 2014. The plant will be located in the Port Elizabeth's COEGA Industrial Development Zone, and the partners have the option to ramp capacity to 600MW to meet expected demand in the country.

> "Several major plans have been announced that are expected to trigger something of a renaissance in thin-film manufacturing."

At home, JA Solar is keeping ingot/wafer production steady at 1GW each, but said that cell production would increase 300MW to 2.8GW in 2014. The big step function, however, is module capacity, with the company planning to add 1GW of capacity to reach parity with its planned cell expansion.

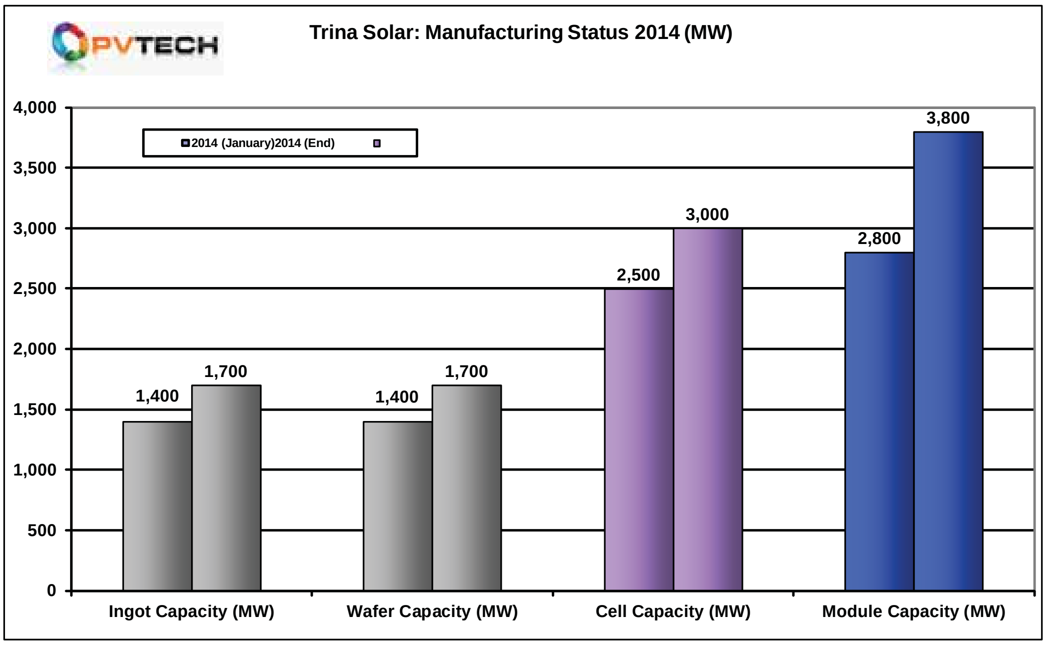
Major thin-film capacity expansion plans

The manufacturing sector that has suffered the most significant bankruptcies and plant closures in the last two years has been thin film. Even leading players, such as First Solar, cancelled significant capacity expansions in the USA and Vietnam during this period. However, several major plans, currently driven by CIGS-technology-based capacity expansions, have been announced that are expected to trigger something of a renaissance in thin-film manufacturing.

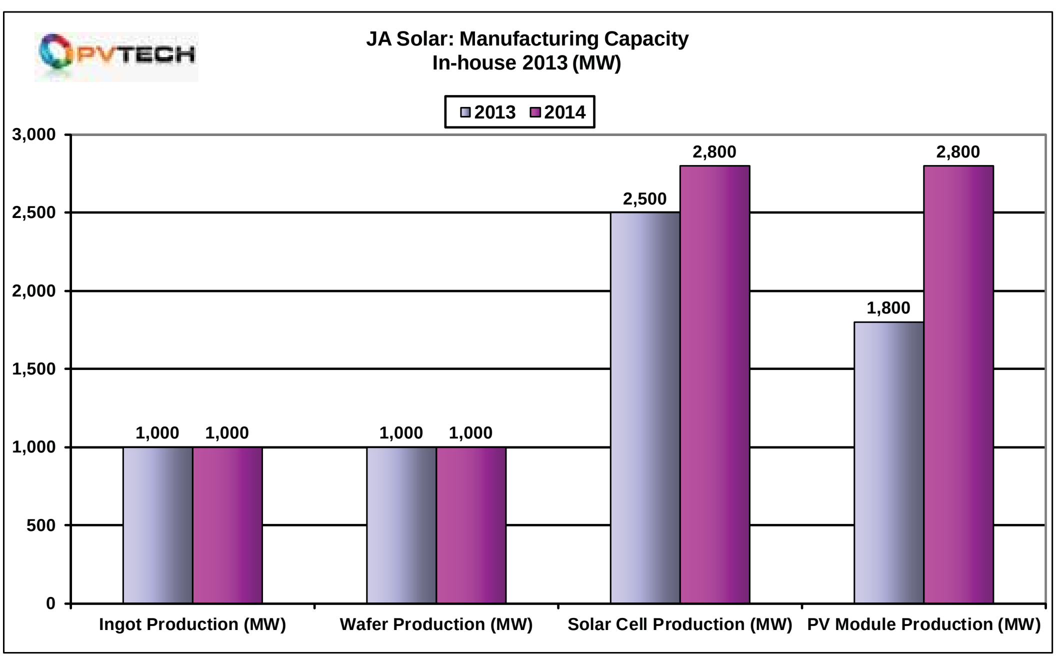
Hanergy Solar

Hanergy Solar was to begin construction in March 2014 of a planned 3GW CIGS thin-film manufacturing complex in Caofeidian, Hebei Province, China, with tool install commencing by the end of the year. The company is establishing a subsidiary, Hebei Caofeidian Hanergy Photovoltaic Co. Ltd., to own and operate the new complex. Initial plans are to build two separate production lines with a total nameplate capacity of 600MW.

Hanergy Solar said one of the turnkey lines, with a nameplate capacity of 300MW, would employ MiaSolé-based CIGS sputtering process technology, while the second line, with a further



Trina Solar is planning to increase production capacity in all its main areas of business in 2014.



JA Solar is keeping ingot and wafer production at existing levels this year, but is ramping cell and module output.

300MW, would employ Solibro's co-evaporating manufacturing process technology. Both CIGS manufacturers were acquired by Hanergy Group and their technology licences transferred to Hanergy Solar and subsidiaries. The initial 600MW phase-one construction and equipment spending is estimated to be approximately US$780m.

Hanergy had also requested a two-year extension for its expansion plans for the existing MiaSolé plant in Santa Clara, California, from the California Alternative Energy and Advanced Transportation Financing Authority (CAEATFA). Funding for the expansion is expected to be in place by the fourth quarter of 2015.

Solar Frontier

Leading CIS thin-film PV module manufacturer Solar Frontier began construction of a new 150MW CIGS plant in Japan's Tohoku region in March 2014. The company had previously said that its new plant will potentially become a benchmark for new production facilities in various key PV markets around the world.

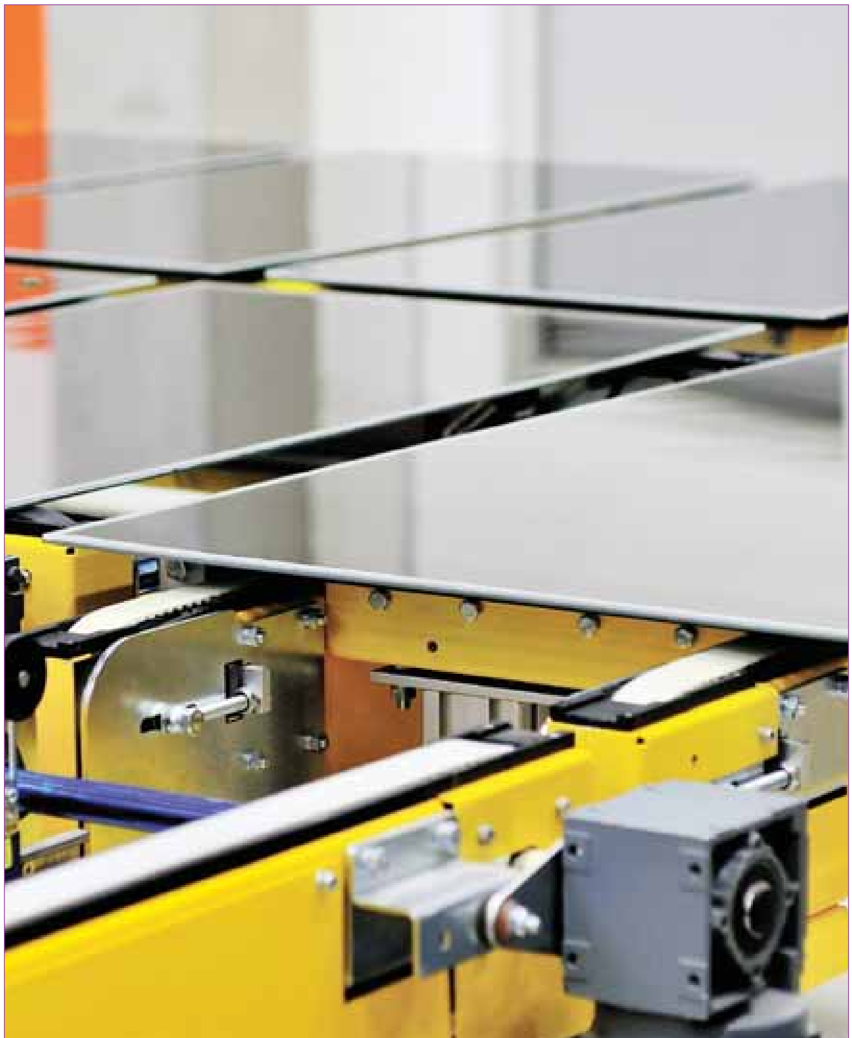
Solar Frontier's main Kunitomi Plant (900MW nameplate capacity) was said to have operated at full capacity from the start of 2013, while its Miyazaki Plant, with an annual production capacity of 60MW, also resumed production in July 2013.

Very recently, the company said it was considering establishing a 150MW production plant in Buffalo, New York, after signing a memorandum of understanding (MOU) with the State University of New York College of Nanoscale Science and Engineering (SUNY CNSE).

Ascent Solar

Although US-based flexible CIGS thin-film manufacturer Ascent Solar had previously announced a joint-venture thin-film plant in China, the company recently updated on the plans. The company noted that the joint venture would build a 100MW CIGS thin-film manufacturing plant in the Suqian Economic and Industrial Development Science Park with the Municipal City of Suqian in Jiangsu Province.

The initial production capacity, however, will be 25MW, and the plant will be fully operational in the first quarter of 2016, with the 100MW ramp-up taking place over a six-year period. Suqian was originally said to be providing cash of approximately US$32.5m for the joint venture and retaining a minority share. Under the revised agreement, however, Suqian is expected to provide approximately US$4.8m in cash and to have a majority interest of 75%.



Source: Solibro

Proposed CIGS-based technology expansions promise something of a renaissance for thin-film.

TSMC Solar

The CIGS thin-film firm TSMC Solar recently told PV Tech that it was also expanding production in 2014 at its plant in Taiwan from 40MW to 120MW. The company noted that equipment purchases have been made and tool install is expected to be completed by the end of the third quarter of 2014. TSMC Solar expects to achieve the new ramped-up capacity in the fourth quarter of this year.

First Solar

In March, during its annual analyst day event, First Solar highlighted its next major CdTe thin-film production capacity expansion phase, but this would not occur until 2015 with an additional 1GW of nameplate capacity. Nameplate capacity would remain at 1.8GW in 2014, excluding the 100MW c-Si TetraSun production plant currently under construction that was announced in 2013.

However, First Solar is planning a combination of existing manufacturing line throughput and module efficiency gains, as well as new line capacity, to provide a nameplate capacity of around 2.8GW by the end of 2015. Effectively, First Solar is only adding approximately 200MW of new capacity in 2015, although that additional new capacity rate would steadily increase to around 400MW in 2016 and to around 700MW in 2017 and 2018.

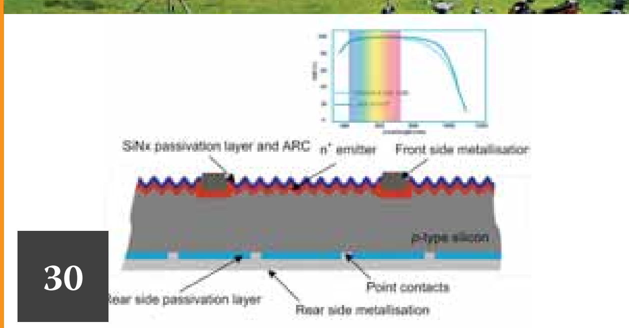
> "PV manufacturers could announce the next significant wave of capacity additions later in the year."

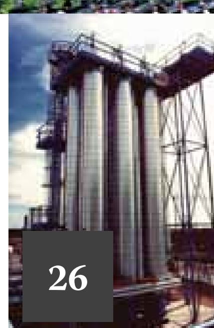
Conclusion

With end-market demand set for strong growth over the next two years, it is clear that major capacity expansions are already under way in 2014. As the 'effective' 45GW plus of capacity is expected to become exhausted in 2014, PV manufacturers could announce the next significant wave of capacity additions later in the year, with many sites having to be greenfield.

Materials


26


SiNx passivation layer and ARC
n+ emitter
Front side metallisation
p-type silicon
30
ear side passivation layer
Point contacts
Rear side metallisation

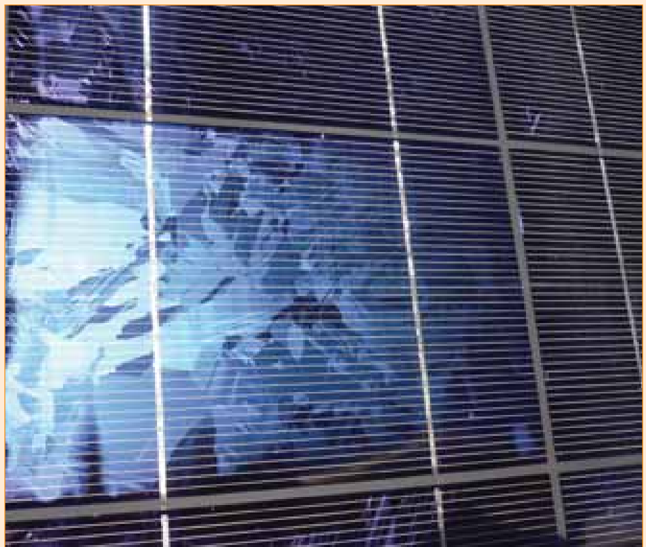

26

GCL-Poly secures major new polysilicon and wafer contracts

Major China-based polysilicon and solar wafer producer, GCL-Poly has secured 'near-term' supply contracts with Jinko Solar, GD Solar, Tongwei Solar, and Hareon Solar.

The company said that the contract would begin in 2014 and run through 2016, totalling approximately 9.3GW of high efficiency wafers and polysilicon. The company did not break out the supply deals nor provide financial details of the individual deals, although GCL-Poly noted that it would receive undisclosed advance deposits.

JinkoSolar recently advised that it would focus limited capital expenditure on expanding PV module and solar cell capacity through the recent acquisition of distressed assets but would not be adding ingot/wafer production in 2014. The tier-one module manufacturer plans to boost PV module production 3GW in 2014, while ingot/wafer production would be held at 2GW. Tongwei Solar took over the solar cell and PV module operations of LDK Solar (Hefei) last year, with plans to ramp cell production to its nameplate capacity of 2GW and PV module capacity to 500MW.



Source: Georg Slickers

GCL-Poly has secured wafer contracts with a number of leading manufacturers that will run up to 2016.

Shipment Increases

Solargiga Q1 shipments and sales jump

Solar wafer-to-module processing service provider, Solargiga Energy Holdings, has reported preliminary unaudited, first quarter 2014 sales and shipments that are significantly higher than the same period a year ago.

The company reported external combined shipments (ingots/wafers, solar cells and modules) of 260.7MW, up 74.6% from the previous year period.

First quarter sales were RMB809.3 million (US$129.7 million), up 131.4% when compared to the first quarter of 2013. Solargiga noted that the majority of shipments were related to its processing services. The company made a loss of around US$18.6 million in 2013.

OCI's polysilicon shipments reach new quarterly record

Korean-based materials and PV project developer, OCI, has reported a new quarterly record in polysilicon shipments and higher average selling prices (ASPS), reflecting the continued strong demand in the PV industry in the first quarter of 2014.

The company said that polysilicon revenue increased on the back of higher shipments, higher ASPs and continued cost reductions in production, which have been in the order 33% over the last five years (excluding impact of foreign exchange rates).

Increased polysilicon demand has enabled OCI to operate plants at higher utilisation rates.

OCI's Basic Chemical Division, which includes polysilicon production, posted first quarter 2014 revenue of KRW521 billion (US$501 million), up from KRW501 billion in the previous quarter.

Increased shipments and ASPs supported a return to an operating profit of KRW14 billion (US$13.4 million).

ReneSola's PV module shipments increase 142% in 2013

Although the shutdown of its Sichuan Phase I polysilicon production line impacted profitability in 2013, tier one PV manufacturer, ReneSola reported a 142.5% year-on-year increase in PV module shipments, reaching 1,728.8MW with plans to reach 2.5GW in 2014.

ReneSola reported full-year net revenue of US$1,519.6 million, 56.8% higher that the previous year. Gross profit was US$103.3 million with a gross margin of 6.8%, compared to a gross loss of US$35.7 million with a gross margin of negative 3.7% in 2012.

However, the company reported a full-year operating loss of US$222.1 million with an operating margin of negative 14.6%, mainly due to a non-cash impairment charge of US$202.8 million from the third quarter with the shutdown of its Sichuan Phase I polysilicon production line, deemed not to be competitive.

Net loss attributable to holders of ordinary shares was US$259.5 million in 2013.

Daqo prepping new 6,000MT polysilicon plant on increased demand

China-based polysilicon and wafer producer, Daqo New Energy Corp, reported narrowing quarterly losses on improved shipments of polysilicon and wafers in the fourth quarter of 2013.

The company said that its new Xinjiang polysilicon production facility had reached close to its nameplate capacity of 6,150MT per annum, with production of 1,445 MT in the fourth quarter of 2013, up from 1,311MT and 962MT in the third and second quarters of 2013, respectively.

Daqo said that it shipped approximately

Source: LeoCRogers wiki commons

Daqo is planning a new polysilicon plant following increased demand.

4,240MT of polysilicon and 33.5 million pieces of solar wafers during 2013, compared to 3,585MT of polysilicon and 15.1 million pieces of solar wafers in the previous year. The company also shipped approximately 119.6MT of silicon ingots during 2013, compared to 500MT in 2012.

Previous plans to double polysilicon production at its Xinjiang production complex are going forward with the company saying that it would commence ground preparing construction on a new expansion at the Xinjiang facility in April of 2014.

Neo Solar Power and Topcell have signed new wafer contracts with GCL-Poly.

Wafer Sales

Green Energy Technology's wafer sales slide 10% in March

Major Taiwan-based solar wafer producer, Green Energy Technology (GET) has reported a sales decline of 10% in March.

The company had sales of NT$1,154,421 (US$38.4 million approx) in March 2014, compared to NT$1,287 million (US$42.47 million) in February, which were 3.9% down from January.

The company said that the revenue decline in March was primarily related to an increase in OEM business as the company supported key customers due to the risk of volatile polysilicon prices.

On a year-on-year basis, sales in March were 22% higher and 41% higher on a quarterly basis. GET said that it also planned to cooperate with supply chain partners on a more efficient manufacturing process as well as customized high-end quality products.

NSP and Topcell extend wafer supply deals with GCL-Poly

Two Taiwan-based solar cell manufacturers, Neo Solar Power (NSP) and Topcell Solar International (TSI) have concluded new short-term wafer supply contracts from GCL-Poly totalling approximately 4GW.

Both cell producers have been previous customers of GCL-Poly. According to GCL-Poly, NSP has signed a three-year long term supply contract, while TSI's deal is for two years only.

Individual company wafer quantities were not disclosed or financial terms.

Trade Disputes

EnergyTrend: US trade case delay could drive up PV prices

The delay to the US solar trade case could further increase PV prices, which are already on the up due to high demand, according to consultancy firm EnergyTrend.

The US department of commerce pushed back its anti-subsidy ruling from 28 March to 2 June. According to EnergyTrend, Chinese manufacturers are now looking to take advantage of this period to sell stock into the US.

The company's latest report expect Q2 2014 polysilicon prices of US$25/kg and Taiwanese manufacturers' high-efficiency cell price in excess of US$0.42. EnergyTrend has tracked rising prices in the early part of the year. A previous assessment in January had predicted cell prices under the US$0.42 mark for February and a US$25/kg polysilicon price was given as the upper limit for the month.

Source: Wikimedia/Frydolin

The US solar trade case could drive up PV prices, says EnergyTrend.

Wacker agrees minimum polysilicon pricing deal with China

Wacker Chemie has agreed a minimum pricing deal with China's Ministry of Commerce (MOFCOM) that will allow the chemical producer to continue exporting polysilicon made at its plants in Europe to China.

Shortly after, MOFCOM confirmed that it will apply anti-dumping and anti-subsidy tariffs to polysilicon imported from the EU for the next two years.

A statement on the ministry website stated that Wacker Chemie, by far the largest exporter of polysilicon to China, would be exempt from the tariff, as long as Wacker continues to remain within the parameters set out in its deal. A Wacker statement issued 18 March said the company could continue to supply polysilicon into China at "competitive prices".

The agreement will be in effect from 1 May this year until the end of April 2016. Wacker chief executive Rudolf Staudigl said he was pleased that "existing differences" over polysilicon prices had been successfully resolved through dialogue.

The resolution of the EU-China polysilicon dumping investigation last year exempted EU polysilicon producers including Wacker from duties being imposed by China due to 'special conditions,' despite evidence of dumping.

Polysilicon Production

GCL-Poly increased polysilicon production 36% in 2013

GCL-Poly reported 2013 annual polysilicon production increased 36% to approximately 50,440MT, retaining nameplate capacity at 65,000MT resulting in utilisation rates above 75% for the year.

The company reported polysilicon production costs decreased by 13.7% from US$19.7/kg in 2012 to US$17.0/kg at the end of 2013, despite lower utilisation rates at the beginning of the year. Polysilicon ASPs were said to have been US$17.4/kg in 2013.

Revenue from GCL-Poly's solar material business in 2013 amounted to approximately US$2.26 billion, up 34.1% from the previous year. GCL-Poly sold 16,329MT of polysilicon not used for in-house solar wafer production, up 29.7% from the previous year.

News

Wacker and GCL-Poly compete for polysilicon production leadership

Although GCL-Poly has topped the nameplate capacity rankings for polysilicon for several years it has actually produced less polysilicon than nearest rival, Wacker Chemie.

However, the China-based producer appears to have sneaked by its German rival for the first time in 2013. GCL-Poly recently reported that its annual polysilicon production increased 36% to approximately 50,440MT in 2013, while retaining its nameplate capacity at 65,000MT.

Wacker has reported polysilicon shipments for 2013 of 49,000MT a new record figure and an increase of around 30%, compared to the previous year. The only real difference between the two competitors was production utilization rates, with Wacker at 90% and GCL-Poly at around 75% for 2013.

GCL-Poly has held nameplate capacity at 65,000MT due to chronic overcapacity during the last few years, while Wacker has persistently delayed the start of production at its new polysilicon plant in the US, which is now expected to ramp in mid-2016, over two years later than originally planned.

GTAT wins US$336 million polysilicon equipment and technology deal

GT Advanced Technologies (GTAT) has secured a major US$336 million polysilicon equipment and technology deal with Cosmos Chemicals Berhad as part of plans to build a 25,000MT integrated polysilicon plant in Sarawak, Malaysia.

According to GTAT, Cosmos Chemicals is currently in the process of securing financing for the major project, which is also being sponsored by Project Management & Development Company (PMD) of Saudi Arabia. Cosmos Chemicals is a subsidiary of Cosmos Petroleum & Mining, which is in turn an affiliate of PMD.

However, Johannes Bernreuter, head of the polysilicon market research firm Bernreuter Research said he had doubts about the project. The polysilicon project in Malaysia was previously estimated to cost at least US$1.6 billion with funding from the project expected to come from investors in the Middle East and Southeast Asia.

GTAT is expecting to provide its complete suite of polysilicon production equipment and technology for the project.


Source: Warut Roonguthai

GT Advanced Technologies has won a US$336 million polysilicon order.

Name Changes

Shunfeng name change due

China-based wafer manufacturer and operator of Wuxi Suntech, Shunfeng Photovoltaic International has said that it proposed to change its name to reflect its priority in becoming a major downstream photovoltaic energy provider.

The company proposes to be called Shunfeng International Limited, dropping 'Photovoltaics' from its current name. Shunfeng Photovoltaic International, has reported full-year 2013 revenue of approximately US$246.2 million, compared to US$170.5 million in the previous year.

Name change expected for GCL-Poly

The holding company of polysilicon producer, GCL-Poly, is planning to change the name of the group to GCL New Energy Holdings Limited to better reflect its move into the downstream PV project business and renewable energy in general.

The holding company, Same Time Holdings Limited, incorporated in Bermuda is also changing its name to GCL New Energy Holdings Limited. GCL-Poly is incorporated in the Cayman Islands and listed on the Hong Kong Stock Exchange.

A special general meeting will be held to gain shareholder approval for the name change, according to the company. GCL-Poly recently reported that it had approximately 100MW of PV projects currently under construction and 18MW of US based PV power plants in operation at the end of 2013.

Materials Investment

Materials still critical cost reduction driver in latest ITRPV

The fifth edition of the International Technology Roadmap for Photovoltaic (ITRPV) released today, continues to emphasise the critical need to reduce material costs from wafers to modules, but also highlights the need for increased cell efficiencies and higher throughput fabrication equipment as material cost reductions get harder to implement.

The latest ITRPV reports that the cost reduction learning curve, in which the doubling of cumulative PV module shipments results in the average selling price declining by over 20%, has continued and is expected to do so over the next few years.

However, increased global PV demand has seen polysilicon prices increase as well as solar cells, which the ITRPV noted have not been fully transferred to the price of PV modules, adding to the challenges of overall cost reductions. Indeed, pricing of polysilicon, wafers, multicrystalline solar cells and modules has been stable throughout 2013, according to the ITRPV, which means that prices are not expected to compensate for cost increases.

Chinese investment firm takes 50% stake in Elkem Solar

Guangyu International, based in Hong Kong has invested US$200 million in solar-grade silicon wafer producer, Elkem Solar based in Norway for a 50% stake in the company.

The company said that the deal had been in the making for some time. Elkem Solar had almost shut down its 6,000MT production facility due to the collapse in polysilicon prices. However, production ramp was said to have restarted in January 2014 on the back of improved pricing and demand.

Product Reviews

Heraeus

Heraeus offers metallization pastes designed for ultra-lightly doped emitters

Product Outline: Heraeus has introduced two pastes for Ultra-Lightly Doped Emitter cells, the SOL9620 Series and the SOL9621 Series. Both pastes provide better contact for higher cell efficiency and Voc. With higher fill factor, both pastes demonstrate better compatibility with different emitter types.

Problem: The PV industry and cell manufactures are working to increase the output of cells and modules. Crystalline wafers with reduced surface doping concentration have the potential to provide higher outputs, but many pastes lack adequate contact formation.

Solution: The Heraeus SOL9620 Series and SOL9621 Series were designed to provide higher cell efficiencies on wafers up to 110Ω/sq. Several major cell manufactures have confirmed higher cell efficiencies relative to the best commercially available front-side pastes, according to the company. Their improvements ranged between 0.05% and 0.20% absolute on 90Ω/sq. wafers, with even greater gains on 110Ω/sq. wafers, depending on their process and reference paste. SOL9620 Series is able to contact lowly doped and ultra lowly doped emitter wafers with long-term cell efficiency stability.

Applications: Front-side applications for conventional and advanced cell designs such as n-type and PERC.

Platform: SOL9620 Series has a lower peak temperature firing requirement relative to the SOL9610 Series. This lower temperature characteristic is ideal for both PERC and n-type cell applications. SOL9620 Series has improved flooding and low bleeding for easier processing. Post-firing, SOL9620 exhibits improved line uniformity, smoother line shape and a significant reduction in line width.

Availability: Currently available.

DSM

DSM's 'KhepriCoat' maximizes light transmission by minimizing reflection for solar cover glass

Product Outline: DSM's 'KhepriCoat' is claimed to maximize light transmission by minimizing reflection for solar cover glass, while boosting the cost/ performance ratio of solar energy. By enabling more-light to enter a solar device, KhepriCoat is claimed to significantly increase its efficiency, and can make a major contribution in the quest for clean energy generation.

Problem: Wherever glass meets air, about 4% of the light hitting the glass at a perpendicular angle is reflected. And that percentage rises steeply as the light's angle of incidence increases. Boosting module conversion efficiencies while providing improved overall module operation at low cost is required.

Solution: KhepriCoat is designed to maximize light transmission by minimizing reflection, leading to a 3-4% energy gain over uncoated modules, according to the company. KhepriCoat adds value by improving the cost/ performance ratio, thus lowering the levelized cost of electricity (LCOE). KhepriCoat can be used on both rolled (patterned) and float glass, and can be applied on one or both sides of the glass. The closed surface structure also prevents dirt and residue from penetrating or adhering to the coating's surface. This makes cleaning the modules during assembly and installation easier.

Applications: Crystalline-silicon modules, thin-film photovoltaic modules, concentrated photovoltaic (CPV) and solar thermal collectors.

Platform: KhepriCoat features patented technology with a smooth, closed structure and surface that reduces the risk of degradation, and gives the coating improved durability in extreme weather conditions.

Availability: Currently available.

Meyer Burger

Meyer Burger's diamond wire saw enables ultrathin wafer production

Product Outline: Meyer Burger is offering the DW 288+ as the first diamond wire saw system designed specifically for monocrystalline solar wafer applications. The DW 288 platform enables the slicing of silicon bricks into ultrathin wafers.

Problem: Diamond wire cutting technology is now replacing slurry-based wafer processing. The first generations of machines for this purpose are currently being introduced into the market, but there is still potential for improvement in the diamond wire cutting process. On the basis of production experience and data analysis, diamond wire has proved to be by far the largest cost driver in the wafering process. A better understanding of the factors that influence the lifetime and performance of diamond wire is therefore necessary.

Solution: The DW 288+ is unique because it includes a brand-new technology for diamond wire management during the cutting process. This innovative and patented wire management system significantly increases the diamond wire performance and therefore helps to substantially reduce wafering costs, according to the company.

Applications: The DW 288 platform can be used to slice silicon, sapphire and other brittle materials.

Platform: Additional features of the wire saw, such as the wire-web monitoring system or the one-touch carrier system, allow integration in to the Meyer Burger 'WaferLine' for integrated production systems (IPS). Meyer Burger's in-depth knowledge about the entire photovoltaic module production process enables the company to design products and product interfaces with optimized material flows and yields.

Availability: Currently available.

State-of-the-art c-Si cell manufacturing: Trends in materials, processes and products identified in the 5th edition of the ITRPV roadmap

Markus Fischer & **Alexander Gerlach**, Hanwha Q CELLS GmbH, Thalheim, Germany

ABSTRACT

The crystalline silicon (c-Si) module price has been fluctuating slightly around the US$0.72/Wp level for the last 18 months. This pricing, at an estimated cumulative PV module shipment volume of 149GWp, indicates a trend change for the PV industry. C-Si module pricing appears to be currently above the production cost and should therefore yield a profit margin. However, there is still a mismatch between manufacturing capacity and future market demand. A closer look at the pricing figures reveals that there is no indication to give the all-clear during the ongoing consolidation process in the PV industry. C-Si module pricing is not reflecting the increase in polysilicon and wafer prices, and therefore the pressure to reduce the cell and module conversion costs remains a looming fact. This paper describes state-of-the-art c-Si cell manufacturing solutions that are in line with identified trends in materials, processes and products recently published in the 5th edition of the International Technology Roadmap for Photovoltaic (ITRPV). Currently available c-Si cell technologies offering higher efficiencies as well as materials savings will be discussed. The need for implementing these technologies in mass production without significantly increasing the cost per piece and in the face of more-complex manufacturing processes will be established. The findings of the ITRPV regarding the reduction in levelized cost of electricity (LCOE) will be discussed, leading to the conclusion that contemporary cell technology supports the long-term competitiveness of PV-based power generation.

Introduction

The evolution of the sales price of PV modules has been exhibiting a continuous learning curve on the part of the PV industry for nearly 60 years [1]. Fig. 1 shows the price learning curve of PV modules for the last 37 years, from 1976 to 2013 [2]. The log–log plot displays the average module selling price in 2011 US$ as a function of cumulative module shipments. Apart from some kinks around 100MWp, the curve appears to be almost linear up to a shipment value of around 3.1GWp, which represents the cumulated shipments at the end of 2003. The linear fit shown in Fig. 1 reveals a learning rate (LR) of 21.5%, indicating that there is an average module-price reduction of 21.5% for every doubling of the cumulative module shipment.

"The evolution of the sales price of PV modules has been exhibiting a continuous learning curve on the part of the PV industry for nearly 60 years."

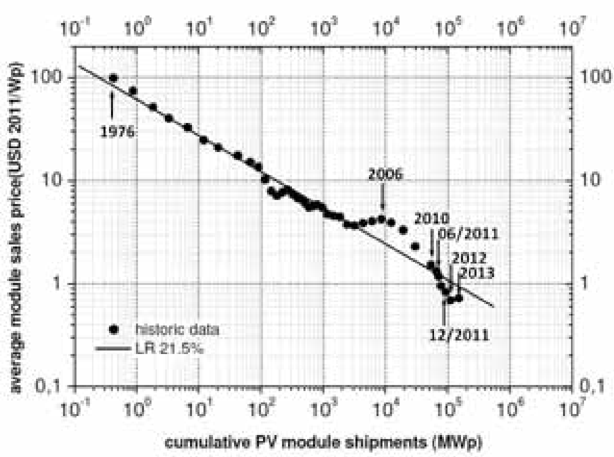


Figure 1. Historic price learning curve for PV modules from 1976 to 2013, indicating the average sales price in 2011 US$/Wp and the corresponding cumulated PV module shipments [1].

The deviations from this linear trend after 2003 were caused by strong market fluctuations. Following price increases until 2006 (8.5GWp), prices dropped again as the shipped volume increased significantly. The $1/Wp threshold was crossed in 2011 at a cumulative shipment of 77GWp, with a price of $0.95/Wp. The oversupply situation in 2011 and 2012 caused the big price drop to $0.69/Wp, which was well below the learning rate of 21.5%, and the 100GWp landmark was passed at the end of 2012, with a cumulative shipment of 110GWp. The recording of the data points of the average module price and worldwide shipment volume of PV modules at the end of 2013 ($0.72/Wp/149GWp) [2,3] in Fig. 1 indicates a small trend change in the historic price learning curve, with a big influence on the global situation of the PV industry.

Price and cost considerations

An examination of the price development of c-Si PV modules between 2010 and April 2014 indicates that the module price dropped steadily from 2010 until the end of 2012, with only minor changes occurring throughout 2013. A detailed price trend is plotted in Fig. 2, showing the pricing of polysilicon (poly-Si), multicrystalline silicon (mc-Si) wafers, c-Si cells and modules.

The inset in Fig. 2 outlines the shift in the percentage share of the different value chain elements for c-Si modules. While in 2010, at a module price of \$1.87/Wp, cell and module conversion accounted for about 25% and 33%, respectively, of the module price, these shares changed to 22% and ~50%, respectively, in January 2013, at a price of \$0.69/Wp. Since then the module price has been fluctuating around \$0.70/Wp, feigning a price stabilization, but the percentage price portion, especially for module conversion, has fallen by over 10%. Module and cell suppliers have to lower their prices while poly-Si and mc-Si wafer prices are increasing. This change, and the assumption that the global PV module production capacity of 63GWp or more in 2014 will still exceed the expected market demand of about 44GWp [5], clearly shows the market pressure on module and cell manufacturers. Finding and implementing measures for driving cost reductions in consumables and materials as main non-silicon cost elements [6] therefore remain major tasks for c-Si cell and module manufacturers in order for them to be successful in the continued PV industry consolidation phase.

ITRPV findings in cell manufacturing

The International Technology Roadmap for Photovoltaic (ITRPV) [7] discusses topics in three areas: materials, processes and products. Analogous to this, topics related to cell manufacturing, as well as the corresponding responses of the PV industry, will be discussed in the following sections.

Cell materials

Mc-Si wafers account for about 60% and 30% of the mc-Si cell price and c-Si module price respectively, as indicated in Fig. 2. Reducing the c-Si wafer price may be achieved by cost reductions in crystallization and wafer sawing and by a more efficient use of poly-Si, namely by a reduction in wafer thickness. Fig. 3 summarizes the expected thickness reduction trend for the conventional 156mm x 156mm wafer dimensions.

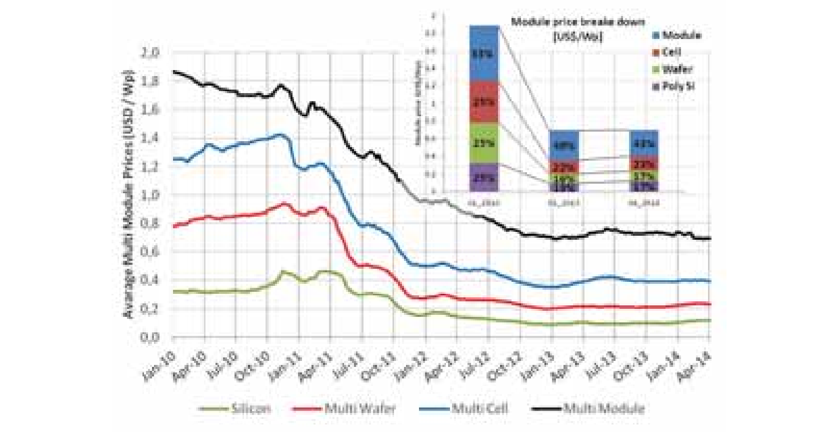


Figure 2. Price trends for poly-Si, mc-Si wafers, mc-Si cells and modules [4]. A percentage breakdown of the specified elements is shown in the inset top right. Assumptions: 44.1 wafers/kg with ~22.7g/wafer; average mc-Si cell efficiency ~17.3% (4.2Wp).

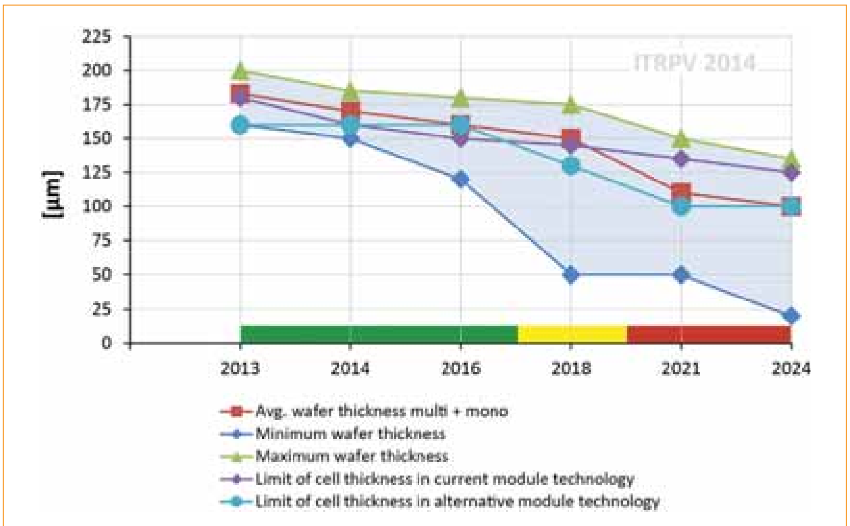


Figure 3. Predicted trends for the minimum, maximum and average as-cut wafer thicknesses in the mass production of c-Si cells and modules. (Colour coding: green = technology is available and manufacturable; yellow = technology is available but not yet in mass production; red = industrial solution not known.)

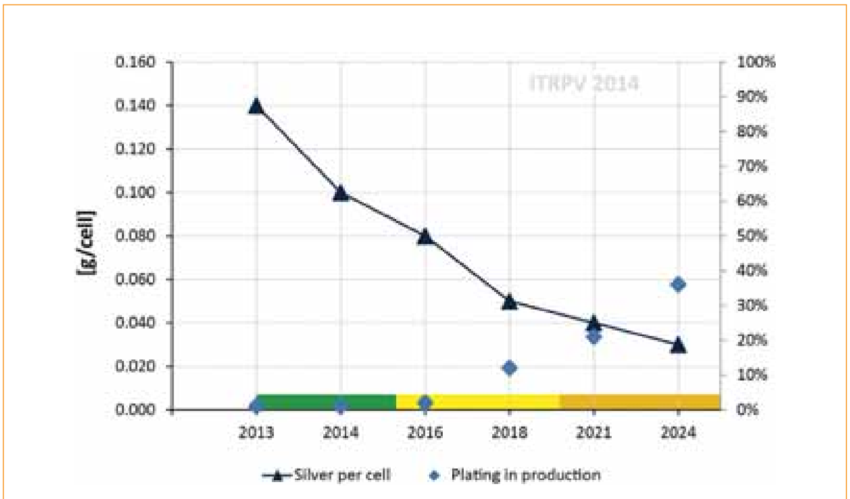


Figure 4. Trend of the reduction in silver usage per cell (156mm x 156mm) and predicted share of plating technology in production. (Colour coding: green = technology is available and manufacturable; yellow = technology is available but not yet in mass production; orange = interim solution is known but not yet suitable for mass production.)

Current minimum as-cut wafer thickness in 2014 is expected to be between 150 and 180µm. This reduction is in line with cell and module trends, and thicknesses are expected to attain 100µm in 2024. High-efficiency cell concepts and modules have to deal with this reduction in wafer thickness, in addition to the improvements in wafer-sawing technology, wafer handling and module interconnection.

C-Si cell concepts for thin wafers are currently available: different passivated emitter and rear cell (PERC) approaches for p- and n- type wafers [8], or heterojunction with intrinsic thin layer (HIT) for n-type wafers in particular [9].

Metallization pastes containing silver (Ag) and aluminium (Al) are the most costly non-Si materials in c-Si cell processing. A total amount of 140mg of Ag per 156mm x 156mm c-Si solar cell was used in 2013 for the front-side grid and for the rear-side soldering interface, as shown in Fig. 4. The Ag price of $690/kg alone as part of the paste price results in a cost of around ¢2.3/Wp, accounting for around 14% of the current price for the cell conversion of c-Si back-surface field (BSF) cells. As regards processing cost, Ag accounts for approximately 50% of the metallization process cost, as reported by Schuler & Luck [10]. With the assumptions used in Fig. 2, the quantity of Ag needed for 1GWp of c-Si cells is calculated to be 33t/GWp. The reduction of Ag per cell to 100mg in 2014 results in an impressive fall in demand to 24t/GWp. Further reductions in Ag usage per cell are therefore essential, especially with respect to the significant price fluctuations in recent years.

The future trend of Ag reduction for the next ten years is shown in Fig. 4. These projected values are ahead of the predictions of the ITRPV 4th edition [11], demonstrating the progress in screen printing. Ag is still a perfect conductor but expensive. A cost-efficient alternative may be the use of copper (Cu) with the implementation of plating technologies. The introduction of such technologies into mass production, however, is not expected to take place before 2018.

Cell manufacturers put a lot of effort into reducing cost and realizing Ag savings, while ensuring acceptable cell quality and increasing the efficiency. Some approaches – such as sophisticated front-side busbar layouts, optimized finger grids and interrupted busbar structures at the cell rear side – are illustrated in Fig. 5 and compared with designs from 2010.

Cell manufacturing processes

The conventional Al-BSF cell manufacturing process comprises 1) the front-end (FE) processing, including two wet chemical processes (texturing, chemical edge isolation) and two thermal processes (phosphorus diffusion, silicon nitride (SiN) anti-reflective coating (ARC)); and 2) the back-end (BE) processing, consisting of metallization and testing/sorting. These processing steps have been the status quo in production for several years. Regular productivity optimization of the installed production equipment is essential in order to stay cost competitive.

The construction of cell fabs with

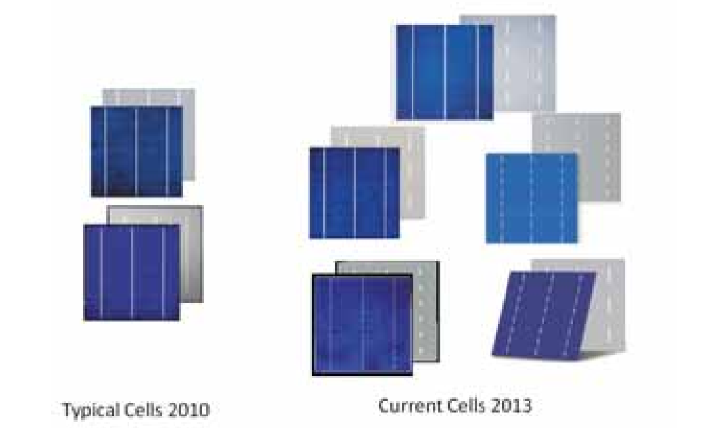


Figure 5. Comparison of c-Si cell layouts in 2010 and 2013, taken from the cell data sheets of Gintech, Hanwha Q CELLS, Hareon, JA Solar and Motech.

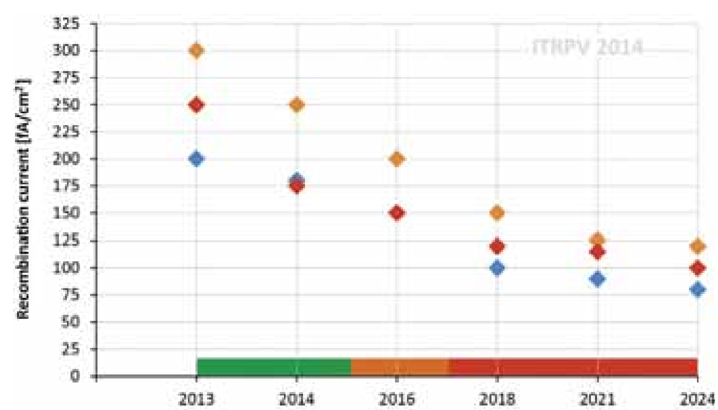


Figure 6. Trends of the recombination currents J_{0bulk}, J_{0front} and J_{0rear} in p-type cells.

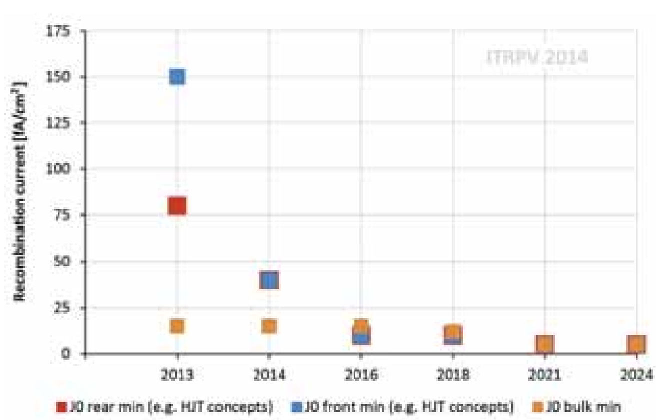
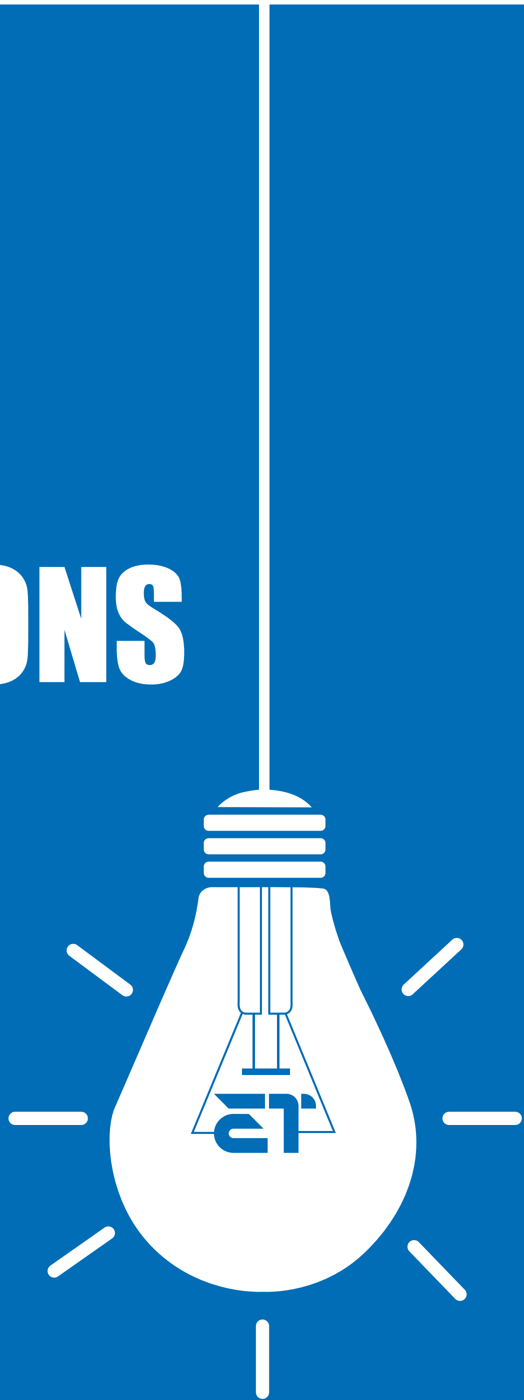
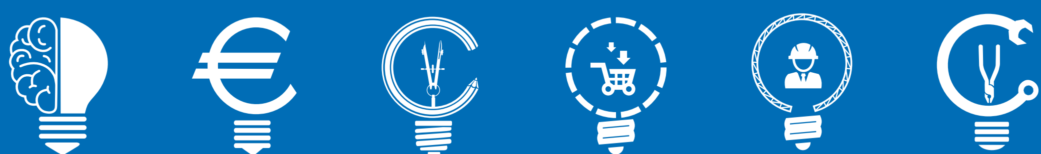


Figure 7. Trends (R&D perspective) of the recombination currents J_{0bulk}, J_{0front} and J_{0rear} for high-efficiency n-type cell concepts.

www.etsolar.com

SMART ENERGY SOLUTIONS PROVIDER





Project Development

Project Finance & Investment

Project Design & Engineering

Project Procurement

Construction Management

Operation & Maintenance

We are devoted to providing optimized solar energy solutions to meet the needs of worldwide industrial, commercial and utility customers. By constantly developing innovative solar technologies and tailored finance solutions, ET Solar is creating smart energy solutions that maximize value, mitigate risk, and optimize the Levelized Cost of Electricity (LCOE).

inter solar EUROPE

Booth: A1-390

Tel: +86 25 86898096 Fax: +86 25 86898097 Email: info@etsolar.com

Towards Excellence

new 'high-throughput' equipment is not yet in line with today's investment cycle. The current challenge for cell manufacturers is to increase tool throughput, tool uptime and process yield, in parallel with increasing the cell efficiency of existing cell products and introducing new high-efficiency cell concepts. The ITRPV 5th edition [7] emphasizes the importance of reducing the throughput mismatch between the FE and the BE. The roadmap suggests a throughput of 7200 wafers/hour for FE and BE as the target to be met by 2024 with new, innovative equipment. Today, smart upgrades of existing cell lines are more important than replacing full lines by new equipment. Those upgrades eliminate existing bottlenecks with single high-throughput tools, selected automation solutions and improvements of the installed tool base regarding manufacturing availability and throughput. Now is also a good time to implement and test new tool concepts in order to be prepared for the next investment cycle.

"Today, smart upgrades of existing cell lines are more important than replacing full lines by new equipment."

Cell process technology

Cell efficiency improvements are directly linked to reductions of the recombination current in the cell bulk (J_{0bulk}), at the cell front side (J_{0front}) and at the cell rear side (J_{0rear}). Fig. 6 shows the trend of the recombination losses for p-type cells. The trend from the R&D perspective for high-efficiency n-type cell concepts is shown in Fig. 7.

The reduction of J_{0bulk} is imperative, since stagnation here would hamper any improvement at the front or rear side of the cell. Mono-Si material provides low J_{0bulk} for p-type cells, and for the cheaper, casted p-type material there are industry solutions: high-performance (HP) mc-Si and mono-like Si material. While HP mc-Si material is available from several wafer manufacturers, the euphoric expectations for mono-like c-Si material as a low-cost alternative to p-type mono c-Si did not materialize and it has not become established in the market. N-type mono material, however, enables the lowest J_{0bulk} as demanded in Fig. 7, and it is mandatory for high-efficiency cell concepts, such as HIT or n-type PERC.

An inspection of the ITRPV assumptions about the market share of casted- and mono-Si materials confirms that no clear statement is possible about a long-term winner. As shown in Fig. 8, it is expected that the mono market share will increase slightly, from currently 40% to 50% by 2024, mainly driven by an increased demand for n-type mono material for more-complex high-efficiency cells. Casted material will remain strong in the market thanks to the shift from mc-Si to HP mc-Si material. Mono-like c-Si material is expected to remain a niche application.

Reducing the J_{0rear} to 100fA/cm^2 and below is a requirement for the cell rear side and a limitation for BSF cells. PERC cell concepts use dielectric passivation layers, enabling J_{0rear} values of ~60fA/cm^2. Solutions for the deposition of SiO_2, SiN_x or Al_2O_3 are available on the market and may be combined with a rear-side aluminium metallization as an IR light reflector, deposited by either screen printing or physical vapour deposition (PVD) methods. Lasers are available for contacting the rear-side metallization with the bulk, either before or after the metal deposition.

Fig. 9 shows the internal quantum efficiency (IQE) behaviour of the Hanwha Q CELLS Q.ANTUM cell, a typical PERC concept with rear-side passivation and laser-fired point contacts applying mc-Si material. The efficiency benefits are realized by the higher usage of infrared light, as illustrated in Fig. 9.

Reducing the J_{0front} to values below 100fA/cm^2 is a requirement, as indicated in Fig. 6. One condition that leads to a reduction in front-surface recombination losses is an increased emitter sheet resistance. The ITRPV trend for the sheet resistance of n-type doped emitters is shown in Fig. 10; with sheet resistances above 100Ω/sq., the trend moves towards more lightly doped emitters. Selective emitter (SE) or homogeneously doped (HD) emitter techniques have been commercially available for some years, as well as solutions with and without additional processing steps to contact these lightly doped regions. SE techniques are available with etch-back or laser-doping processes, with ion implantation or with silicon inks. Solutions for HD emitters are available with techniques that combine fine-line metallization with Ag plating as well as with screen printing techniques using advanced Ag-pastes.

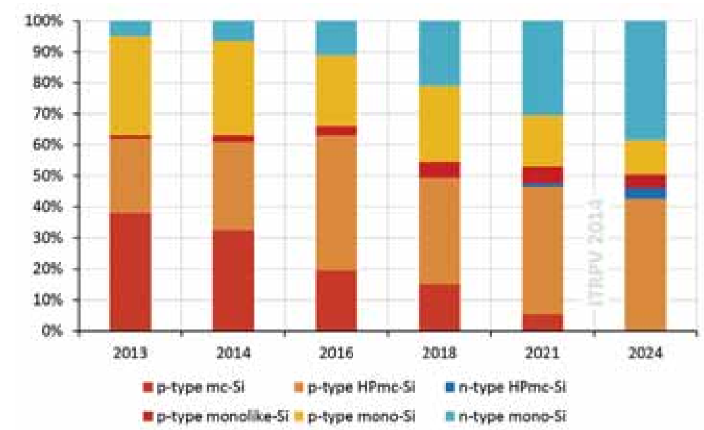


Figure 8. Expected relative market shares for casted and mono-Si materials.

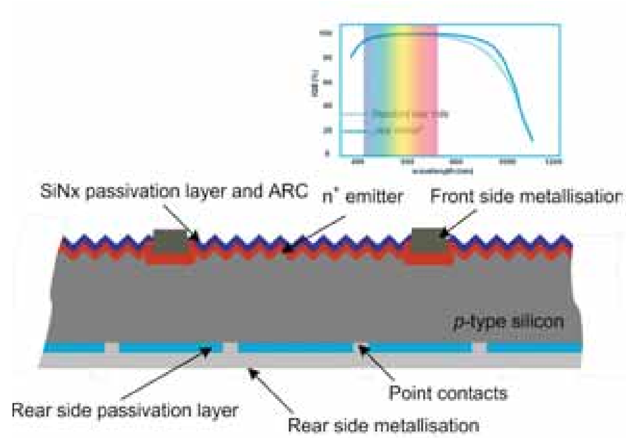


Figure 9. Schematic cross section of Hanwha Q CELLS Q.ANTUM Cell concept with passivated front and rear and laser-fired point contacts (LFC). This cell concept yields efficiencies of up to 19% on mc-Si material [12].

“A trade-off has to be made between following the roadmap for Ag reduction, good contact properties and high conductivity.”

Fig. 11 shows the ITRPV requirements for finger widths and alignment precision. Finger widths of around 65µm are currently in production: this value is significantly lower than that predicted in the 4th edition of the ITRPV [11]. Reducing the finger width increases efficiency; however, a trade-off has to be made between following the roadmap for Ag reduction, good contact properties and high conductivity. There are various technologies for high-quality printing available on the market:

- Single print – the current mainstream technology.
- Double print – a technique requiring an additional printing step and precise alignment, because the fingers are printed twice.
- Dual print – also requires an additional printing step, but the printing of the fingers is separate from the printing of the busbars, enabling the use of busbar pastes with a smaller quantity of silver.

The inset in Fig. 11 shows the expected share of these printing technologies. Single print is therefore expected to stay mainstream until 2016, with the other two methods gaining market share; no clear winner during the period to 2024, however, has so far been identified. Improvements to the screens will be necessary; current screens enable finger widths down to 50µm, with acceptable screen lifetimes. Further reductions to 30µm, in line with the ITRPV roadmap, will require either more precise and robust approaches for screens or new approaches (such as stencils, which are well established in the semiconductor industry). Revolutionary new techniques for mass production are not much in evidence so far. Nevertheless, cell manufacturers have the choice of implementing the most cost-efficient solutions for their production environments.

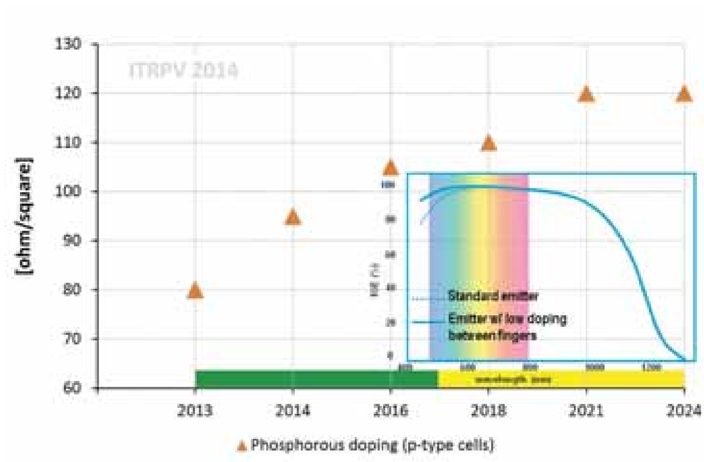


Figure 10. Expected trend for the emitter sheet resistance of n-type emitters. The inset shows the benefit in internal quantum efficiency (IQE) for cells using these improved emitters.

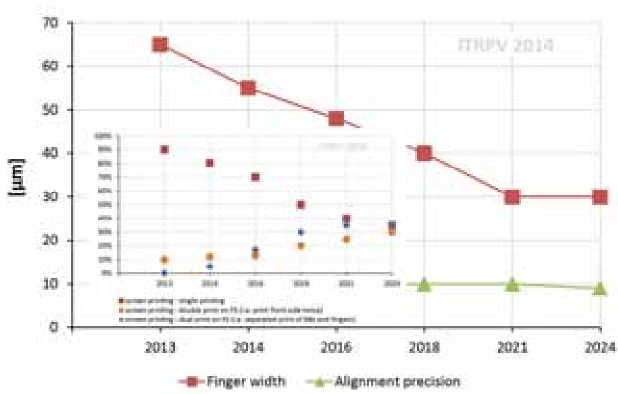


Figure 11. Predicted trend for finger width and alignment precision in screen printing. The inset shows the expected shares of different screen-printing technologies in production over the next years.

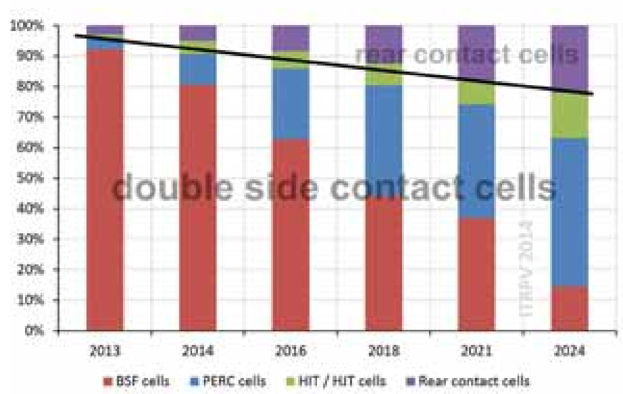


Figure 12. World market shares of different cell concepts, predicted by the ITRPV [7].

Products

The technology trends discussed above address two requirements for c-Si solar cell products: cost reduction per cell and increase in cell efficiency. As an addendum to the materials trend of Fig. 8, Fig. 12 shows the expected market share trend to 2024 of currently available cell concepts. The clear message is that double-side-contact cell concepts will remain mainstream during the next few years. The market share of BSF cells will shrink in favour of PERC concepts for both p- and n-type materials. HIT concepts are expected to gain more share, surpassing 10% by 2024. The market share of rear-contact cells is estimated to be around 20% by 2024 – a greater reduction with respect to the assumptions of the 4th edition of the ITRPV [11].

The average efficiency of c-Si solar cells is expected to steadily increase, as illustrated in Fig. 13. Fig. 14 shows the trend of the corresponding 60-cell modules, assuming a wafer format of

156mm x 156mm (in the case of high-efficiency rear-contact cells, the values are estimated, as these cells are not yet available in this format). N-type cells will yield the highest efficiencies and respective module power classes, with an efficiency advantage of up to 4.5% over p-type cells. Despite the above-discussed progress in casted crystallization – especially the wide availability of HP mc-Si material – it is evident that the argument of the gap between mc-Si and mono-Si materials still remains valid. Acidic texturing is assumed for mc-Si and HP mc-Si cells, and alkaline texturing for mono materials. Fig. 14 clarifies the expectation that HP mc-Si cells will enable 60-cell modules to produce 300Wp.

Conclusion

A prediction of the future cost development for modules and of the LCOE can be made by considering all the available technology improvements and trends discussed above. Cell efficiency improvements, in combination with average unit cost reductions through improved manufacturing productivity and optimized materials consumption, will result in continued reductions in cost/Wp of c-Si modules.

Table 1 summarizes the predicted cost evolution if the average percentage increases in module power (deduced from Fig. 14) and the continual manufacturing cost reductions are combined. The June 2012 price value of \$0.83/Wp represents the average cost from non-Chinese module manufacturers, i.e. the price was at cost level at that time [13]. The module manufacturing cost at the end of 2012 is assumed to be \$0.73/Wp, which is slightly above the module price at that time. The average module production cost of \$0.64/Wp is assumed for the end of 2013 [3]. The stable price development of 2013 driven by the development of the previous two years and anti-dumping initiatives in the USA, Europe, India and China provided breathing room for module production costs to catch up with prices. The industry has currently already reached a price level in 2014 that was expected with a deployment of 350–400GWp of cumulated installed capacity – a level that will most likely be reached between 2016 and 2017 [14]. The values for subsequent years are calculated on the assumption of average cost reductions between 3 and 5% per year. Module shipments in 2014 are assumed to be 50GWp [5]. For the years beyond 2014 an annual growth of between 60 and 70GWp is expected [15].

Fig. 15 shows a plot of the ITRPV cost trend together with the historic price learning curve; the calculated learning rate for this cost trend is 23.5%, slightly ahead of the historic price learning rate. The analysis emphasizes the potential of the c-Si PV industry to support further cost, and hence price, reductions. Future cost reductions for c-Si modules will further improve the cost structure of c-Si-based PV systems, lower the LCOE and increase the potential market size. Moreover, a lower LCOE will enable entire customer groups to supply themselves with low-cost electricity by the end of the decade at well below retail electricity prices – and therefore position PV as a major global source of energy in the 21st century [16].

“The PV industry will be able to provide highly competitive power-generation products compared with conventional and other renewable sources of energy.”

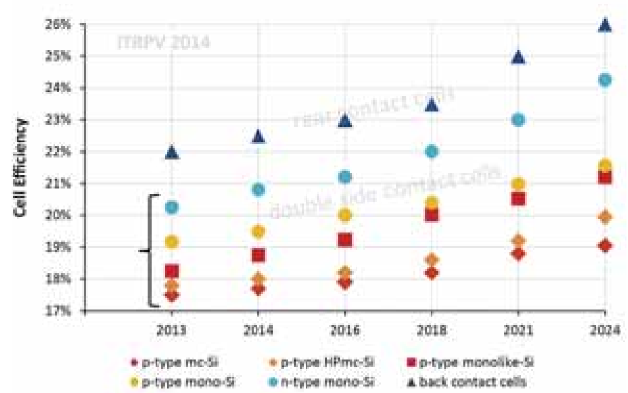


Figure 13. Stabilized cell efficiency trend curves for different c-Si cell concepts.

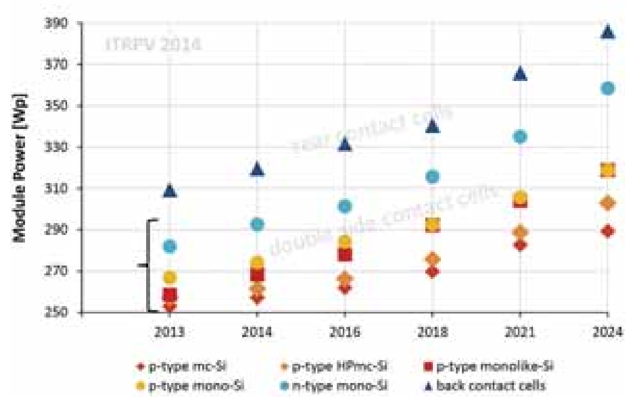


Figure 14. Module efficiency trend curves for different c-Si cell concepts.

	06/2012	12/2012	12/2013	12/2014	12/2016	12/2018	12/2021	12/2024
Cum. volume shipped [GW]	92	110	150	200	320	440	630	850
Avg. Wp increase (period to period)			3%	3%	3%	4%	5%	5%
Cost reduction (period to period)			6%	6%	8%	10%	10%	10%
ITRPV cost trend [US\$/Wp]	0.83 [13]	0.73	0.64 [3]	0.58	0.52	0.45	0.38	0.33

Table 1. Module manufacturing cost trend based on the predictions of the 5th edition of the ITRPV [7].

SCHMID

Imagine You'd Save as Much Silver to Plate the famous Allianz Arena...*

inter solar

June 4th to 6th 2014
Munich, Germany
Hall A3, Booth 490

Expect Solutions. **TinPad.**

Eliminate the need of silver on cell backsides and increase efficiency at the same time. TinPad is a really simple way to apply tin busbars with best adhesion. In a highly competitive market, this tool is a must-have to reduce costs in the short term and a get long ranging profit increase.

In a cell production line with a throughput of 2.200 wph, 95% uptime and 50mg Ag backside consumption you would save as much silver in one year to cover an area of over 270000m^2 with 1μm leaf silver. That's more than enough to plate the ceiling surface of the Allianz Arena. Or to simply increase your profit.

150 YEARS SCHMID Expect Solutions

www.schmid-group.com/tinpad

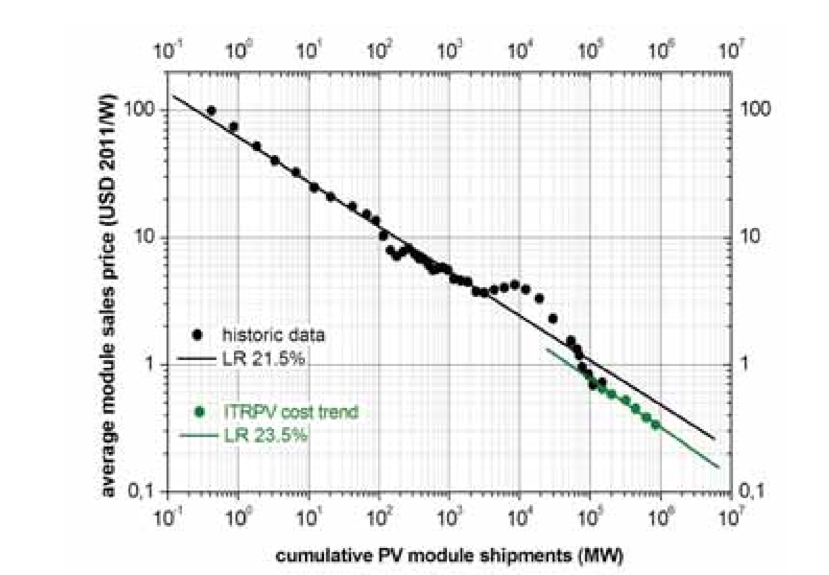


Figure 15. C-Si module cost trend of Table 1 combined with the historic sales price learning curve for PV modules.

The 5th edition of the ITRPV [7] contains an analysis of the LCOE trend at different insolation conditions, taking into account the discussed cost-reduction capabilities of c-Si PV modules. It is shown that today's LCOE of \$0.05–0.10/kWh can reach a level between \$0.03 and \$0.07/kWh. Contemporary c-Si cell technology consequently supports the long-term progress of PV-based power solutions. The PV industry will therefore be able to provide highly competitive power-generation products compared with conventional and other renewable sources of energy.

The data for the ITRPV 5th edition [7] were collected in 2013 from leading international PV manufacturers along the c-Si value chain, PV equipment suppliers, production material providers and PV institutes. Information about how to get involved in the roadmap activities is available on the website www.itrpv.net.

References

[1] Kersten, F. et al. 2011, "PV learning curves: Past and future drivers of cost reduction, *Proc. 26th EU PVSEC*, Hamburg, Germany.

[2] Ristow, A. 2013, compilation of pricing and cumulated c-Si-PV installations, based on data published by Maycock (2001), PVNews (2005–2010), Mehta (2011) and EPIA (2013).

[3] de Haan, S. 2013, "Predictions for the solar Industry in 2014 – Top 10 trends for the year ahead", IHS iSuppli (December) [www.isupplis.com/Photovoltaics/News].

[4] Gerlach, A. 2014, data compilation from Bloomberg New Energy Finance, Energy Trend, Photon Consulting and PV Insights.

[5] de Haan, S. 2014, "Solar PV industry analysis & market overview", presentation 8th SEMI Fab Managers Forum, Shanghai, China.

[6] SEMI PV Group Europe 2012, "International technology roadmap for photovoltaic (ITRVP): Results 2011", 3rd edn (March) [http://itrpv.net/.cm4all/iproc.php/Reports%20downloads/roadmap_itrpv_march_2012_full_web.pdf?cdp=a].

[7] SEMI PV Group Europe 2014, "International technology roadmap for photovoltaic (ITRVP): Results 2013", 5th edn (March) [http://itrpv.net/.cm4all/iproc.php/Reports%20downloads/ITRPV_2014_Roadmap_140314_web_z.pdf?cdp=a].

[8] Kray, D. 2004, "Hocheffiziente Solarzellenstrukturen für kristallines Silicium-Material industrieller Qualität", Dissertation, Universität Konstanz / Fraunhofer-Institut für Solare Energiesysteme, Freiburg im Breisgau, Germany.

[9] Panasonic Corporation 2013, "Recent technological progress of high-efficiency HIT solar cells" [www.nikkeipr.co.jp/pvjapan/seminar4_4en.pdf].

[10] Schuler, S. & Luck, I. 2014, "Cell metallization by screen printing: Cost, limits and alternatives", *Photovoltaics International*, 23rd edn.

[11] SEMI PV Group Europe 2013, "International technology roadmap for photovoltaic (ITRVP): Results 2012", 4th edn (March) [http://itrpv.net/.cm4all/iproc.php/Reports%20downloads/ITRPV_Roadmap_march_2013_web.pdf?cdp=a].

[12] Klöter, B. et al. 2013, "Current status of high-efficiency Q.ANTUM technology at Hanwha Q CELLS", *Proc. 28th EU PVSEC*, Paris, France.

[13] Mehta, S. 2012, "Global PV module manufacturers 2013: Competitive positioning, consolidation and the China factor", GTM Research.

[14] Gerlach, A. 2014, data compilation from Bloomberg New Energy Finance, Bank Analysts (Credit Suisse, Goldman Sachs, Deutsche Bank, Macquarie, Citi Research, UBS) and EPIA.

[15] EPIA 2013, "Global market outlook for photovoltaics 2013–2017" [www.epia.org].

[16] Gerlach, A. & Breyer, C. 2012, "Global grid-parity dynamics on a global and regional level", *Proc. 27th EU PVSEC*, Frankfurt, Germany.

About the Authors

Markus Fischer studied physics at the Dresden University of Technology and received his Ph.D. in electrical engineering in 1997 from the University of Stuttgart. After working in the semiconductor industry in different engineering and management functions at Siemens, Infineon, Philips and NXP, he joined Hanwha Q CELLS in 2007. As director of R&D processes, Markus is responsible for the process development of c-Si solar cells as well as for the Hanwha Q CELLS research and module test lines. Since 2010 he has been a co-chairman of the SEMI ITRPV for c-Si technology.

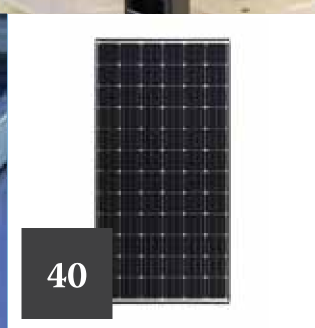
Alexander Gerlach studied business administration and engineering, with a focus on production and processes, at the Clausthal University of Technology, Germany. He joined Hanwha Q CELLS in 2010 as part of the market research team. As a senior specialist responsible for market intelligence within the strategy and planning department at Hanwha Q CELLS, Alexander provides market, customer and competitor information. Since joining the company he has authored and co-authored several papers on grid parity and related topics, both for conferences and for peer-reviewed journals.

Enquiries

Hanwha Q CELLS GmbH
Sonnenalle 17–21
06766 Bitterfeld-Wolfen
Germany

Tel: +49 (0) 3494 6699-0
Fax: +49 (0) 3494 6699-199
Email: m.fischer@q-cells.com
Website: www.q-cells.com

Cell Processing



News

Back contact HIT solar cell from Panasonic pushes efficiency record to 25.6%

Panasonic Corporation has achieved a record conversion efficiency of 25.6% on a commercial sized (143.7 cm^2) monocrystalline-based 'HIT' solar cell.

A key breakthrough in the efficiency record was employing back contact electrodes for the first time with its heterojunction technology. The previous record set by the company in February 2013 used a 101.8 cm^2 cell to produce a conversion efficiency of 24.7%.

Panasonic said that reduction improvements in recombination loss, optical loss and resistance loss were contributors to the new efficiency record.

The reduction in resistance loss was a key aspect of migrating to a back contact cell, while improvements in short circuit current density (Jsc) to 41.8mA/cm^2 compared to its previous 39.5mA/cm^2 were contributing factors from the back contact cell.

Panasonic said that in its previous HIT cell configuration top surface electrodes had been optimised by thinner grid electrodes, but placing the electrodes on the reverse side of the cell reduced the resistive loss when the current was transferred to the grid electrodes.

The company also reported a high fill factor of 0.827, by improving resistance loss in the amorphous thin-film silicon layer.

Panasonic has pushed HIT cell efficiency to 25.6%.

Efficiency gains

Kyocera to produce new higher performance mono and multicrystalline cells

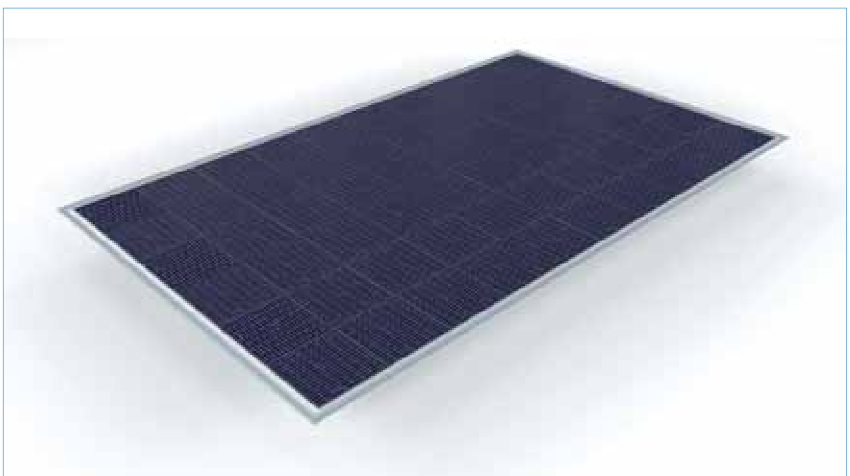
Japanese PV manufacturer Kyocera is preparing to launch solar modules around the halfway point in the year with multicrystalline cells which have a conversion efficiency of 18.6%. The new multicrystalline cells are a significant 0.8% leap from the company's previous record of 17.8%.

Kyocera said that the new record multicrystalline cells benefit from bare wafer quality improvements as well as improvements in the electrode process and the reduction of carrier recombination. Carrier recombination is a phenomenon within a solar cell when positive and negative electric charges recombine - the opposite of electricity generation.

A passivated emitter process on the cell frontside and a locally diffused backside is known to minimize recombination and retaining electrical contact, boosting cell conversion rates. Kyocera also said that it had commercialized its first monocrystalline PV modules for the Japanese market. The company plans to raise the conversion efficiency of its mono-Si cells from 19% to more than 22%, "within the next few years".

GTAT expects first 'Merlin' orders soon

GT Advanced Technologies (GTAT) is expecting first customer purchase orders in the second-half of 2014 for its "game-changing" 'Merlin' cell metallization and interconnect technology. GTAT claims Merlin will boost conversion efficiencies while lowering production costs via significantly reduced silver paste consumption.



Source: GT Advanced Technology

GT Advanced Technologies claims its new 'Merlin' cell technology will boost overall conversion efficiencies.

By eliminating busbars completely, with a flexible mesh providing a unique patented narrow aspect ratio finger profile and importantly eliminating the need for tabbing and stringing processes, GTAT claimed an overall 80% cost reduction in silver paste consumption and an overall 10% cost reduction in system costs.

The 'flexible' screen pattern produces finger bars that form 'segmented' fingers onto the solar cell. The route taken by GTAT was said to be cell design agnostic for both the flexible mesh metallization technology as well as the copper fixed-tab extension on the backside of the cell to enable cell to cell connection.

The only existing step that remains is cell layout. Management noted that customer preference to stay with standard and upgraded fine-line screen printers was a key consideration in the developing the technology. Merlin technology is claimed by GTAT to be easily integrated into existing cell and module manufacturing lines with just a simple change to the screen used for patterning .

ISFH partnership pushes industrial PERC solar cell to record 21.2% efficiency

The Institute for Solar Energy Research Hamelin (ISFH) and a suite of industry partners have produced an industrial PERC (Passivated Emitter and Rear Cell) solar cell (156x156mm2) with 21.2% record conversion efficiency, verified by Fraunhofer ISE CalLab.

According to ISFH, key to the record conversion efficiency were two developments. The first was the use of fine-line dual screen printing process using DEK Solar's Eclipse screen printing platform to fabricate a front side five-


Source: ISFH

ISFH's Thorsten Dullweber display's the record breaking PERC cell.

busbar design with contact finger width to 46μm, significantly reducing shadow losses, boosting efficiency conversion rates.

Specially developed silver (Ag) pastes from Heraeus were used for printing the complete front-side grid, noted ISFH. Secondly, ISFH said that the local rear metal contacts were screen-printed with an improved aluminium (A1) paste provided by DuPont Microcircuit Materials using an optimised contact geometry with narrower contact lines.

Other processing techniques to reach the record conversion efficiency were used including an AlOx/SiNy passivated rear side with a homogeneous phosphorus diffused emitter, together with the boron-doped Czochralski (Cz) silicon wafer.

The 21.2% world record efficiency was achieved within the research project 'HighScreen' funded by the German Federal Ministry of the Environment in collaboration with project partners SolarWorld, Heraeus, RENA, and Singulus Technologies.

Trina Solar collaborative IBC solar cell to be commercialised

An n-type mono 'interdigitated back contact' (IBC) solar cell developed by Trina Solar in collaboration with the Australian National University (ANU), the Solar Energy Research Institute of Singapore (SERIS) and PV Lighthouse is set for commercialization.

The cell is the result of a three-year R&D programme which began in mid-2010. Trina Solar said that the Fraunhofer CalLab in Germany independently tested the lab-based solar cell, confirming it could deliver a conversion efficiency of 24.4%.

However, Trina Solar said that a commercial version of the IBC solar cell as well as an IBC PV module using (125mm x 125mm) mono-Si wafers/cells in a 72-cell format module (238W) had been independently tested by the National Center of Supervision and Inspection on Solar Photovoltaic Products Quality of China, with cell conversion efficiencies above 22%. Trina Solar said that a full commercial product offering would happen soon.

China marches on

Solargiga expands downstream China EPC efforts with acquisition

Chinese monocrystalline wafer producer and wafer-to-module processing service provider, Solargiga, has acquired Chinese solar EPC firm, Jinzhou Wintek Silicon Materials for approximately US$2.5 million.

Solargiga's ingot/wafer subsidiary, Jinzhou Yangguang was responsible for the acquisition.

The company noted that the acquisition of Jinzhou Wintek would provide further sales channels for its existing products as well as support growth in its downstream PV project business.

Yingli Green provides solar cells for French PV manufacturer

Yingli Green is providing an unidentified France-based PV module manufacturer with its polycrystalline solar cells.

The unidentified French firm has already won what was described as "large-volume tenders" under the 'French National Tender Program' which totals around 380MW.

According to Yingli Green, in the recent rounds of French public tenders, 17 out of 38 PV developers won projects that would use Yingli Green's solar cells, representing 185MW out of 380MW in total.

The projects are expected to be completed within the next two years.

Company news

Meyer Burger slashes order backlog as losses increase on plummeting sales

PV equipment supplier, Meyer Burger, has finally stripped away a long-standing tool order backlog from its balance sheet as sales plummeted in 2013.

The company confirmed full-year 2013 revenue of CHF202.7 million, compared to CHF 645.2 million in 2012. Although new bookings started to improve in a later part of the year, the company said that it did not expect to return to profitability in 2014.

Significantly, Meyer Burger had initially reported that its order backlog at the end of 2013 stood at CHF399.6 million, compared to CHF405.5 million at the end of 2012. However, the company noted in its 2013 annual report that it de-booked the order backlog to the tune of CHF210 million, resulting in an order backlog of CHF190.3 million.

BTU International sales rise but company remains cautious on PV orders

Advanced thermal processing equipment supplier, BTU International, has reported first quarter 2014 sales of US$11.7 million, up 6.3% compared the previous quarter.

The majority of business was generated from its electronics manufacturing segment, while the company noted that it remained cautious about capital expenditure increases in the PV sector.

The company reported a net loss for the quarter of US$1.8 million, compared to a net loss of US$3.0 million in the previous quarter. Company management noted despite the lack of solar segment revenues it was more optimistic about single equipment orders for pilot line facilities working on advanced solar cell structures.

RENA enters insolvency proceedings under self-administration

Wet chemicals equipment processing specialist, RENA, has started insolvency proceedings under self-administration as it attempts to restructure after failing to gain a financing solution for debts encountered at a subsidiary, SH+E.

The company said the insolvency proceedings only related to the German operations of RENA GmbH, while other subsidiaries of the RENA Group would continue operating as normal. It stressed that business at RENA GmbH and the other group companies had been improving with new orders received totalling around €22 million with and an order backlog of around €100 million.

Product Reviews

Rofin

Rofin's 'Dual Line c-Si' laser processing system upgrades boost PERC cell productivity

Product Outline: ROFIN-BAASEL Lasertech is launching a new upgraded version of its production proven 'Dual Line c-Si' laser processing system that provides improved productivity and lowers processing costs in volume production of next-generation PERC (Passivated Emitter and Rear Cells) solar cell design.

Problem: PERC and selective emitter processes offer improvements of up to a 1% absolute efficiency gain for c-Si solar cells but the migration to high-volume production and the provision of lower production costs are required.

Solution: Rofin undertook research on short wavelength and short pulse laser tool requirements to minimize sub-surface damage during rear-side contact hole formation and optimization of rear side passivation. The study revealed that complex ultra-short femto and picosecond lasers create completely different surface structures after laser ablation of dielectric layers compared to nanosecond laser pulses. However, studies also showed that rear side passivation opening using green nanosecond laser pulses led to the same level of high-efficiency solar cells as it does with ultra violet picosecond pulses. Important to the optimization of the process was the ability to use industrial lasers, offering up to five times higher power compared to the previously used nanosecond laser source, reducing laser process cycle times per wafer significantly and improving overall wafer throughput.

Applications: Passivated Emitter and Rear Cells (PERC) laser ablation process.

Platform: The Dual Line c-Si can now be equipped with a high power ns-SHG-laser specifically developed for the creation of larger dot diameters without increasing the laser induced damage

Availability: May 2014 onwards.

Roth & Rau

Roth & Rau's MAiA 2.1 platform provides quality coating capabilities at lowest production costs

Product Outline: Roth & Rau, a member of the Meyer Burger group, is one of the world's leading suppliers of inline systems for PECVD, anti-reflection coating (ARC) and front- and back-side layer deposition of substances such as SiN, AlOx and a-Si. With its core competence in plasma technology, the company has extended the process application portfolio of its MAiA (multi-application inline apparatus) system to plasma texturing of c-Si solar cell surfaces.

Problem: PV cell producers need a cost-effective solution for depositing ARC and passivation layers during the production of crystalline solar cells. The technique used must meet the requirements of the different cell technologies, e.g. standard, PERC, and multi- and monocrystalline. It is essential to find a balance between layer quality requirements and production costs, so that the cell producer is able to manufacture its best product.

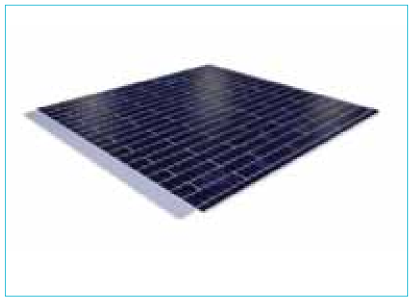
Solution: The MAiA 2.1 platform offers proven process quality at a claimed lowest production costs. The flexible inline system combines a high throughput and a low footprint with the lowest ratio between investment and output. In combination with related components (e.g. automation or gas supply units), the platform can be a complete work centre for producing a high-performance solar cell.

Applications: SiN or AlOx PECVD deposition as the production steps of standard or PERC cells.

Platform: The MAiA 2.1 modular system for inline plasma processes is an evolution of the proven SiNA/MAiA production platform. Improved transport algorithm allows length reduction without throughput loss. It offers improved tool stability for best equipment availability, and has a reduced footprint with retained high throughput.

Availability: Currently available.

GT Advanced Technologies



GT Advanced Technologies 'Merlin' metallization and interconnect technology offers cost savings

Product Outline: GT Advanced Technologies (GTAT) has announced an innovative cell metallization and interconnect technology, dubbed 'Merlin' that is expected to provide savings in the manufacture and installation of solar modules. The new technology includes a flexible grid that replaces conventional two and three silver bus bars, while significantly reducing solver paste consumption.

Problem: According to TUV Rheinland PTL, a number of key issues have been identified, including solder bond failures, hot spots and ribbon-to-ribbon solder bond failures in conventional cell stringing processes for two and three busbar configured cells. Cell manufacturers continue to focus on silver paste cost reduction strategies including the need to reduce consumption, while boosting cell conversion efficiencies.

Solution: The novel attributes of Merlin technology are expected to significantly reduce the amount of expensive silver paste consumed while improving panel efficiency. The resulting modules are expected to be more reliable and durable, as well as lighter and easier to handle, resulting in lower shipment and installations costs. GTAT's patented Merlin technology integrates into existing cell and module manufacturing lines with simple changes. The segmented fingers are thinner and produce less shading than conventional fingers. The combination of the flexible grid and the segmented fingers results in lower resistive losses thereby increasing cell and module efficiency.

Applications: Solar cell metallization and interconnect processes.

Platform: Merlin technology uses mature, proven manufacturing processes to produce the flexible grids.

Availability: Currently available.

Advanced front-surface passivation schemes for industrial n-type silicon solar cells

Bas van de Loo[1], Gijs Dingemans[2], Ernst Granneman[3], Ingrid Romijn[4], Gaby Janssen[4] & Erwin Kessels[1]

[1]Eindhoven University of Technology, The Netherlands; [2]ASM, Leuven, Belgium; [3]Levitech BV, Almere, The Netherlands; [4]ECN Solar Energy, Petten, The Netherlands

ABSTRACT
The n-Pasha n-type silicon solar cell currently achieves an average conversion efficiency of 20.2% using a relatively simple process flow. This bifacial cell concept developed by ECN is based on homogeneously doped p^+ front and n^+ back surfaces. To enhance the cell efficiency, it is important to reduce the carrier recombination within the boron-diffused p^+ region and at its surface. This paper addresses a novel way to tune the boron-doping profile and presents advanced surface passivation schemes. In particular, it is demonstrated that a very thin (2nm) Al_2O_3 interlayer improves the passivation of the boron-doped surface; the Al_2O_3 films were deposited in industrial atomic layer deposition (ALD) reactors (batch or spatial). Moreover, it is shown that the boron-doping profile can be improved by etching back the boron diffusion. On the basis of the results presented, it is expect that n-Pasha solar cells with 21% efficiency will soon be within reach.

Introduction
In 2010 ECN, Tempress and Yingli introduced the n-Pasha cell to the market as a novel bifacial cell concept based on n-type Czochralski-grown (Cz) silicon with homogeneous diffusions, dielectric passivation and printed metallization (Fig. 1) [1]. Recently, Nexolon America selected this cell concept for their production line, enabling the production of bifacial modules [2].

"The bifacial cell concept allows higher power output per installed Wp."

One of the key benefits of a bifacial cell is the capturing of albedo light from the 'open' rear side. Recent field studies [3] have revealed a higher power generation with these bifacial cells than with monofacial cells during the morning and evening hours, which is when indirect light contributes most to the carrier generation. Even when

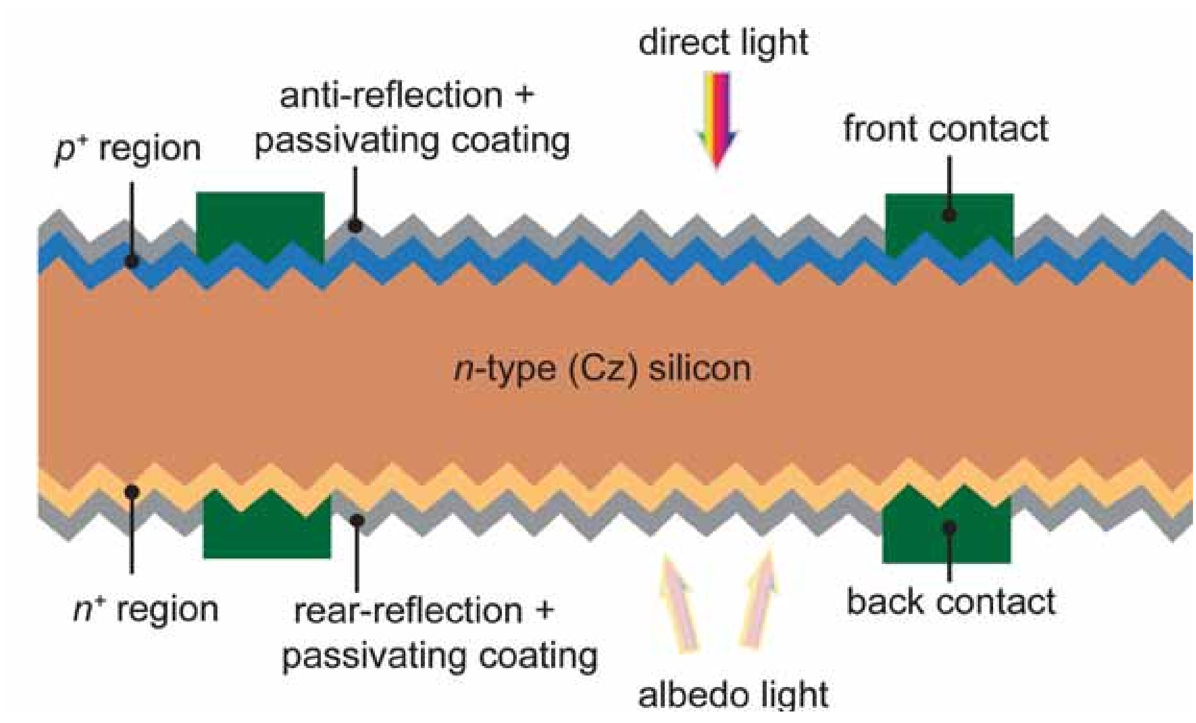


Figure 1. A schematic cross section of the bifacial n-Pasha cell concept, which enables the capture of albedo light.

positioned vertically, for example along roads, bifacial modules are able to generate electricity all day long while the sun moves from east to west. The bifacial cell concept therefore allows higher power output per installed Wp.

The current n-Pasha baseline process yields an average efficiency of 20.2%, with a top efficiency of 20.4% on high-quality Cz material [4]. These cells, and other cells based on n-type Si wafers, compete with p-type PERC cells (rear passivated cells with local contacts) for a spot in the higher-efficiency segment. One of the main advantages of n-type cells as compared to PERC is the absence of light-induced degradation. On the other hand, there are a number of technological and scientific challenges for industrial n-type cells which have to be addressed in order to achieve high efficiencies while remaining cost-competitive:

- (Independent) control of diffused n^+ and p^+ doping profiles.
- Excellent level of passivation of both front and rear surfaces.
- Reduced contact recombination on the p^+ side.
- Minimal consumption of silver paste to contact both sides.
- Insensitivity of cell efficiencies to variations in resistivity of the n-type base.

The last two issues in the list have been successfully addressed in previous articles in this journal [5,6]. After a general discussion on recombination, this paper will address the first two topics, currently the limiting factors of n-Pasha solar cells [7]: the optimization of the boron-doping profile and the passivation.

Physics of carrier recombination in solar cells

The recombination of light-generated electron-hole pairs reduces the conversion efficiencies of solar cells. Although to a certain extent this recombination is inevitable because of intrinsic processes such as Auger and radiative recombination, the recombination can also be enhanced by lattice defects. These defects can form energy states within the silicon band gap, via which charge carriers can effectively recombine: this mechanism is known as *Shockley Read Hall (SRH) recombination*. Such defect states are omnipresent in solar cells as a result of (lattice) defects both in the silicon bulk and at the silicon surface.

Towards n-type silicon base material

Electronically active defects within the bulk of the silicon, such as defects at the grain boundaries and boron–oxygen complexes, can effectively be mitigated by using, respectively, monocrystalline silicon rather than multicrystalline silicon, and n-type silicon rather than (boron-doped) p-type silicon. Switching to n-type silicon is also beneficial, as this material is much less sensitive to transitional metal contaminants, such as Fe [8]. It is precisely these benefits in terms of bulk quality that were the incentive for many institutes and companies to develop solar cells based on n-type monocrystalline silicon base material, such as the n-Pasha cell concept.

Surface recombination

Although a high-quality bulk material in principle allows for high conversion efficiencies, to achieve this potential at the cell level care must be taken to reduce carrier recombination near the surfaces of the cells (Fig. 2). More specifically, one can distinguish between recombination at the metallic contacts and recombination in the well-passivated regions in between.

Since metallic contacts exhibit a very high density of states across the silicon band gap, the metal–silicon interface acts as a ‘catalyst’ for electron–hole pair recombination. If the silicon underneath the contacts (conventionally termed *emitter* and *back-surface field*) is heavily doped, the conductivity of *one* carrier type is reduced, while it is drastically enhanced for the other. In this way, the metal contacts are effectively made selective for one carrier type (i.e. selective electron or hole contacts are formed [9]), and recombination is suppressed. A parameter governing both the carrier selectivity and the recombination is the recombination current parameter, or (thermal equilibrium) recombination current density [9] (formerly referred to as *emitter* saturation current density, which should ideally be as low as possible. Unfortunately, heavy doping leads to a trade-off, as it enhances Auger recombination, which varies as a function of the square of the majority-carrier density. It is for these reasons that initiatives using (semi-conducting) passivated selective contacts without the necessity of heavy doping have emerged: very high efficiencies have been demonstrated [10]. A well-known example is the use of intrinsic and doped amorphous Si layers in silicon heterojunction solar cells.

Although for metallic contacts heavy doping is consequently required to ensure a low contact resistance and an adequate carrier selectivity, for the regions in between the metallic contacts the function of the doped regions is solely to conduct the carriers laterally. In homogeneously diffused solar cells, such as n-Pasha, the recombination in between the contacts consists of both Auger recombination due to the heavy doping, and surface recombination due to the presence of surface defects (where the interface defect density

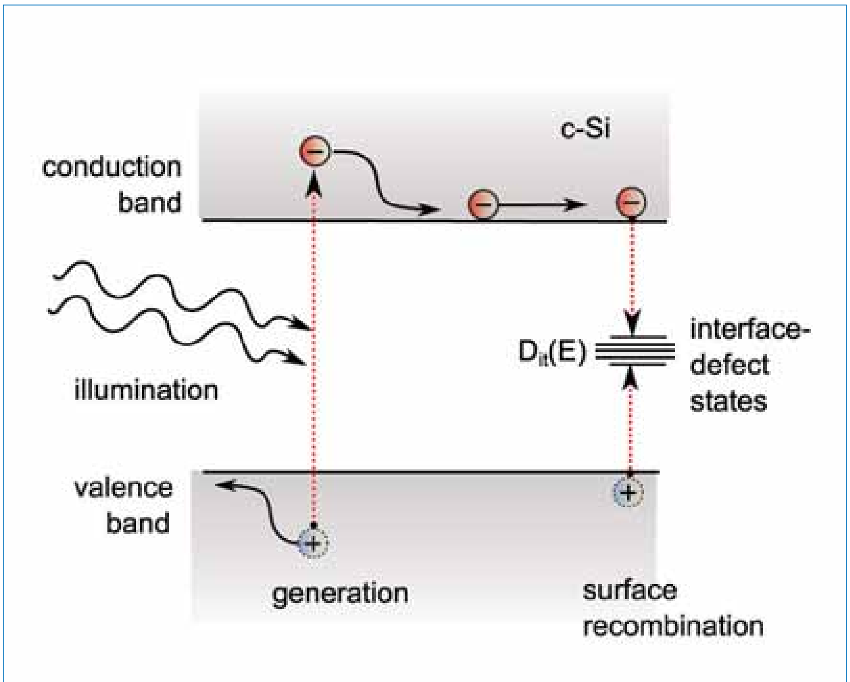


Figure 2. A schematic band diagram of silicon, showing the generation of excess carriers by the absorption of light and the surface recombination of excess charge carriers via interface defect states.

INTRODUCING

SinTerra

- Reliability
- Performance
- Value

SinTerra, the latest technology for metallization drying and firing from BTU, offers outstanding value by providing high-performance heating and cooling technologies. SinTerra delivers the lowest Cost of Ownership with industry-leading uptime, unmatched process repeatability and competitive pricing. BTU follows a simple design philosophy; focusing on reliability, process repeatability and thermal performance.

BTU

www.btu.com

PIONEERING PRODUCTS & PROCESS SOLUTIONS

IN-LINE DIFFUSION | METALLIZATION | THIN FILM is denoted by D_{it}). In the following sections, improvements to the p^+ doped region and to the surface passivation, both aiming to reduce the front-surface recombination, will be addressed.

Doping-profile optimization

For the n-Pasha cells, the boron and phosphorus diffusions are performed in a Tempress industrial tube furnace using BBr_3 and $POCl_3$ as precursors, respectively. The phosphorus n^+ region at the rear provides additional lateral conductivity for electrons, which makes the n-Pasha concept less sensitive to changes in the n-type bulk resistivity and allows the use of a bulk material with a high resistivity of 10Ω•cm [6]. The latter consideration is of importance for n-type solar cells, as the variation in base resistivity of n-type ingots is higher than for p-type ingots because phosphorus has a higher segregation coefficient than boron. The efficiency improvements of n-Pasha cells through using a shallower doped n^+ region, while maintaining the lateral transport properties, have recently been reported by the authors [5,6]. Here, however, the focus will be on improving the boron-doping profile.

Fig. 3(a) shows the electrochemical capacitance–voltage (ECV) profile of a standard boron diffusion of the n-Pasha cell with a sheet resistance R_s of 60Ω/sq. This standard profile (profile 1) exhibits a boron-depleted region within the first 10 to 30nm; the depleted region originates from the higher solubility of boron in SiO_2 than in Si. SiO_2 is intentionally formed after boron diffusion to reliably remove the boron-rich layer (BRL), a Si-B compound which is otherwise difficult to remove and is detrimental to surface passivation [11]. The boron-depleted region of profile 1 can, however, be etched back, resulting in doping profiles 2 and 3. Note that the application of dielectrics for surface passivation in the work reported in this paper does not reintroduce such a depletion region because of the synthesis at low temperatures.

To study the effect of the three different doping profiles of Fig. 3(a) on the recombination current density, the profiles served as input for 2-D Atlas simulations [12]. In Fig. 3(b) the simulated J_0 value of each profile is shown as a function of the surface recombination velocity (SRV). Removal of the boron-depleted region in profiles 2 and 3 yields a reduction in J_0, both for well-passivated surfaces with low SRVs and for surfaces without passivation, such as the contacted regions, having high SRVs. A recent study by Black et

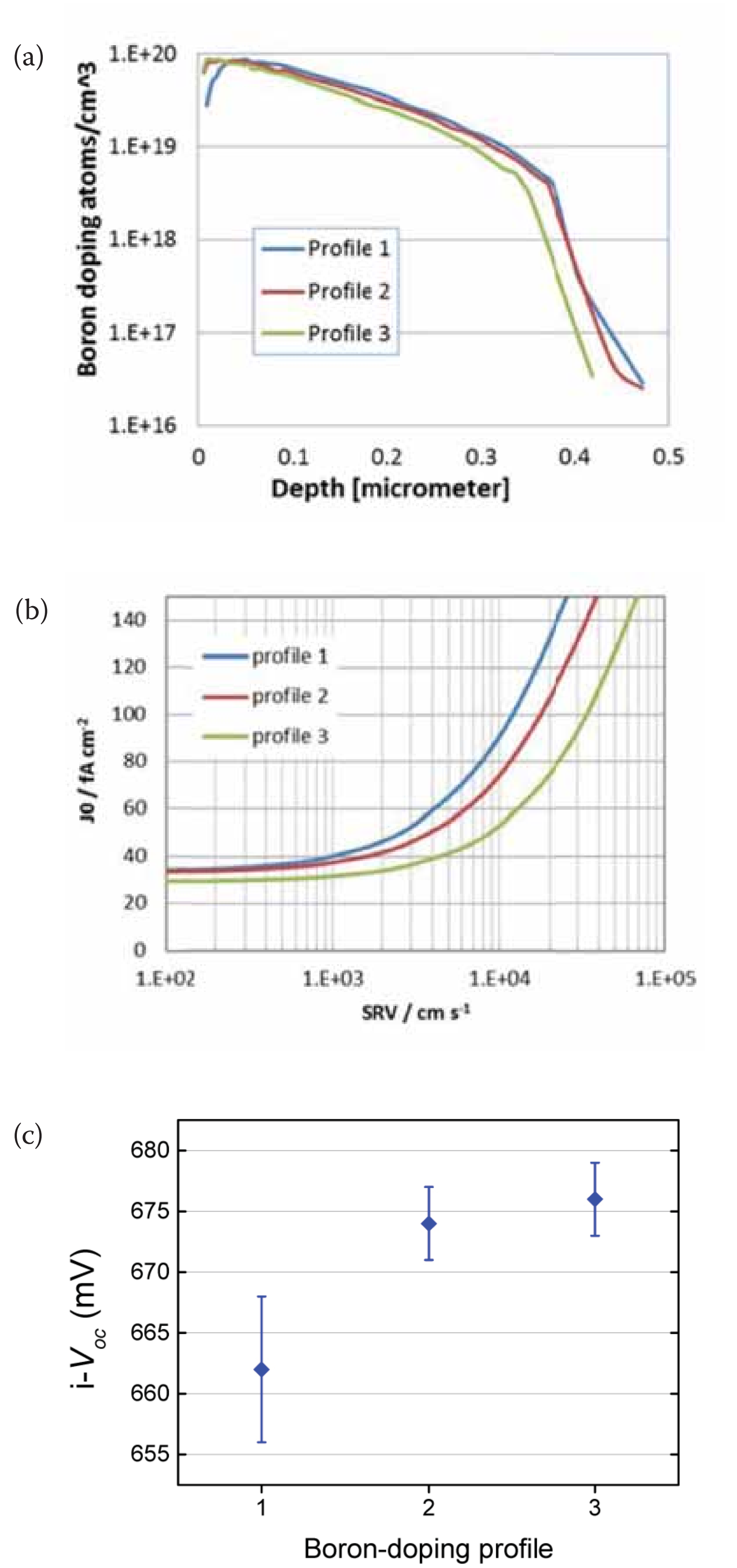


Figure 3. (a) ECV profiles of a standard boron-doped surface (profile 1) and after etching (profiles 2 and 3); (b) J_0 as a function of the SRV of the boron-doped surfaces, from Atlas simulations; (c) implied open-circuit voltage of symmetrically diffused $p^+/n/p^+$ samples passivated by NAOS/SiN_x, measured by QSS-PC.

al. [13] showed that the interface defect density (D_{it}) is independent of the boron-dopant concentration at the Si surface of the $Si/SiO_2/Al_2O_3$ interface. The benefits of etching the boron-depleted region can therefore be fully explained by the decreased minority-carrier (i.e. electron) concentration at the surface, which results in a lower surface recombination and hence in a lower J_0.

To experimentally determine J_0 of the different diffusion profiles, symmetrically diffused and textured $p^+/n/p^+$ samples were fabricated with the diffusion profiles in Fig. 3(a). The samples were passivated by the conventional n-Pasha front-passivation scheme: nitric acid oxidation (NAOS) [14] plus 70nm hydrogenated amorphous silicon nitride (a-SiN_x:H, or in short, SiN_x), deposited by (remote) plasma-enhanced chemical vapour deposition (PECVD). This SiN_x layer also serves as an anti-reflection coating. The results from quasi-steady-state photoconductance (QSS-PC) measurements are shown in Fig. 3(c). Etching back the diffusion profile 1 to profile 2 leads to an improvement of ~12mV in the implied open-circuit voltage i-V_{oc}, corresponding to a significant reduction in J_0 of 50fA/cm² per side. The additional i-V_{oc} gain obtained by extending the etch, however, is quite small (profile 3). Moreover, profile 3 results in a higher sheet resistance than for the other two profiles: 85Ω/sq. vs. 60Ω/sq. for profiles 1 and 2. The higher sheet resistance reduces the lateral conduction of holes and may affect the fill factor of the cells. For diffusion profile 2, however, there is no significant increase in sheet resistance.

> "Etching back the p⁺ region is both a simple and an effective approach for optimizing diffusion profiles."

The benefit of using doping profile 2 is also confirmed at the cell level. The V_{oc} of the cells increases by 6mV, resulting in an efficiency gain of ~0.2% abs. (Table 1). Therefore, etching back the p^+ region is both a simple and an effective approach for optimizing diffusion profiles. The next step is to improve the passivation of the p^+ surface.

Surface passivation of n-Pasha cells

For a long time, no satisfactory solution existed for the passivation of boron-doped p^+ surfaces. It is known that passivation by thermally grown silicon dioxide, although initially providing reasonable levels of passivation, is subject to significant light-induced degradation [15]. Moreover, the passivation of boron-doped surfaces by SiN_x, which is the commonly used material for the passivation of n^+ surfaces, generally results in low passivation, or even none at all [14]. The poor passivation performance on a p^+ surface can be explained by its large positive fixed charge density ($Q_f > 2 \cdot 10^{12} cm^{-2}$), which increases the minority-carrier (i.e. electron) density near the surface.

In 2008 ECN reported the significant improvements in the passivation of p^+ doped Si by adding a chemical oxide below the SiN_x; the oxide is grown at room temperature by a nitric acid oxidation of silicon (NAOS) [14]. This breakthrough in the passivation of boron-doped surfaces enabled the industrial development of low-cost n-type Si solar cells. Around the same time, however, a superior passivation of p^+ surfaces was discovered: Al_2O_3 prepared by atomic layer deposition (ALD) [16]. The excellent level of passivation could be attributed to a

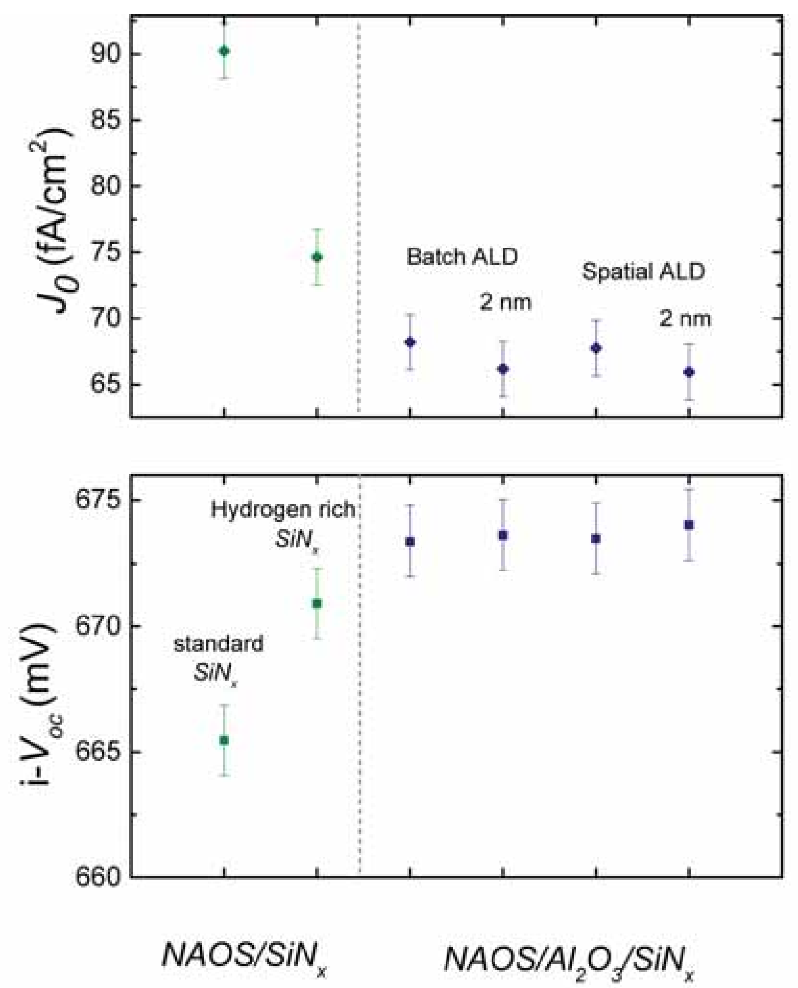


Figure 4. Recombination current density (a) and implied open-circuit voltage (b), as measured by quasi-steady-state photoconductance measurements of symmetrically boron-diffused p+/n/p+ samples with random-pyramid texture (Rs = 60Ω/sq.), passivated by different passivation schemes.

		I_{sc} [A]	J_{sc} [mA/cm²]	V_{oc} [V]	*FF*	η [%]
Boron profile 1 (standard)	avg	9.31	39.0	0.647	0.784	19.7
Boron profile 2 (etched back)	avg	9.35	39.1	0.653	0.779	19.9

Table 1. *I-V* results for cells with the boron-doping profiles 1 and 2, passivated by NAOS/SiN_x.

Cell Processing

very low interface defect density and a high *negative* fixed charge density ($Q_f \approx -5 \cdot 10^{12} cm^{-2}$) [17]. However, reactors with significant throughput were not available at the time. Since the discovery of passivation by Al_2O_3, industry has put a lot of effort into high-volume manufacturing by ALD, resulting in the development of, for example, spatial and batch ALD reactors for Al_2O_3. Although Al_2O_3 can also be deposited by PECVD, the requirement of very thin (~1–3nm) Al_2O_3 films for p^+ passivation of cells makes ALD the ideal candidate. A comparison between ALD Al_2O_3 passivation and the conventional passivation scheme of the p^+ surface of n-Pasha is therefore highly relevant.

Several industrial passivation schemes for symmetrically diffused and textured $p^+/n/p^+$ samples were compared with the conventional boron profile of n-Pasha (profile 1 of Fig. 3(a)). First, the standard surface passivation of n-Pasha cells (NAOS/SiN_x) was directly compared with the passivation by Al_2O_3 films on NAOS. The Al_2O_3 films were deposited in a batch ALD reactor from ASM or by spatial ALD in a Levitech reactor, and capped by 70nm PECVD SiN_x. Generally, Al_2O_3 passivation is enhanced by annealing the films around the optimum temperature of 400°C. In this case, however, the passivation was activated by the thermal budget of the PECVD SiN_x deposition process and a subsequent firing step (~800°C). The results are summarized in Fig. 4. The passivation schemes comprising 2nm Al_2O_3 yield a significant reduction in J_0, from 90fA/cm² to 66fA/cm², as compared to conventional passivation; this can be attributed to the very low interface defect density and the high negative fixed charge density associated with the Al_2O_3 films. The Al_2O_3 films prepared by the two ALD deposition systems performed similarly, indicating the robustness of the ALD process.

"The passivation schemes comprising 2nm Al_2O_3 yield a significant reduction in J_0, as compared to conventional passivation."

Second, it was found that the conventional p^+ surface passivation by NAOS/SiN_x can also be improved. A reduction in J_0 from 90fA/cm² to 75fA/cm² was achieved by tuning the a-SiN_x:H towards a more hydrogen-rich composition. This improvement can be attributed to an increased level of chemical passivation induced by the additional hydrogenation of the Si/SiO_2 interface [18]. More details concerning the specific experiments on p^+ surface passivation can be found in the literature [19], in which the passivation of the n^+ surface is also addressed.

Interestingly, the high level of passivation of the p^+ surface by Al_2O_3 can be further enhanced by improving the surface pretreatment, which conventionally consists of a diluted hydrofluoric (HF-) dip. Fig. 5 shows the effect on the i-V_{oc} of using a novel chemical pretreatment on a $p^+/n/n^+$ lifetime sample with boron-doping profile 1, passivated by NAOS/SiN_x. The gain in i-V_{oc} is even higher when the new pretreatment is combined with Al_2O_3 passivation of the p^+ surface (i.e. NAOS/Al_2O_3/SiN_x), yielding i-V_{oc} values of 676mV. Table 2 shows the *I-V* results for cells having the new chemical pretreatment but using the standard passivation scheme. Improvements solely to the chemical pretreatment led to a gain in conversion efficiency of 0.3% abs., which is the result of a higher V_{oc}. It is expected that this efficiency will be increased even further by implementing Al_2O_3 surface passivation.

Conclusions and outlook

The efficiency of n-Pasha solar cells is limited by the charge carrier recombination within the boron-doped p^+ region and at its surface. In this paper several industrially feasible approaches have been identified for reducing the recombination at the front side. First, the boron-depletion region can be reduced by etching the boron-doped surface; in combination with NAOS/SiN_x passivation, this results in a lower recombination current density and higher cell efficiencies. Second, the passivation of a standard p^+ diffusion profile can be improved by using 2nm Al_2O_3 deposited by batch or spatial ALD. Finally, a novel chemical pretreatment, in combination with

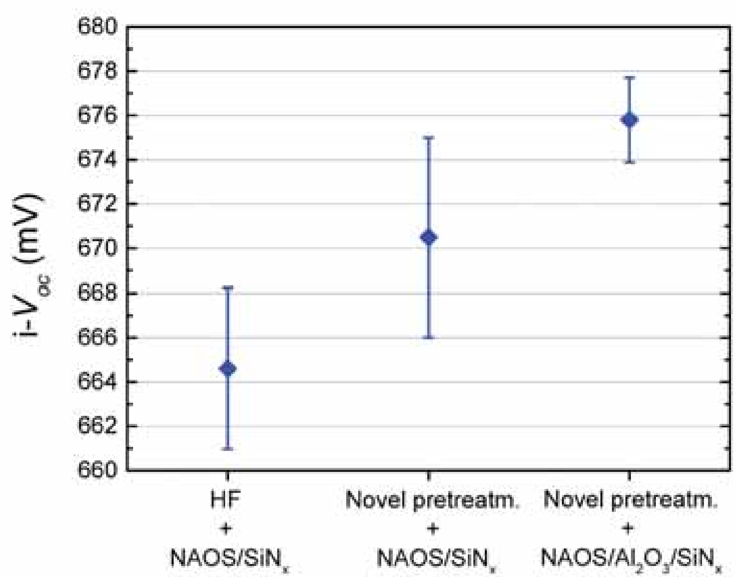


Figure 5. Implied open-circuit voltage for textured $p^+/n/n^+$ samples having different surface pretreatments and different p^+ surface passivation, with NAOS/SiN_x passivation of the n^+ surface.

		I_{sc} [A]	J_{sc} [mA/cm²]	V_{oc} [V]	*FF*	η [%]
Standard HF dip	avg	9.31	39.0	0.649	0.785	19.8
Improved oxide pretreatment	avg	9.30	38.9	0.655	0.788	20.1

Table 2. *I-V* results for improved oxide pretreatment on the p^+ surface vs. the standard HF dip in combination with symmetrical NAOS/SiN_x passivation.

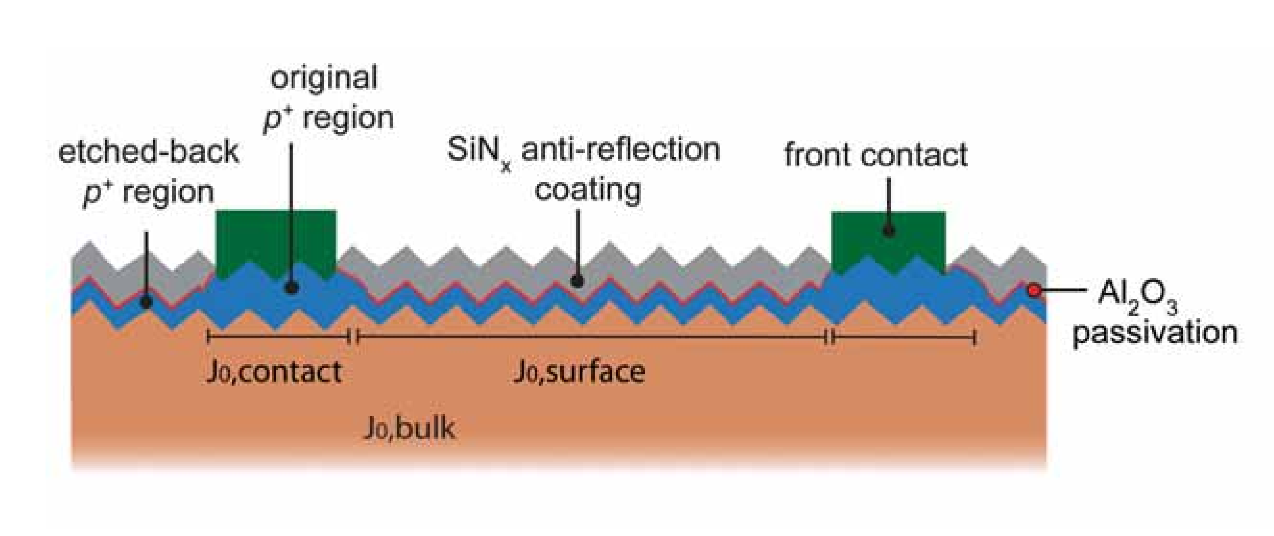


Figure 6. Schematic cross section of a potential new design of the front side of an n-Pasha cell, comprising Al_2O_3 surface passivation and selective p^+ regions which are highly doped under the metallic contacts.

standard passivation by NAOS/SiN_x, also demonstrates improvements in n-Pasha efficiency of 0.3%. Photoconductivity measurements indicate that further improvements in efficiency may be gained by combining the novel pretreatment with Al_2O_3 passivation.

> "Further improvements in efficiency may be gained by combining the novel pretreatment with Al_2O_3 passivation."

The results presented in this paper will be implemented in n-Pasha cells in the next few months. These modifications pave the way for realizing conversion efficiencies of 21% on high-quality Cz wafers.

As a next step to reducing J_0 of the front surface, an implementation of selective doping under the contacts

is being considered for n-Pasha cells (Fig. 6). This area selectivity allows a separate optimization of $J_{0,\text{contact}}$ and the contact resistance on the one hand, and of $J_{0,\text{surface}}$ and the lateral conduction of holes on the other. This helps to reduce the metal contact recombination associated with the p^+ diffusion, which is an important loss factor for n-type Si cells.

Acknowledgements

Dr. H. Knoops and D. Saynova are gratefully acknowledged for their contributions to this work, which was part of the Dutch top consortia for knowledge and innovation (TKI) DutchNess programme, 'Dutch technology for high-efficiency n-type solar cells.'

References

[1] Burgers, A.R. et al. 2010, "19% efficient n-type Si solar cells made in pilot production", *Proc. 25th EU PVSEC*, Valencia, Spain, pp. 1106–1109.

[2] PR Newswire 2013, "n-PASHA alliance awarded 100 MW n-type technology and equipment order for Nexolon Turnkey Project in USA" [http://www.prnewswire.com].

[3] Van Aken, B. & Carr, A.J. 2014, "Relation between indoor flash testing and outdoor performance of bifacial modules", *Proc. 29th EU PVSEC*, Amsterdam, The Netherlands [forthcoming].

[4] Romijn, I. 2014, presentation at SNEC 8th Int. PV Power Gen. Conf., Shanghai, China.

[5] Romijn, I. et al. 2012, "Industrial n-type solar cells : Towards 20% efficiency", *Photovoltaics International*, 15th edn, pp. 81–90.

[6] Romijn, I. et al. 2013, "Cost effective n-Pasha solar cells with efficiency above 20%", *Photovoltaics International*, 20th edn, pp. 33–40.

[7] Janssen, G.J.M. et al. 2013, "Power loss analysis of n-Pasha cells validated by 2D simulations", *Proc. 28th EU PVSEC*, Paris, France.

[8] Macdonald, D. & Geerligs, L.J. 2004, "Recombination activity of interstitial iron and other transition metal point defects in p- and n-type crystalline silicon", *Appl. Phys. Lett.*, Vol. 85, No. 18, p. 4061.

[9] Cuevas, A. et al. 2013, "Misconceptions and misnomers in solar cells", *IEEE J. Photovolt.*, Vol. 3, No. 2, pp. 916–923.

[10] Feldmann, F. et al. 2014, "Passivated rear contacts for high-efficiency n-type Si solar cells providing high interface passivation quality and excellent transport characteristics", *Solar Energy Mater. & Solar Cells*, Vol. 120, pp. 270–274.

[11] Vlooswijk, A.H.G., Venema, P. & Komatsu, Y. 2010, "Boron processing in solar cell industry: Boron diffusion in silicon wafers", in *Boron: Compounds, Production and Application*, Perkins, G.L., Ed. Hauppauge, New York: Nova Science Publishers, pp. 543–549.

[12] Silvaco 2014, Atlas Device Simulation Framework [http://www.silvaco.co.uk/products/tcad/device_simulation/atlas/atlas.html].

[13] Black, L.E. et al. 2014, "Effect of boron concentration on recombination at the p-Si–Al_2O_3 interface", *J. Appl. Phys.*, Vol. 115, No. 9, p. 093707.

[14] Mihailetchi, V.D., Komatsu, Y. & Geerligs, L.J. 2008, "Nitric acid pretreatment for the passivation of boron emitters for n-type base silicon solar cells", *Appl. Phys. Lett.*, Vol. 92, No. 6, p. 063510.

[15] Thomson, A.F. & McIntosh, K.R. 2009, "Degradation of oxide-passivated boron-diffused silicon", *Appl. Phys. Lett.*, Vol. 95, No. 5, p. 052101.

[16] Hoex, B. et al. 2007, "Excellent passivation of highly doped p-type Si surfaces by the negative-charge-dielectric Al_2O_3", *Appl. Phys. Lett.*, Vol. 91, No. 11, p. 112107.

[17] Dingemans, G. & Kessels, W.M.M. 2012, "Status and prospects of Al_2O_3-based surface passivation schemes for silicon solar cells", *J. Vac. Sci. Technol. A: Vac., Surf., Films*, Vol. 30, No. 4, p. 040802.

[18] Dingemans, G. et al. 2011, "Effective passivation of Si surfaces by plasma deposited SiO_x/a-SiN_x:H stacks", *Appl. Phys. Lett.*, Vol. 98, No. 22, p. 222102.

[19] Saynova, D.S. et al. 2013, "Dielectric passivation schemes for high efficiency n-type c-Si solar cells", *Proc. 28th EU PVSEC*, Paris, France, pp. 1188–1193.

About the Authors

Bas van de Loo is currently working towards a Ph.D. in the plasma and materials processing group at Eindhoven University of Technology. His research focuses on the surface passivation of crystalline silicon solar cells by atomic layer deposition.

Gijs Dingemans works at ASM on process development for solar and semiconductor applications. He received his Ph.D. in 2011 from Eindhoven University of Technology. Gijs has authored and co-authored more than 35 publications in the field of thin-film deposition, surface passivation and solar cells.

Ernst Granneman is one of the founders of Levitech BV, which specializes in developing ALD Al_2O_3 processes and systems for the passivation of c-Si solar cells. Prior to joining Levitech in 2009, Ernst worked for ASM International in various capacities. He carried out his Ph.D. research at the FOM Institute for Atomic & Molecular Physics in Amsterdam.

Ingrid Romijn joined ECN Solar Energy in 2004, where she started working as a researcher and later on (2006) as a project leader in the crystalline silicon group. Research topics included passivating layers, optimization of SiN_x deposition systems and (advanced) p-type solar cell concepts. During 2011 the focus of her work shifted towards the development and industrialization of n-type cell concepts. In 2012 Ingrid became the topic coordinator for industrial n-type cells and modules at ECN Solar Energy.

Gaby Janssen joined ECN in 1986 as a researcher and project manager. She has been working on topics relating to the simulation, characterization and optimization of materials for energy conversion technologies. In 2011 she joined the solar energy department at ECN, where she is now working on the modelling and simulation of PV cells.

Erwin Kessels is a professor at Eindhoven University of Technology, leading the plasma and materials processing group in the Department of Applied Physics. The group's research focuses on the deposition of (ultra)thin films by methods such as (plasma-enhanced) chemical vapour deposition and atomic layer deposition, with the main application areas being nanoelectronics and photovoltaics. Erwin has been working on surface passivation since the early 2000s and he was one of the pioneers in the field of Al_2O_3 films for Si surface passivation.

Enquiries

Plasma & Materials Processing Group
Eindhoven University of Technology
P.O. Box 513
5600 MB Eindhoven
The Netherlands
Tel: +31 40 247 4095
Email: b.w.h.v.d.loo@tue.nl
Website: www.phys.tue.nl/pmp

All-purpose cell and module architecture for low-irradiance and concentrator applications

Tobias Fellmeth, Matthieu Ebert, Raphael Efinger, Ingrid Hädrich, Florian Clement, Ulrich Eitner & Daniel Biro,
Fraunhofer Institute for Solar Energy Systems (ISE), Freiburg, Germany

ABSTRACT

The combination of metal-wrap-through technology with a unit cell design, referred to as *AP-MWT architecture*, is proposed for the purpose of operating under low and concentrated irradiance. On the illuminated side, the negative polarity is electrically separated by using an emitter window surrounding the perimeter of each unit cell. The final functioning silicon-based device consists of an arbitrary amount of unit cells with perimeter dimensions ranging from 1cm × 2.25cm to 14cm × 13.5cm. The Czochralski-based bulk material, as well as the assembly approach, conforms with state-of-the-art industrially feasible technologies. For irradiances corresponding to 1 and 10 suns, median efficiencies of 19.8% and 20.9% and top efficiencies of 20.2% and 21.0% have been achieved. Thanks to the flexibility in size, interconnection and irradiance, a wide range of current–voltage ratios are covered, providing customized solutions beyond the conventional flat-panel market.

Introduction

The majority of silicon-based solar cells today are designed to operate under terrestrial sunlight in a flat-panel module [1]. For this reason, the IEC consortium offers a guideline for standard testing conditions (STC) [2], in which (among other testing conditions) a perpendicular irradiance of 1000W/m^2 is stipulated. Testing at different irradiances becomes a necessity when operational conditions vary from normal exposure to sunlight. This is the case for concentrator solar cells and for cells designed for operation under low irradiance conditions, for example indoor applications. The dimensionless concentration factor C defines the fraction of irradiance E, relative to the reference irradiance of E_{ref} = 1000W/m^2 at STC, at which the current–voltage characteristics (*I-V* curve) are recorded. For $C > 1$, concentration conditions apply, whereas for $C < 1$, the so-called *low-light* or *low-irradiance* conditions prevail.

Concentrator solar cells are designed to operate under enhanced irradiance ($C > 1$), typically within systems that contain an optical set-

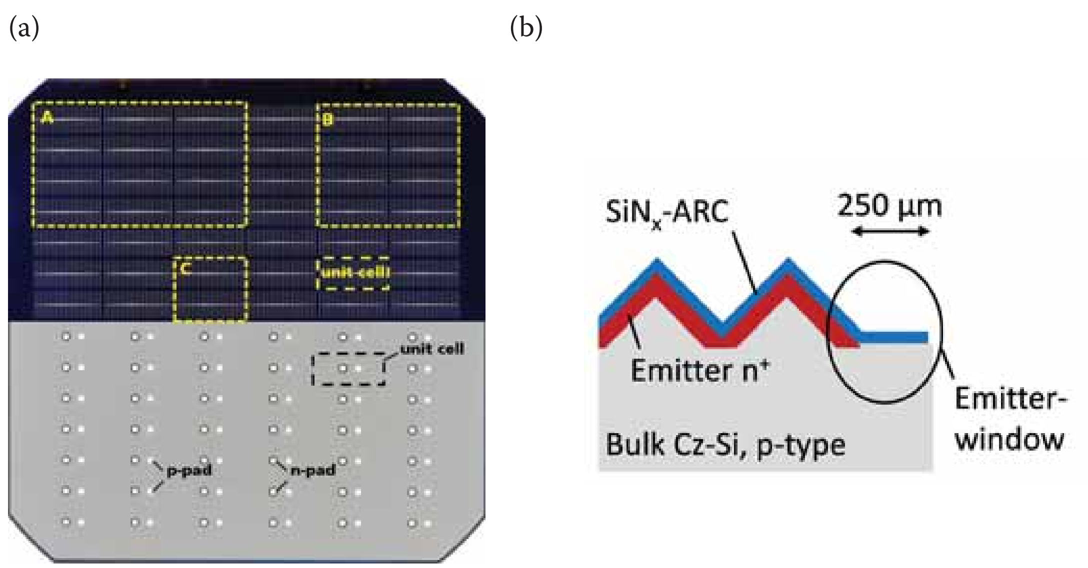


Figure 1. (a) Front (top) and rear (bottom) views of an AP-MWT wafer of the first generation, with edge lengths of 15.6cm, consisting of 84 solar cells called *unit cells*. The indicated examples A, B and C represent possible formats of a final cell, consisting of different numbers of unit cells of size 1cm × 2.25cm. In this case, the front-grid metallization is optimized for C = 10; the grid is adapted according to the respective irradiance. (b) Schematic cross section of the physical edge of an AP-MWT cell. The n$^+$ region is not extended to the edges, leaving an embedded emitter with the purpose of reducing edge recombination. Particularly for low light and small cell dimensions, the impact of edge recombination increases.

up which focuses the light onto a photovoltaically active element called the *receiver* [3]. The reduction in size of the solar cell, which is inversely proportional to the concentration factor, offers the potential for cost reductions, provided that all other system components are cost effective. Furthermore, the concentrator application allows higher cell efficiencies, mainly because of the logarithmic increase in open-circuit voltage V_{oc} [4] with concentration.

Silicon-based concentrator solar cells have been widely investigated in the past, generally using devices with the external polarities located on both sides or using back-contact back-junction (BCBJ) technology, in which the emitter and both external polarities are located on the rear side. For the former, the laser-grooved buried contact technology patented by the UNSW [5] and fabricated by BP Solar [6] represents an example that has been successfully introduced in manufacturing, which was assessed by the Euclides project [7]. The concentrator BCBJ cell was mainly investigated in the late 1970s and 1980s, resulting in the independently confirmed world-record efficiency of 27.6% [8] for a silicon solar cell. Only recently, SunPower Corporation modified their BCBJ cells to operate under an optical concentration of around 7 suns [9].

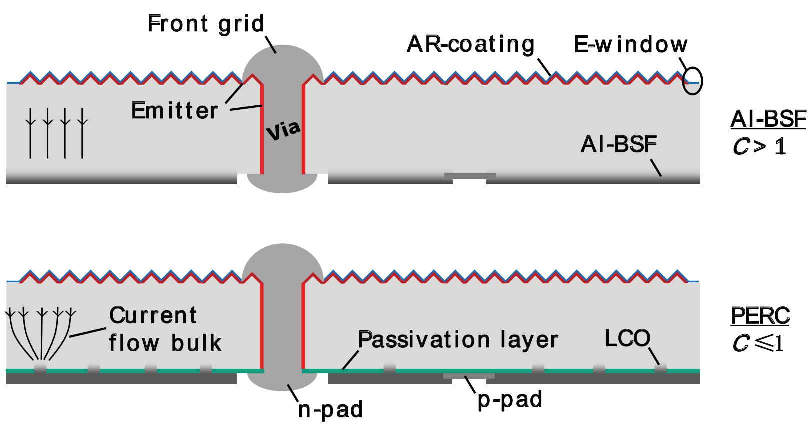


Figure 2. The AP-MWT architecture, featuring PERC technology (bottom), exhibits local contact openings (LCO), which substantially reduce the contacted fraction, leading to a low surface recombination velocity. In contrast, the full-area Al-BSF technology offers a low resistive solution, avoiding spreading resistance [12] in the bulk. For both approaches, the current flow towards the rear metal contact is indicated.

Low-irradiance conditions occur indoors and are associated with sensor technology or building-integrated solutions; these conditions can even occur outdoors in the case of mobile solutions in which the PV elements are mostly misaligned with the sun. Currently, the main solar cell supply for low-light applications comes from conventional solar cells being cut into smaller pieces, presenting the negative polarity on the illuminated side and the positive polarity on the rear.

Both concentrator and low-irradiance types of application share the need for flexible solutions in terms of their current–voltage ratios and perimeter dimensions. In the case of concentrator applications, a low current (I) device is desirable: resistive losses, which are proportional to I^2, are reduced. Low-light applications need high voltages and are often restricted to certain dimensions that are far below the standard wafer sizes of 5″ or 6″.

Fraunhofer ISE is therefore introducing a multipurpose silicon-based back-contacted solar cell architecture for use in a variety of bias light conditions. The cell front metal grid and perimeter dimensions are readily adaptable.

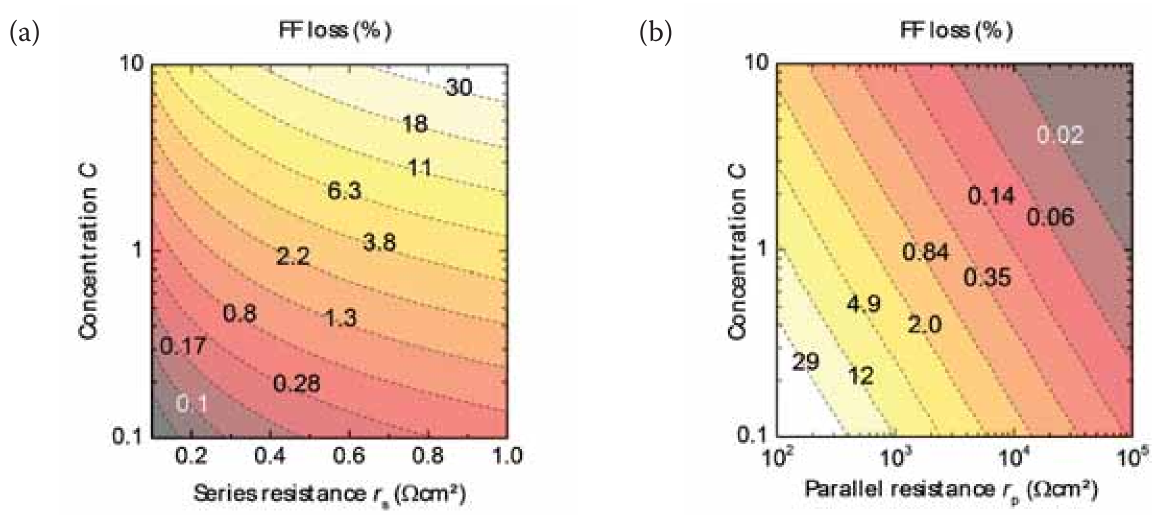


Figure 3. Regime shifts as a function of the concentration factor *C*, where *FF* losses are dominated by (a) series resistance, or (b) parallel resistance. Constant input parameters for the one-diode model: photo-generated current density at 1 sun j_{ph} = 37mA/cm²; j_{01} = 700fA/cm²; r_p = 0 in (a); r_s = 0 in (b). The impact of a second diode j_{02}, which corresponds to the behaviour similar to that of a parallel resistance reducing mainly the *FF*, is not shown.

SNEC
May 20 – 22, 2014
Shanghai, China
Booth E3-565

ASYS SOLAR

Fiducials and Pre-Inspection? No Longer Required!

DOUBLE PRINTING BY ASYS

Flexible Approaches for Double Print (DoP) Alignment
Unique: grid-structure alignment

4 GW Installed Worldwide
Leading installed base for Double Print on n-type cells

High Speed at Highest Precision and Repeatability:
3,200 cph at ±12.5 μm @ 6 Sigma
Screen monitoring in first print step (option)
Closed loop process control

ASYS PRECISION LABEL 6σ APPROVED

ASYS GmbH
Benzstraße 10, 89160 Dornstadt, Germany

www.asys-solar.com

The approach

Metal-wrap-through (MWT) [10] technology is combined with a flexible unit cell design, capable of producing an MWT device with dimensions between 1cm × 2.25cm and 14cm × 13.5cm, for operation between C = 0.1 and C = 25. This design will be referred to as *all-purpose MWT* (AP-MWT).

Fig. 1 shows the front and rear sides of an AP-MWT solar cell, illustrated on a 15.6cm semi-square monocrystalline wafer. The approach offers flexible sizes, indicated by the examples A to C, each consisting of a different number of unit cells. Each unit cell provides two solder pads for external contacting. The emitter of each unit cell is electrically separated by means of a 0.25mm-wide emitter window around the cell's perimeter, which reduces edge recombination when cut out of the wafer. As a result of the process sequence, the small perimeter area does not have any texture. On account of being MWT technology, both external polarities are located on the rear side, allowing an advanced interconnection in terms of exploiting the whole cell

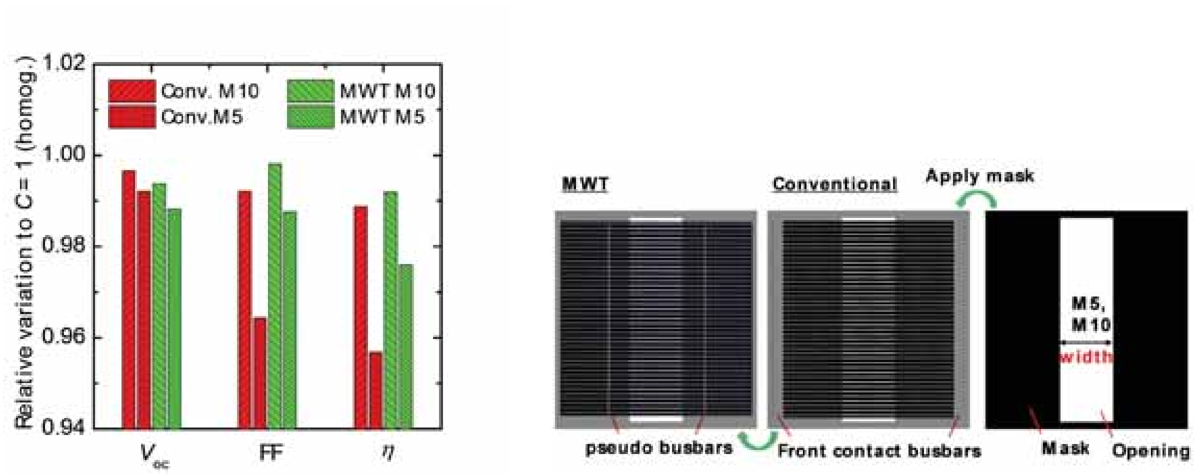


Figure 4. Sensitivity analysis as a result of applying a mask with different aperture widths of M5 = 5mm and M10 = 10mm. The unity reference represents a homogeneous irradiance of C = 1. After applying a mask, irradiance is increased until the short-circuit current corresponds to that for the homogeneous, C = 1, case.

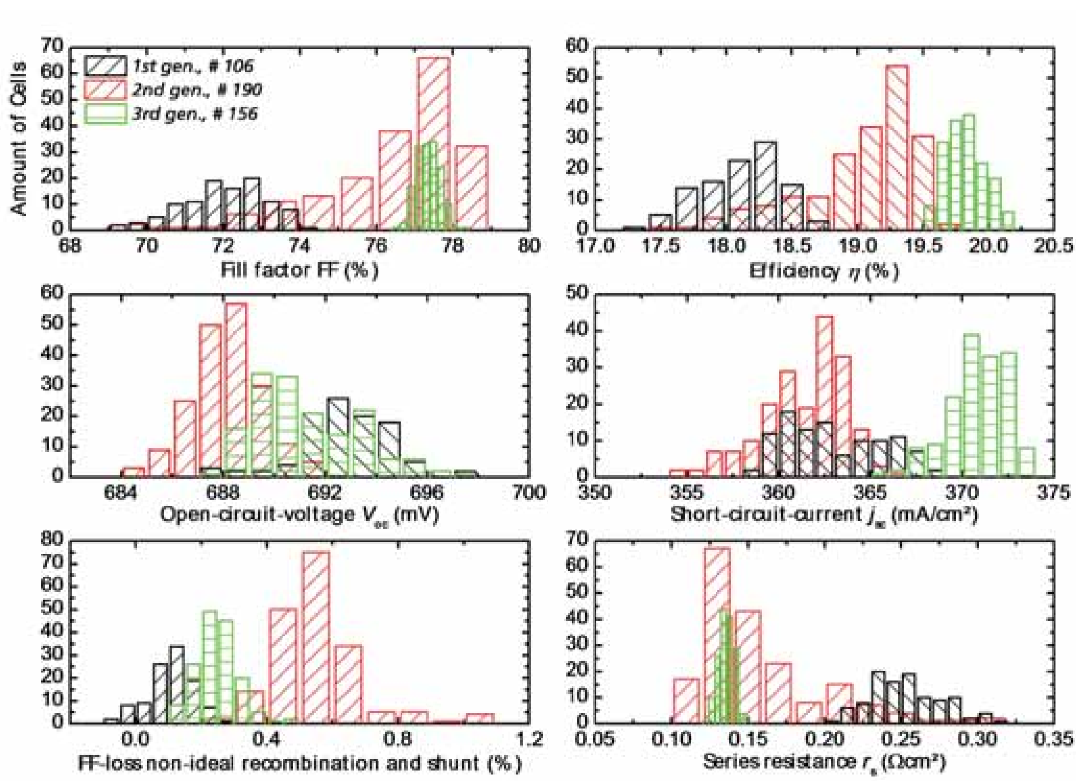


Figure 5. Evolution of *I-V* curve parameters for first, second and third generation cells. The *I-V* curves are recorded in the individualized cell state, whereas the dimensions of the first and second generations correspond to format A, and the third generation to format B (see Fig. 1). A clear trend towards higher mean and peak efficiencies is evident, but, at the same time, the variation is significantly reduced. Conditions: C = 10 (E_{in} = 10kW/m^2), T = 25°C, spectrum AM1.5g, stabilized.

manz
passion for efficiency

As one of the world's leading technology providers in the photovoltaic industry, with production and R&D facilities in Europe and Asia, Manz offers a full range of single equipment or totally integrated production lines.

Enable high efficiency cell concepts at the lowest CoO with our advanced PECVD Coating technology for front and back side passivation of crystalline solar cells, and with our fully automated Laser Ablation system for local contact opening of rear passivation layers.

Boost your PERC cell efficiency levels now with Manz high-tech equipment and achieve efficiency levels up to 20.5%.

www.manz.com

Solar Business focus
THE INDISPENSABLE GUIDE FOR PROFESSIONALS IN SOLAR

THE INDISPENSABLE GUIDE FOR PROFESSIONALS IN SOLAR

Solar Business Focus is a **bi-monthly publication** aimed at key stakeholders responsible for purchasing decisions driving solar project deployment globally. It provides essential information on all aspects of large-scale project delivery, including project design, deployment barriers, key enabling technologies, investment and finance, and more. The publication offers **in depth reports** on key and emerging solar markets worldwide as well as **expert analysis** of operating conditions within these markets.

Highlights from the past year include a special report on PV power plant technology, an investigation into post-subsidy solar and a comprehensive guide to the new movers and shakers in South Africa's burgeoning PV market.

Published in **digital and print** versions, Solar Business Focus is circulated at all the **major international trade events**, including Intersolar Europe and Solar Power International in the US.

SUBSCRIBE TODAY. IT'S FREE!* WWW.SOLARBUSINESSFOCUS.COM

* Digital edition free from www.solarbusinessfocus.com; registration required.

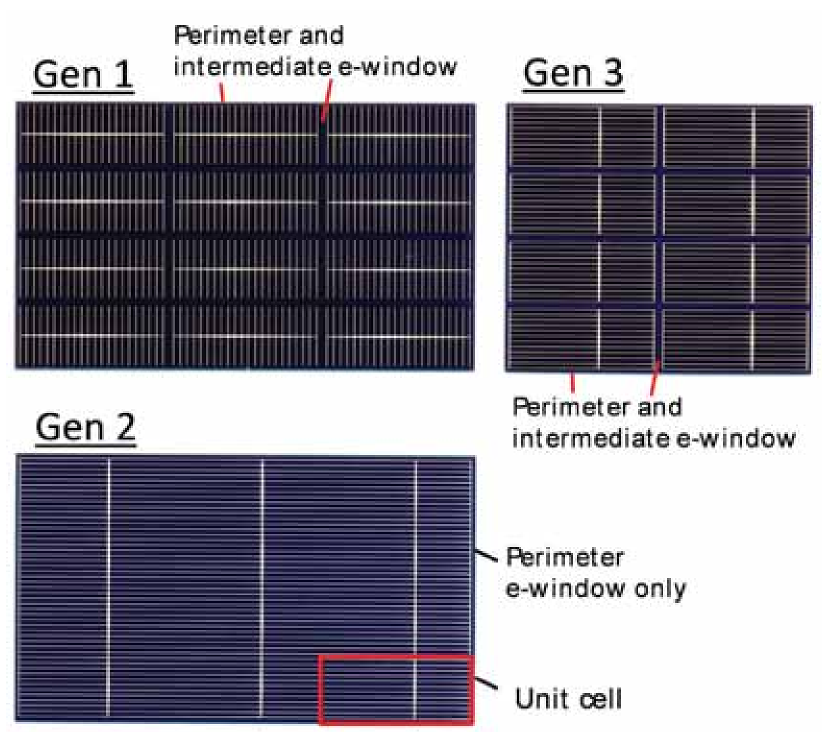


Figure 6. Individualized AP-MWT cells throughout all generations, optimized for an irradiation of 10 suns. The second generation provides perimeter emitter-windows only, allowing continuous metallization and decreased reflectance losses.

area in each direction. Prior to individualization, a solder resist (not shown) is screen printed on the entire rear side, allowing the full degree of freedom in terms of interconnection. Furthermore, no solder structures are used on the illuminated side, thus reducing any potential shading of the front side.

> "The AP-MWT architecture facilitates an efficient cell design that will withstand over two decades of irradiation."

Fig. 2 shows a schematic cross section of the AP-MWT architecture; exclusively industrially available processing technologies – for example Cz-Si p-type silicon bulk material, screen-printing and shallow emitter formation – are taken into account. The AP-MWT architecture facilitates an efficient cell design that will withstand over two decades of irradiation. For $C > 1$, the full-area alloyed aluminium back-surface field (Al-BSF) technology

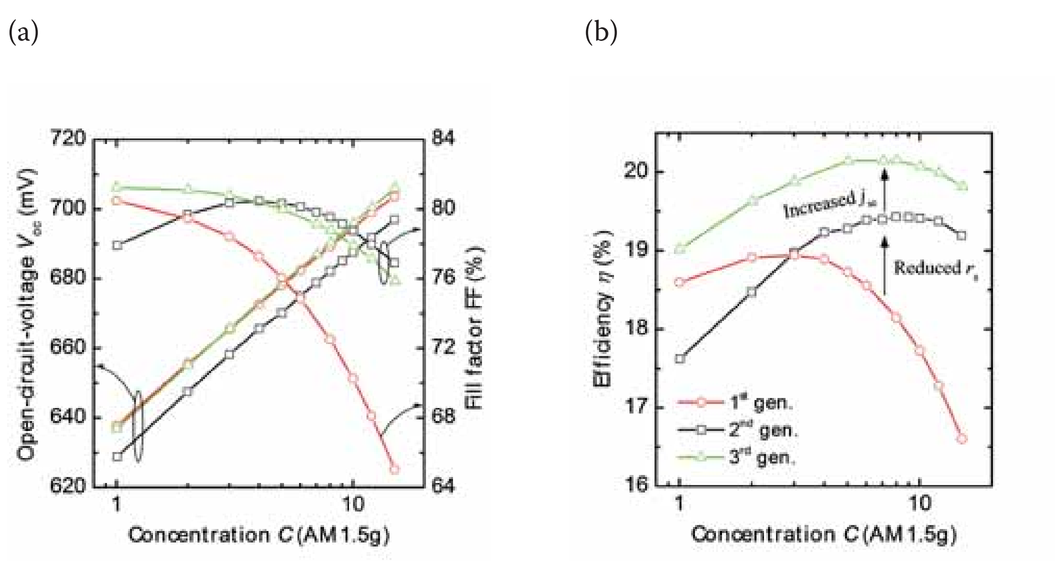


Figure 7. (a) Dependence of V_{oc} and *FF* on the concentration factor; (b) corresponding efficiencies for three selected cells from each generation. According to Equation 1, an efficiency gain can be expected until *FF* losses offset gains in V_{oc}.

	j_{sc} [mA/cm²]	V_{oc} [mV]	*FF* [%]	η [%]
Mean (10 samples)	39.5±0.1	663±0.7	79.7±0.1	20.9±0.1
Best	39.5	664	79.9	21.0

Table 1. Mean and best value at STC for the AP-MWT cell incorporating PERC technology in accord with the cross section shown in Fig. 2. The *I-V* curves have been recorded 'in-wafer' by applying a mask with an opening of 26.94cm², corresponding to the dimensions of format A (see Fig. 1).

is used, providing an efficient contact of virtually no resistance to the semiconductor. For 1 sun, and particularly for low-light conditions, resistive losses are minor; a second technological route – the passivated emitter and rear cell (PERC) approach – therefore offers the potential of higher conversion efficiencies [11].

Impact of illumination conditions on *I-V* curve parameters

The short-circuit current I_{sc} and the respective short-circuit current density j_{sc} are assumed to vary linearly ($j_{sc} = C \cdot j_{sc}^{C=1}$) [13] with the irradiance E_{in}. A possible sublinearity in the case of inversion layer formation [14] or resistance-limited short-circuit current [15] is excluded over the relevant range of concentration factors that are treated here. Therefore, the conversion efficiency η depends only on the product of the open-circuit voltage V_{oc} and the fill factor *FF*:

$$\eta = \frac{j_{sc}}{E_{in}} \cdot V_{oc} \cdot FF \propto V_{oc} \cdot FF \quad (1)$$

In Fig. 3, fill factor losses induced by series and parallel resistance in accordance with the one-diode model are demonstrated. If a series resistance of 0.7Ωcm² is considered (typical for a standard solar cell produced today), at 10 suns this would lead to a drop in *FF* of 30% abs. By contrast, a parallel resistance of 500Ωcm² would be sufficient in order to reduce shunting losses to less than 0.3% abs. This behaviour is explained by the logarithmic dependence of the shunt current and the linear dependence of the external current on the concentration factor. At 1/10 sun, the characteristics are reversed, with the parallel resistance having a dominating influence.

Why MWT solar cells?

Besides the benefits mentioned earlier associated with interconnection and packaging, the MWT approach offers advantages in the case of inhomogeneous irradiance occurring typically at the system level [3]. Fig. 4 shows the front side of an MWT solar cell and a conventional cell which have been partially shaded in order to simulate inhomogeneous irradiance. Compared with the results without masking (homogeneous irradiance), the conventional design shows a significant drop in *FF*, which is attributed to the greater distance between current-collecting busbars located at the edges of the active area. The present experiment shows the inherent drawback of the front-contacted concentrator cell of being limited to a certain extension parallel to the grid fingers. In the direction along the busbar, this effect is enhanced because of the limited width provided by the external contact (busbar) for interconnection. In the case of the MWT approach, narrow pseudo-busbars with a constant pitch transfer collected current to the external contact pads, so there is no dependence on the cell width.

Results for concentrated irradiance

Fig. 5 shows the evolution of the relevant parameters from corresponding illuminated *I-V* curves for three cell generations processed at Fraunhofer ISE. The *I-V* curves were recorded at an irradiance corresponding to C = 10; the reference spectrum corresponds to the global AM 1.5. The efficiency is based on the full illuminated area corresponding to the full cell area – including metallized, perimeter and intermediate emitter window areas – and not just on the designated areas common to concentrator solar cell *I-V* testing.

Out of the three generations, with C = 10, it was possible to achieve median efficiencies of 18.2±0.3% for the first and 19.8±0.15% for the third, with a maximum efficiency of 20.2%. The main improvement in going from the first to the second generation was achieved by rotating the grid approximately 90 degrees (first generation, see Fig. 1), which resulted in a reduction in series resistance from 0.25±0.02 to 0.14±0.04Ωcm². Furthermore, the second generation offers no intermediate emitter windows between the unit cells, thus allowing a continuous metal grid on the front side. With this design, a solution is provided if final cell size is already known.

For the third generation, paste optimizations led to a contact resistivity of 0.3±0.1mΩcm², which equates to a reduced overall variation in the output parameters. A boost in efficiency is mainly related to the use of higher resistive base material, in the range 1.2 to 1.9Ωcm, leading

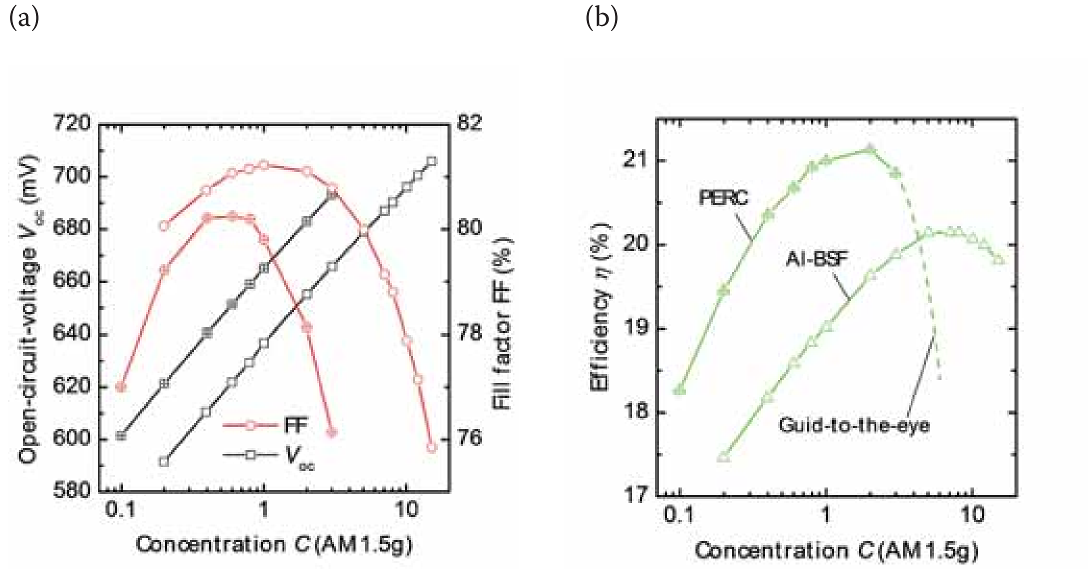


Figure 8. (a) Dependence of V_{oc} and *FF* on the concentration factor; (b) corresponding efficiencies for the AP-MWT PERC (crossed symbols) and Al-BSF (open symbols) devices.

to a significant current gain. Fig. 6 shows a photograph of the front side of the second- and third-generation AP-MWT cells.

> "With increasing concentration factor, the reduction of the series resistance associated with minor losses in j_{sc} and V_{oc} is key to maximum performance."

The concentration-dependent *I-V* parameters are shown in Fig. 7 for three representative AP-MWT solar cells from each generation. As a result of the increasing V_{oc}, the efficiency increases accordingly, until the series resistance limits the *FF*. Thus, with increasing concentration factor, the reduction of the series resistance associated with minor losses in j_{sc} and V_{oc} is key to maximum performance.

Results for STC and low-light conditions

With decreasing concentration factor, resistive losses associated with the series resistance of a solar cell decrease accordingly: therefore the PERC approach offers the superior technology in the case of STC and, in particular, low-irradiance conditions.

Table 1 shows *I-V* curve parameters recorded at STC for the AP-MWT architecture incorporating PERC technology. An average conversion efficiency of 20.9%, with a minor standard deviation of 0.1% abs., is reported. The local alloying of Al, on the one hand, provides an efficient contact to the bulk and, on the other, allows a high V_{oc} exceeding 660mV.

Results for different irradiances for AP-MWT PERC and Al-BSF devices are shown in Fig. 8. The front metal grid for the PERC device has been adapted to perform best at STC, whereas the AP-MWT Al-BSF has been optimized for 10 suns. A gap in V_{oc} between the two technologies, mainly attributed to the superior rear side of the PERC device, is observed throughout the range of concentration factors. With increasing concentration, however, the resistive losses start to dominate the *FF*, leading to the superior performance of AP-MWT Al-BSF technology.

The analysis shows the need for adaptions in terms of grid and technological optimizations when the cells are used in varying irradiance. The AP-MWT architecture provides a framework for alternative technological routes in the case of back-contact solar cells, while simultaneously offering a unified interface when it comes to receiver and module assembly.

Receiver and module technology

For reliable and efficient use in the field, the solar cells are assembled in strings and integrated into a receiver or a module. In concentrator applications the receiver protects the active solar cells from environmental influences and allows mounting on the tracking system or other type of fixture. The receiver is the interface to the cooling system, which is crucial in concentrated PV (CPV) systems for efficient operation.

The components and materials of the receiver and module have to be well matched with regard to optical, electrical, thermal and mechanical properties. Because of this requirement, the receiver development becomes a multidisciplinary key task in the entire CPV system.

General receiver description

The receiver concept for AP-MWT cells consists of a generic base profile providing mechanical stability to the cells and allowing the receiver to be easily mounted on any kind of heat sink device. The cells are enclosed in highly transparent encapsulant covered by a glass pane; they are bonded to the base profile by a thin layer of thermally conductive adhesive to enable an efficient thermal management.

Fig 9(a) shows one of the first receivers built and presented at Inter Solar 2013. Fig. 10 shows how the strings are bonded in the aluminium base profile.

The designed receiver can easily be mounted on any kind of active or passive cooling system, enabling it to operate as a PVT (photovoltaic-thermal) absorber for electrical and thermal energy cogeneration. Fig. 11 shows the cross section of a typical design.

> "The modules based on AP-MWT architecture developed at ISE exhibit a low serial-resistance loss at the interconnection level and a high packing factor as a result of minimized cell gaps."

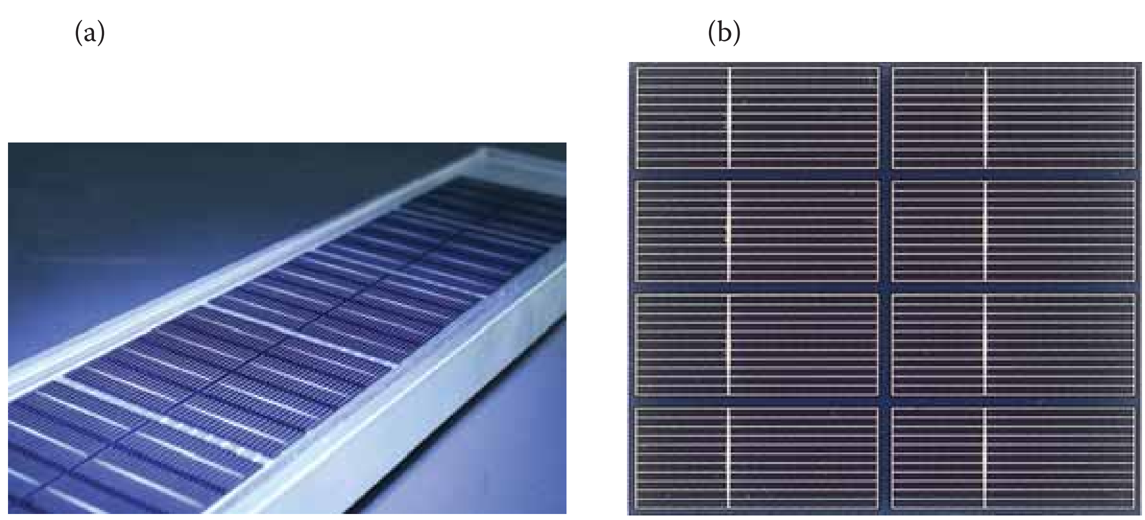


Figure 9. (a) Full string made out of 2 × 4 cells; (b) definition of the X and Y axes in the wafer.

SNEC 9th (2015) International Photovoltaic Power Generation Conference & Exhibition

SNEC 2015
PV POWER EXPO
Dialogue & Conference & Exhibition

www.snec.org.cn

180,000sqm Exhibition Space | 1,800+ Exhibitors | 5,000+ Professionals | 150,000 Visitor Attendances

May, 2015

Shanghai New International Expo Center
(2345 Longyang Road, Pudong District, Shanghai, China)

member of GLOBAL SOLAR ALLIANCE

Tel: +86-21-64276991 +86-21-33561099
Fax: +86-21-33561089 +86-21-64642653
For exhibition: info@snec.org.cn
For conference: office@snec.org.cn

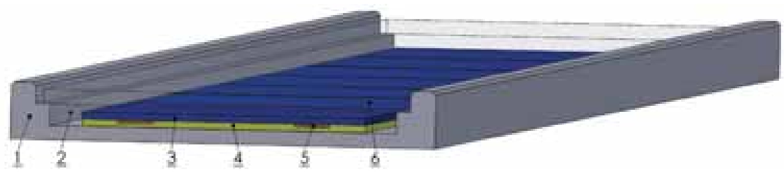
Other than the liquid PDMS (polydimethylsiloxane) silicone encapsulation necessary for CPV applications, the cell and interconnection technology is compatible with low-cost standard EVA lamination or polyurethane encapsulation for 1-sun (or below) applications. The modules based on AP-MWT architecture developed at ISE exhibit a low serial-resistance loss at the interconnection level and a high packing factor as a result of minimized cell gaps. This makes the modules suitable for a large range of applications in which various module formats and specific *I-V* characteristics are required. Because of the high efficiency potential of the MWT cell design, high packing factors and small footprints of the active cell matrix become possible, which is especially beneficial for device integration (see Fig. 12).

Interconnection technology

Solar cell efficiency is maintained at the string and receiver level by the use of an optimized interconnection technology. For AP-MWT architecture, an interconnection concept has been developed in order to suit any cell size extracted from a wafer to full strings. The base interconnector is made of ETP (electrolytic tough pitch) copper foil, which can be adapted to the cell current in order to minimize losses in a concentration range of 1 to 30. The interconnection is designed to keep the resistive power losses below 1% relative to the cell power. The interconnector design is optimized by means of electrical FEM (finite element method) simulations.

Fig. 13 shows, as a function of concentration, the simulated relative power loss for interconnectors of thicknesses 70, 100 and 120μm, for a constant power generation of 0.513W/sun at a current density of 37mA/cm^2 from 1 to 30 suns. The dashed line representing a 1% power loss shows that the 70μm interconnectors are sufficient for applications of less than 5 suns, and that the 100μm interconnectors would carry enough current for values of *C* up to approximately 14. For higher concentration ratios the thickness would need to be adapted accordingly.

Figure 10. Photograph of assisted string handling during receiver production.



1. Aluminium profile
2. Encapsulation material
3. PV string
4. Thermal adhesive
5. Copper interconnectors
6. Glass cover

Figure 11. Schematic of the layer set-up of a receiver.

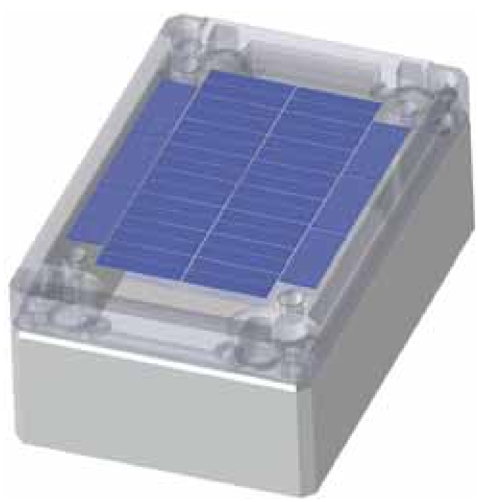


Figure 12. 3-D CAD model of an electronic case with integrated PV module for 1-sun applications.

C	I_{sc} [A]	V_{oc} [V]	P_{mpp} [W]	V_{mpp} [V]	I_{mpp} [A]	*FF* [%]	η [%]	CTM_{PMPP} [%]	CTM_{FF} [%]
1	0.97	4.44	3.50	3.8	0.92	80.8	18.1	99.66	101.1
9.7	9.40	4.87	32.9	3.78	8.7	71.9	17.6	94.6	99.2

Table 2. *I-V* measurement results for receiver at 1 sun and approximately 10 suns (CTM = cell to module).

String layout

Depending on the concentration level and the interconnector thickness (standard is 100µm), the cell length is adapted in order to minimize the resistive losses and to maximize the string efficiency. The results of the FEM calculation are fed into an electrical string model, to determine the optimal cell size for a given cell gap as a function of the concentration level, as shown in Fig. 14.

The cell width is a multiple of the unit cell width and is therefore independent of the concentration level, as each unit cell has its own interconnector path. The resulting characteristic curve allows the cell length to be chosen and the string to be designed, depending on the desired concentration level.

Performance results

Table 2 shows the *I-V* results of a prototype receiver with first-generation cells. The receiver is characterized from 1 to 20 suns using a sun simulator under non-calibrated conditions. The short-circuit current measured for 1 sun under calibrated conditions is used to determine the effective concentration at the cell level for the concentrated measurements. The *I-V* data is measured using a flash simulator with a 1ms intensity plateau. Two *I-V* curves are recorded during two consecutive flashes: the module voltage is switched from I_{sc} to V_{oc} during the first flash, and from V_{oc} to I_{sc} during the second. The comparatively short measurement time leads to the occurrence of hysteresis effects [16] between these two *I-V* curves, mainly affecting the fill factor. Because of these effects, the *FF* reported here might vary from ±1.8% to ±0.8% relative to the true value, with a tendency for this variation to decrease with increasing concentration. The results shown in Table 2 correspond to the mean values of the two recorded *I-V* curves.

The measurement results are shown in Fig. 15 for different concentrations. The calculated efficiency is related to the string area, which consists of the net cell area plus a gap of 1.2mm between the cells, corresponding to a packing factor of 97.5%.

The cell-to-module (CTM) ratio for the maximum power is 94.6% at ~10 suns and 99.66% at 1 sun (Table 2); this ratio takes into consideration all the losses caused by receiver integration, such as interconnection and encapsulation. The CTM ratio for the fill factor is 99.2% at ~10 suns and 101.1% at 1 sun; these high CTM fill-factor ratios demonstrate the high interconnection efficiency in the presented concept. The fill factor CTM ratio gain (> 100%) at 1 sun is related to the reduced current in the receiver (as a result of mismatch effects and optical losses) compared with the initial cell currents. This leads to a reduced impact of the serial resistance and to an increase in fill factor.

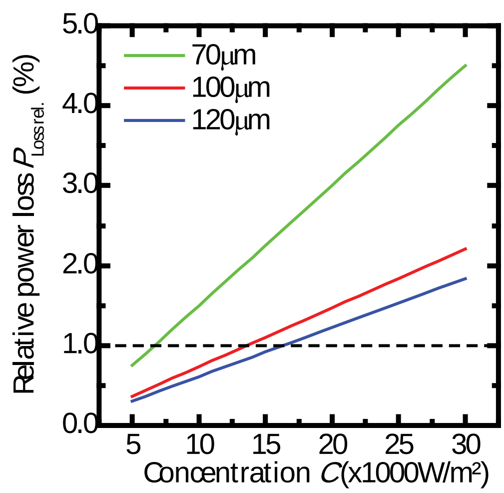


Figure 13. Calculated relative power loss for three different interconnector copper thicknesses as a function of concentration *C*.

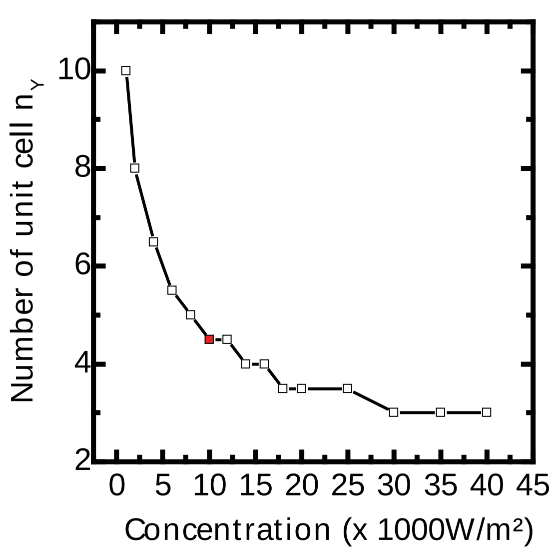


Figure 14. Theoretical optimal number of unit cells n_Y in the Y direction (see Fig. 9(b)), in relation to string efficiency, as a function of concentration. The red symbol indicates the 10-sun data point.

Conclusion

This paper has presented a highly efficient and versatile cell and receiver technology that is able to serve a large variety of applications, ranging from low-light irradiance conditions to a concentration factor of 25. The all-purpose metal-wrap-through (AP-MWT) architecture combines the MWT cell concept with existing state-of-the-art technologies, such as full-area Al-BSF and PERC, in a unit cell design. Thanks to the flexible design, the perimeter dimensions of a final cell can vary between 2.25 and 189cm², which allows a wide range of current–voltage ratios, offering customized solutions besides the conventional flat-panel market.

> "For STC and low-light applications, PERC technology offers a higher potential than Al-BSF, delivering top efficiencies of 21.0% at 1 sun and 18.3% at 1/10 sun."

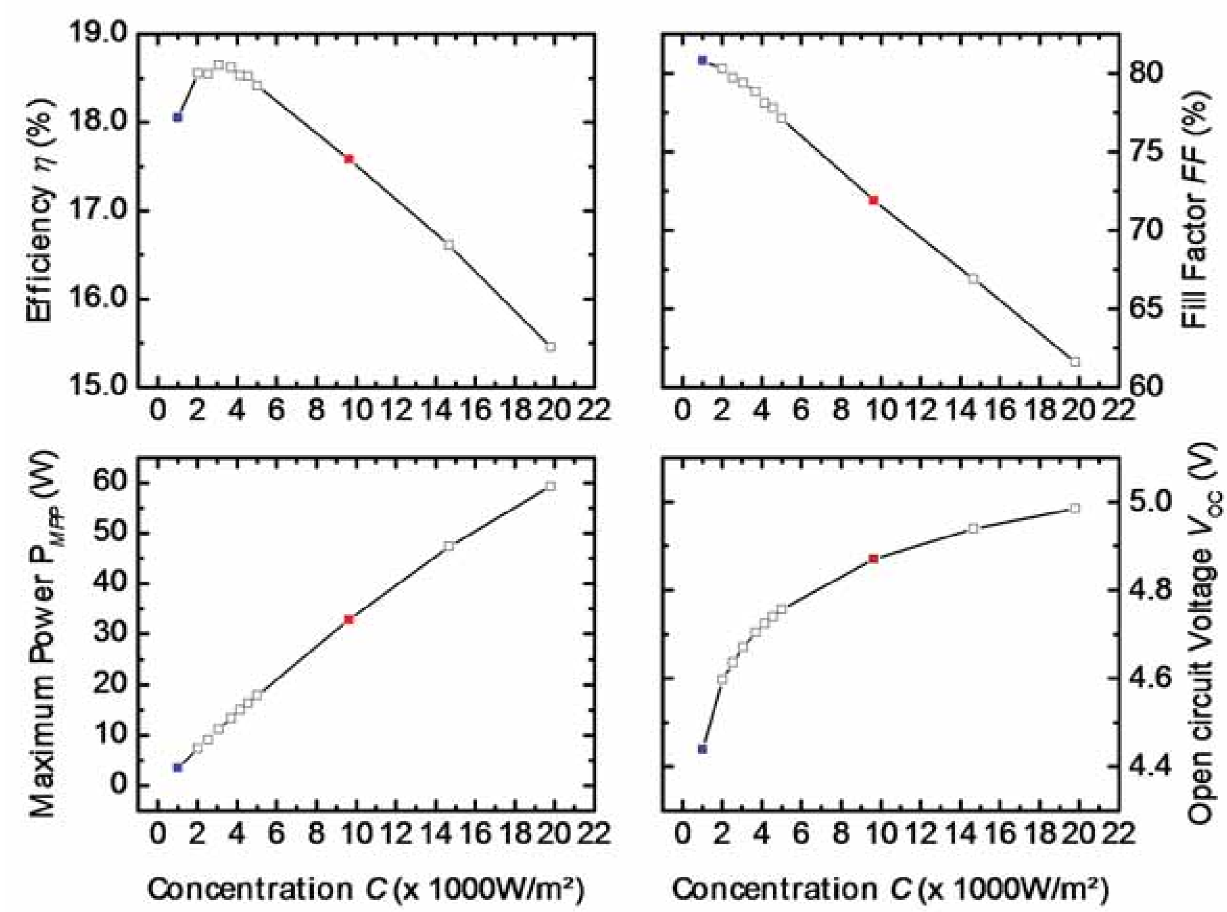


Figure 15. Non-calibrated sun simulator measurements for the receiver for *C* ranging from 1 to 20 (*C* × 1000W/m^2). (Blue symbol: 1-sun data point; red symbol: ~10-sun data point.)

The full-area Al-BSF approach allows low series resistances for use beyond concentration factors of 5 suns, resulting in a top efficiency of 20.2% at 10 suns. In contrast, for STC and low-light applications, PERC technology offers a higher potential than Al-BSF, delivering top efficiencies of 21.0% at 1 sun and 18.3% at 1/10 sun.

An interconnection and packaging technology has subsequently been developed that is able to maintain the high power of the cell at the module (1 sun) and receiver (C > 1) levels. A CTM ratio of 94.6% for the maximum power level for 10 suns is reported. This prototype receiver demonstrates that the optical and electrical components harmonize well, transferring the high cell efficiency to a respectable receiver efficiency. The next development step consists of an outdoor evaluation to characterize the thermal behaviour of the receiver.

Acknowledgements

The authors would like to thank the Photovoltaic Technology Evaluation Center team for its support, especially A. Sharaiha, T. Chipei and C. Harmel. Special thanks go to Abengoa SE – our project partner supporting the mutual concentrator activities.

References

[1] SEMI PV Group Europe 2014, "International technology roadmap for photovoltaic (ITRVP): Results 2013", 5th edn (March) [available online at http://www.itrpv.net/Reports/Downloads/].

[2] ISO/IEC 17025:2005, "General requirements for the competence of testing and calibration laboratories".

[3] Luque, A.L. & Viacheslav, A. (Eds) I. 2007, *Concentrator Photovoltaics*. Berlin: Springer.

[4] Spaderna, D.W. & Navon, D.H. 1978, "Solar-cell operation under concentrated illumination", *IEEE Trans. Electron. Dev.*, Vol. ED-25, pp. 1290–1297.

[5] Wenham, S.R. & Green, M.A. 1986, "Laser grooved solar cell", US Patent No. 4,626,613.

[6] Mason, N.B., Bruton, T.M. & Balbuena, M.A. 2002, "Laser grooved buried grid silicon solar cells from pilot line to 50 MWp manufacture in ten years", plenary paper, *Proc. PV in Europe*, Rome, Italy, pp. 227–229.

[7] Vivar, M. et al. 2010, "Laser grooved buried contact cells optimised for linear concentration systems", *Solar Energy Mater. & Solar Cells*, Vol. 94, pp. 187–193.

[8] Slade, A. & Garboushian, V. 2005, "27.6% efficient silicon concentrator solar cells for mass production", *Proc. 20th EU PVSEC*, Barcelona, Spain, pp. 1–2.

[9] Bunea, M.M. et al. 2010, "Simulation and characterization

of high efficiency back contact cells for low-concentration photovoltaics", *Proc. 35th IEEE PVSC*, Honolulu, Hawaii, USA, pp. 000823–000826.
[10] van Kerschaver, E. et al. 1998, "A novel silicon solar cell structure with both external polarity contacts on the back surface", *Proc. 2nd World Conf. PV Solar Energy Conv.*, Vienna, Austria, pp. 1479–1482.
[11] Blakers, A.W. et al. 1989, "23% efficient silicon solar cell", *Proc. 9th EU PVSEC*, Freiburg, Germany, pp. 328–329.
[12] Brooks, R.D. & Mattes, H.G. 1971, "Spreading resistance between constant potential surfaces", *Bell System Tech. J.*, Vol. 50, pp. 775–784.
[13] Reich, N.H. et al. 2009, "Crystalline silicon cell performance at low light intensities", *Solar Energy Mater. & Solar Cells*, Vol. 93, pp. 1471–1481.
[14] Saint-Cast, P. et al. 2012, "A review of PECVD aluminium oxide for surface passivation", *Proc. 27th EU PVSEC*, Frankfurt, Germany, pp. 1797–1801.
[15] Fellmeth, T. 2009, "Entwicklung einer MWT (metal wrap through) Silizium Solarzelle zur Anwendung in niederkonzentrierenden PV-Systemen", Diplomarbeit, Department of Physics, University of Konstanz, Germany.
[16] Lipps, F. 1995, "Vergleich und Modellierung von stationär und transient gemessenen I-U Kennlinien an PV-Modulen", Diplomarbeit, Department of Physics, University of Freiburg, Germany.

About the Authors

Tobias Fellmeth studied physics at the University of Konstanz, Germany, and finished his diploma thesis on concentrator MWT solar cells at Fraunhofer ISE in 2009. Tobias is currently working on silicon-based concentrator solar cells in the final year of his Ph.D. degree.

Matthieu Ebert holds a master's in renewable energy systems from HTW Berlin. In the past he has worked at Fraunhofer ISE in the modules development group and at ANU (Canberra, Australia) on LCPVT projects. Since 2012 he has been working as a scientist within the crystalline photovoltaic modules group at Fraunhofer ISE, where he focuses on new module concepts, such as lightweight module designs and the industrial feasibility of low-concentrating concepts.

Raphael Efinger studied printing technology at the University of Printing and Media in Stuttgart and graduated in 2008. From 2009 to 2011 he worked at Day4 Energy Inc. as a research scientist in the field of cell-to-module integration using the multiwire busbar approach. Since 2012 Raphael has been working as a research engineer at Fraunhofer ISE.

Ingrid Hädrich studied industrial engineering at the technical university in Freiberg, Germany. After finishing her diploma thesis on the optical and thermal evaluation of flat plate crystalline solar modules at Fraunhofer ISE, she worked for two years as a scientist in the crystalline photovoltaic modules group. Since 2010 she has been the head of the module efficiency and new concepts team at Fraunhofer ISE, focusing on alternative module concepts, such as device integrated concepts, BIPV, low concentrating receivers and lightweight modules.

Florian Clement is head of the MWT solar cells and printing technology group at Fraunhofer ISE. He received his Ph.D. in 2009 from the University of Freiburg. Florian's research focuses on the development of highly efficient pilot-line-processed MWT solar cells, as well as on the development and evaluation of printing technologies.

Ulrich Eitner studied technical mathematics at the University of Karlsruhe, Germany. From 2006 to 2011 he worked on the thermomechanics of PV modules at the Institute for Solar Energy Research Hamelin (ISFH) and obtained his Ph.D. from the University of Halle-Wittenberg. Ulrich has been managing the photovoltaic modules group at Fraunhofer ISE since 2011.

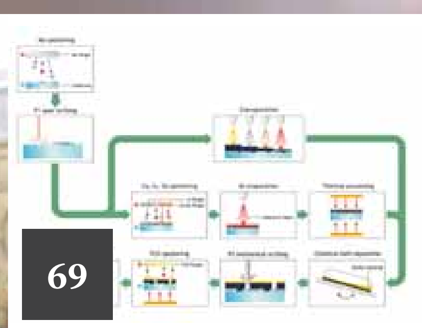
Daniel Biro studied physics at the University of Karlsruhe, Germany, and at the University of Massachusetts Amherst, USA. He received his Ph.D. in the field of silicon solar cell diffusion technologies in 2003 from the University of Freiburg. After joining the silicon cell characterization group at Fraunhofer ISE in 1995, Daniel moved to the silicon solar cell production technology group in 1999. He is currently head of the thermal, PVD and printing technology / industrial cell structures department.

Enquiries

Fraunhofer Institute for Solar Energy Systems (ISE)
Heidenhofstrasse 2
79110 Freiburg
Germany

Tel.: +49 (0) 761 4588 5596
Email: info@ise.fraunhofer.de
Website: www.ise.fraunhofer.de

Thin Film



Hanergy supplies Tesla with 'supercharging' stations in China

Thin-film manufacturer Hanergy Solar has supplied electric supercar maker Tesla with two solar charging stations for electric vehicles in China.

The carport charging stations were unveiled as Tesla marked its first delivery of cars to China at a ceremony in Beijing. Designed to shade and protect the cars as well as charging them, Hanergy will initially provide Tesla with carports in Beijing and Jiading, in Shanghai. Hanergy acquired US flexible thin-film firm Global Solar Energy (GSE) in July last year.

The Beijing carport will utilize GSE modules, and is designed for ease of transportation and assembly. Conversely the Jiading carport will be a fixed structure, utilizing CIGS high-efficiency modules manufactured by MiaSole, another thin-film start-up purchased by Hanergy.

Elon Musk, Tesla's founder, said that the company aimed to invest in and quickly expand the charger network.

He said that Tesla planned to build seven 'super charger' networks in China, initially targeting built-up cities. Utilising energy storage, Tesla claims the carports can charge cars 24 hours a day.

Source: flikr – theregeneration

Hanergy Solar has supplied Tesla with two EV charging stations in China.

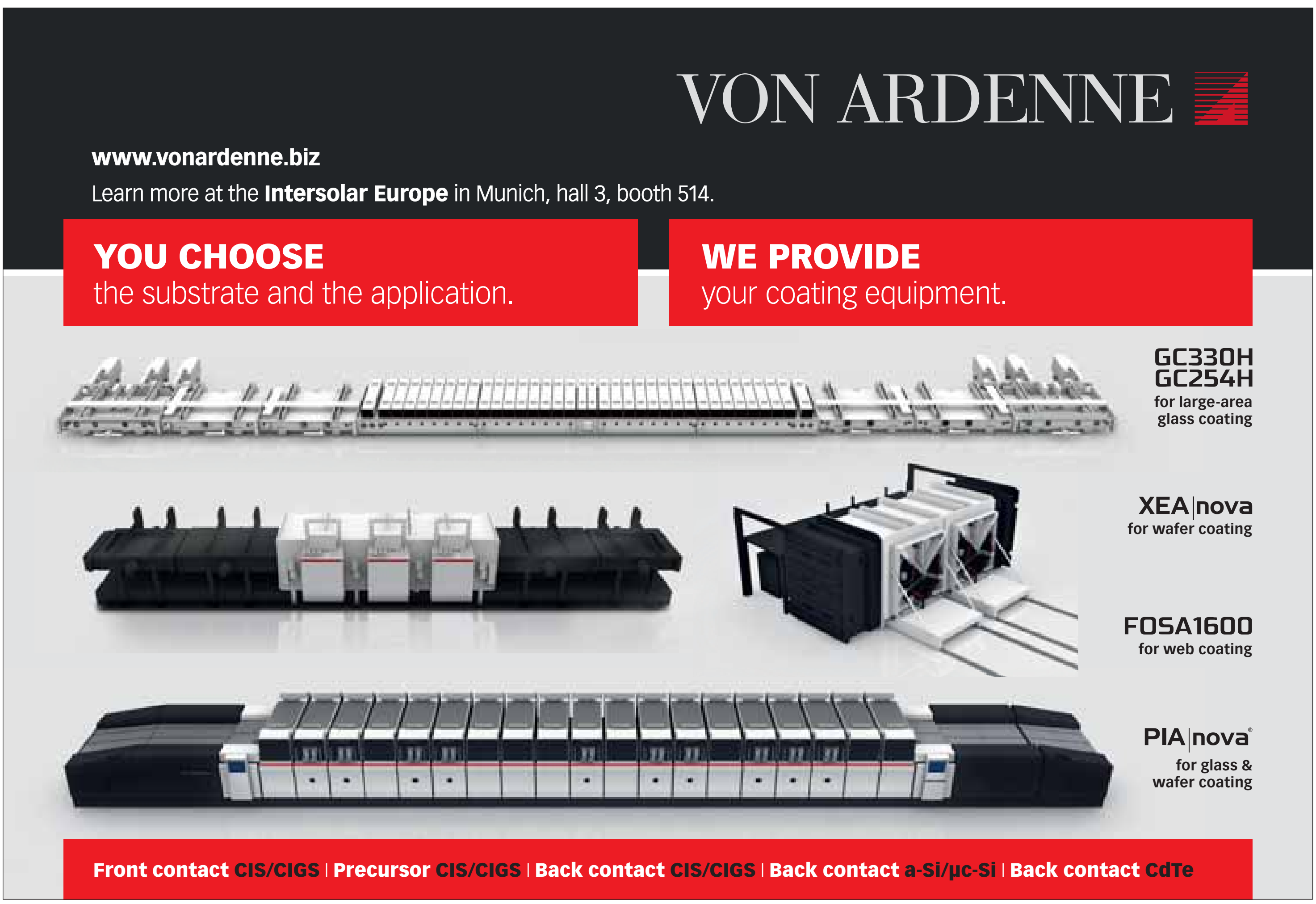
New Thin-Film Facilities

Solar Frontier looking at New York State for first offshore production plant

Major CIS thin-film producer, Solar Frontier, is considering establishing a production plant in Buffalo, New York after signing a memorandum of understanding with the State University of New York College of Nanoscale Science and Engineering (SUNY CNSE).

The company said that it would conduct a technical and economic feasibility study for both R&D possibilities with SUNY CNSE and manufacturing of CIS thin-film modules in Buffalo.

CNSE already has a Solar Energy Development Center in Halfmoon, which



Source: Oxford Photovoltaics

Oxford Photovoltaics has appointed a new CTO.

has prototyping and demonstration line capabilities for next-generation CIGS thin-film solar cells and supports CNSE's key roles in the US Photovoltaic Manufacturing Consortium (PVMC), and is part of over US$20 billion in high-tech investments since CNSE's foundation in 2004.

Solar Frontier currently operates a 900MW CIS thin-film manufacturing plant in Kunitomi, Japan.

Hanergy Solar planning 400MW PV power plant in Ghana

Hanergy Solar said it was in the early stages of developing a 400MW PV power plant in the Northern Region of Ghana at an estimated cost of approximately US$1.1 billion.

The company said that the project would be one of the largest thin-film solar power projects in the world and the first large-scale project by Hanergy Solar in Africa. The company said that Savanna Solar, in which Hanergy Solar has a 70% equity holding, had secured a 25-year power purchase agreement (PPA) with the relevant authority in Ghana in June 2013.

Hanergy Solar also noted that an investment holding company, Savanna Pride, which the thin-film firm had a 30% stake in, was also partnering on the project. The grid connection agreement as well as the transfer of land use rights from Savanna Pride were said to be pending, though such matters were expected to be completed in May 2014.

Hanergy Power Group was said to have been responsible for the investments in Savanna Solar and Savanna Pride.

New Commercial Opportunities

Oxford PV appoints CTO to push commercialization of Perovskite thin-film solar cells

Perovskite thin-film solar cells could be closer to commercialisation than expected after Oxford Photovoltaics (Oxford PV) made a critical appointment of a veteran leading-edge semiconductor manufacturing technologist as its chief technology officer, Dr. Chris Case.

Having started a distinguished career in PV thin-film technology, Dr. Case is returning to the field after a short foray running his own consultancy firm for global high-tech materials firms such as French speciality gasses company, Air Liquide.

Perovskite thin-film solar cells have received increasing attention by several start-up companies as well as a lot of attention at research institutes and universities around the world as several recent efficiency breakthroughs in lab environments show conversion efficiencies inline with current conventional c-Si solar cells but potentially a fraction of the cost.

However, taking novel materials form R&D laboratories to robust long-life high-volume manufacturing at a true low-cost is something very different. Oxford PV is developing Perovskite thin-film solar cells initially to meet the BIPV market and has already raised £7 million in equity and grant funding.

EMCORE supplying ZTJ triple-junction solar cell modules to NASA satellite

CPV solar cell producer, EMCORE will make the modules for a NASA satellite using its ZTJ triple-junction III-V solar cells.

The company was awarded the module contract by Sierra Nevada Corporation (SNC) for NASA's Cyclone Global Navigation Satellite System (CYGNSS). The CYGNSS mission is planned for launch, October 2016.

The company previously delivered solar panels to SNC for the ORBCOMM Generation 2 (OG2) satellites in 2010.

Source: First Solar

First Solar has claimed a new area module efficiency of 17%.

New Conversion Efficiencies

Hanergy's Solibro has 20.5% CIGS solar cell verified by NREL

Hanergy Solar's German-based subsidiary, Solibro has achieved a conversion efficiency of 20.5%, which have been verified by the US Department of Energy's National Renewable Energy Laboratory (NREL).

In December, 2013 Solibro had reported a CIGS solar cell had achieved a conversion efficiency of 19.6%, then verified by Fraunhofer ISE.

Hanergy Solar is preparing to build and ramp production of Solibro's technology in China as part of its drive to become a major integrated PV Energy Provider (PVEP). The plan also included technology from its US based subsidiary MiaSole.

Stion claims CIGS cell conversion efficiency of 23.2%

US-based CIGS thin-film developer, Stion, has claimed a prototype CIGS cell has achieved a 23.2% conversion efficiency using scalable commercial processes.

The company did not disclose if the module results had been independently verified. Stion said that its tandem CIGS technology development efforts were targeting the commercialisation of thin-film modules with >20% efficiency.

The company said it expected to scale the CIGS technology from a prototype module (20 cm x 20 cm) to a monolithic modules (65 cm x 165 cm) in the 20-22% efficiency range at its pilot production line in San Jose, California.

First Solar claims new 17% record CdTe module efficiency

First Solar has also revealed a new total area module efficiency record for its CdTe thin-film technology of 17%, a significant increase from 16.1%, set in April 2013. Tests were performed by the US Department of Energy's National Renewable Energy Laboratory (NREL).

First Solar also confirmed an aperture area conversion efficiency of 17.5% module, which was developed and produced by its research team at its Solar Research and Development Center in Perrysburg, Ohio, using production-scale processes and materials, according to the company.

Solar Frontier produces record 20.9% CIS thin-film solar cell

Thin-film producer, Solar Frontier has produced a CIS solar cell with a record conversion efficiency of 20.9% at the Atsugi Research Center, Japan in collaboration with the New Energy and Industrial Technology Development Organization (NEDO).

Using sputtering-selenization process, which is Solar Frontier's deposition method of choice at its volume production facilities, researchers achieved the 20.9% conversion efficiency on a 0.5cm2 CIS cell, verified by the Fraunhofer Institute ISE.

The latest record results surpass Solar Frontier's previous CIS cell record of 19.7%.

Image Solar frontier, credit Solar frontier

NREL verifies 16.6 % conversion efficiency of CIS thin-film lab module from AVANCIS

Saint-Gobain subsidiary, AVANCIS has reported a 30 x 30 cm^2 champion CIS thin-film module with a conversion efficiency of 16.6%, verified by the National Renewable Energy Laboratory (NREL).

The thin-film manufacturer claimed the verified efficiency of an encapsulated CIS module was a new record, surpassing its last externally certified efficiency record in 2011.

According to previous data from IMS Research in late 2011, AVANCIS was offering commercial CIS modules ('PowerMax') with conversion efficiencies of 12.6%, equal at the time to module efficiencies of current CIS market leader by capacity and shipments, Solar Frontier.

The company highlighted that the conversion efficiency gains were driven by the optimization of the buffer layer through enhancements to the 'InxSy' bandgap, band matching, and transmission in a short wavelength range.

Transmittance and the sheet resistance of the sputtered ZnO:Al front contact was also said to have been optimized and the dead zone between the series-connected cells was reduced by employing a picosecond laser process.

First Solar set to miss out in India PV auction

The Indian government has revealed the financial bid results for its auction for 750MW of solar energy, with US firm First Solar looking likely to miss out, according to analysts.

The auction in February was inundated with proposals for phase II, batch I of the national solar mission (JNNSM).

Overall 58 developers bid for 122 solar projects. The financial bids followed a technical qualification round.

Developers competed in the reverse-bid auction in two parts. Half the 750MW available had a mandatory domestic content requirement (DCR), and the other 375MW was left open with no domestic requirement.

The US filed a complaint to the World Trade Organization earlier this month claiming that it should have equal access to the procurement round.

First Solar has previously dominated the thin-film market via a loophole in previous JNNSM bids, now closed, which did not include thin -film modules under DCR. The company has worked with the US Export-Import Bank on a number of projects in India. Under the DCR, another 15 PPAs are to be signed for 21 projects, totalling 375MW.

Centrosolar America becomes exclusive supplier of TSMC Solar CIGS modules in US

In a strategic move ahead of possible new anti-dumping duties being imposed on c-Si PV manufacturers in China and Taiwan, CIGS thin-film producer, TSMC Solar has selected Centrosolar America as its exclusive distributor in North America.

Thin-film technologies are not part of the US ITC investigation, therefore will not be affected by any AD or countervailing duties.

Centrosolar America will be responsible for supplying TSMC Solar's modules in residential and commercial solar markets in the US, Canada, Mexico, Virgin Islands and Puerto Rico.

Organic PV firm Heliatek claims to achieved a conversion efficiency of 7.2% with an organic cell.

Organic Solar Cells

Heliatek touts organic solar cell with 7.2% efficiency with 40% light transparency

Organic thin-film producer, Heliatek, has claimed a lab-based OPV solar cell has achieved a conversion efficiency of 7.2% with 40% light transparency to meet the needs of glass manufacturers for both building integrated PV (BIPV) and automotive roof markets.

The company noted that it already held the conversion record for opaque (non-transparent) organic solar cells at 12%.

The company has therefore demonstrated the ability to adjust the balance between light and electricity generation for a wide range of novel applications, noting that the production of its transparent film was possible with the inclusion of transparent conductive layers at the front- and back-side of the solar cells.

Imec claims a fullerene-free OPV cell record conversion efficiency

Having dropped organic solar cells (OPV) that used fullerenes as the acceptor materials, imec has reported in Nature Communications that it has produced a fullerene-free OPV cell with a record conversion efficiency of 8.4% and a 156cm2 module with a conversion efficiency of 5.3%.

The research centre noted that although fullerenes are the dominant acceptor materials in current OPV cells, the small absorption overlap with the solar spectrum limits the photocurrent generation in fullerene acceptors, while the deep energy level for electron conduction limits the open-circuit voltage.

By introducing two fullerene-free materials as acceptors, open-circuit voltages increased compared to standard OPV cells with fullerene acceptors, while high short-circuit currents were achieved by developing a multilayer device structure (discrete heterojunctions) of three active semiconductor layers with complementary absorption spectra, and an efficient exciton harvesting mechanism to generate higher conversion efficiencies.

VDMA establishes working group for organic PV research

A new working group has been formed in Germany to support organic PV (OPV) firms and research institutes developing the thin-film technology.

The OE-A (Organic and Printed Electronics Association), part of German engineering body, VDMA, has started a new working group on Organic Electronics Energy (OEE).

Not limited to German firms or organisations, the OEE is attempting to offer a pan-European approach to OPV activities, including standards.

Initial participating companies include Amor Group, Belectric OPV, DisaSolar, Eight19, Heliatek and Mekoprint, while research institutions such as VTT, Holst Centre, CSEM as well as CEA are also participating in the new group.

OEE expected more international companies along the entire value chain of OPV to joining the working group over the next several months.

Source: Oerlikon

Domestic content rules have precluded thin-film firms such as First Solar from the latest PV project tendering round in India.

Competitiveness of CIGS technology in the light of recent PV developments – Part 1: The state of the art in CIGS production

Ilka Luck, PICON Solar GmbH, Berlin, Germany

ABSTRACT

For some years CIGS was seen as the great white hope of the PV industry, until c-Si revealed its true competitiveness in mass production. Most companies dedicated to the commercialization of CIGS, many of which were VC financed, did not survive this development. Nonetheless, the industry has recently seen new corporate entrants with impressive plans for the roll-out of CIGS. The motives for these strategic actions are of interest, so a cost-of-ownership calculation was performed for a state-of-the-art CIGS production: the result is that current production cost for a CIGS module is €0.44/Wp, with material and depreciation being the main cost drivers. Although significant progress has been made in the last few years, this is still higher than the production costs for standard c-Si modules. However, the costs for CIGS coating materials, which correspond to the wafer in a c-Si module, are significantly lower than those for a wafer. Could this be a motive for the actions that have been witnessed in the CIGS industry? The next task would be to evaluate the further cost-reduction potential of CIGS and the likelihood of its realization.

CIGS comeback?

PV has come a long, long way. In 1839 Becquerel detected the photoelectric effect, and Einstein explained it in 1904. In 1940 the photoelectric effect was observed in crystalline silicon (c-Si), and Bell Labs presented the first c-Si solar cell in 1945. The 1970s oil crises gave PV a certain momentum but not enough to create a sustainable market in the megawatt – let alone gigawatt – range. The efficiency of cells and modules improved only gradually, and the outward appearance of a PV module did not change significantly for several decades. It is no wonder that around the turn of the millennium a PV module based on crystalline silicon was considered to be a fully developed product with little potential for further enhancements in performance or reductions in production costs.

By this time it was becoming more and more obvious that the use of renewable energies would become mandatory for one reason or another – pollution, exhaustibility of fossil fuels and climate change. With the accepted deficiencies of c-Si in mind, developers turned their attention to thin-film PV; the materials involved are direct semiconductors having absorption coefficients a hundred times higher than c-Si, allowing absorber layers in the single-digit micrometre range, as shown in Fig. 1. Attention was focused particularly on those materials with high efficiency potential: cadmium telluride (CdTe) and $CuIn_{1-x}Ga_x(Se_{1-y}S_y)_2$ (CIGS). The production process – shown in Fig. 2 for CIGS – enables cell and module production to be intertwined, which was another feature that would offer the possibility of significantly lower production costs. Back then, two commercial ventures existed that used these materials, both having several decades' history: Solar Frontier (the offspring of Arco Solar) and First Solar (which started off as Solar Cells Inc.). Interestingly, it is these two companies that are today involved in true mass production – Solar Frontier has 1GWp production capacity at two sites in full swing and has reported a record-beating 14.6% (180Wp) with its module.

This particular focus of attention on CIGS has resulted in the founding of countless start-ups commercializing the numerous approaches of the technology, first in Europe, then, with a few years' delay, in the USA. PICON Solar estimates that up until 2012 roughly $5000m had been spent. Only a few of these start-ups still exist, which is due, on the one hand, to home-grown reasons: the commercialization took longer and required more resources, namely money, than initially expected. On the other hand, the product development was more challenging,

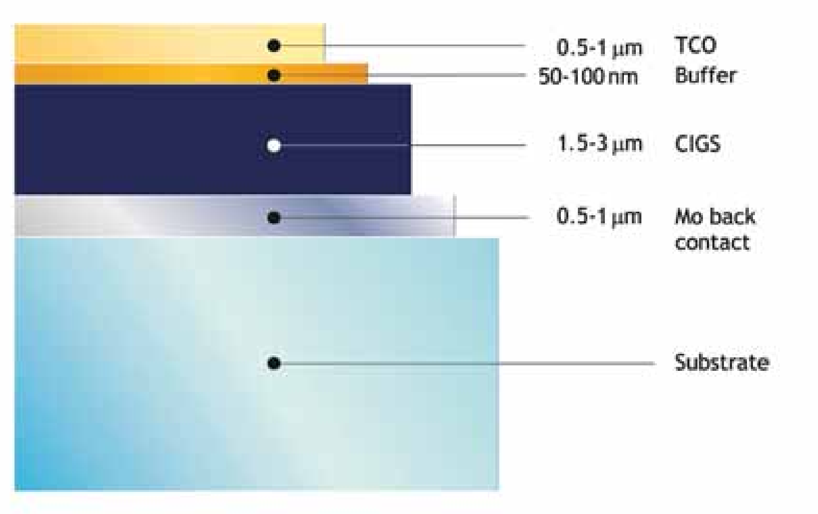


Figure 1. Schematic cross section of a CIGS thin-film device.

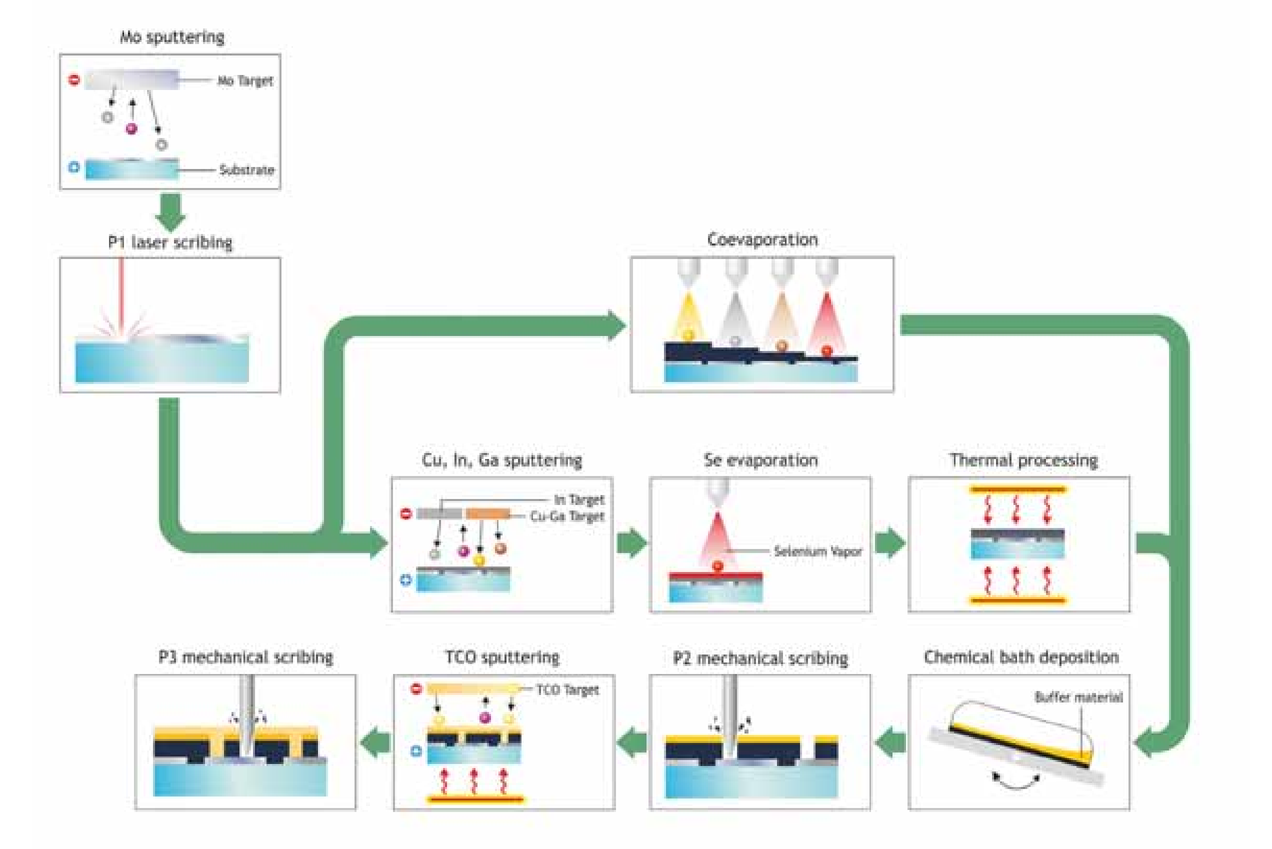


Figure 2. Production scheme for CIGS thin-film modules.

as thin-film modules turned out to be more delicate than their c-Si counterparts in terms of long-term stability. But this is what you expect from VC-financed start-ups. More crucial was the fact that they were (and still are) chasing a moving target.

After the removal of all bottlenecks in the supply chain, the prices of c-Si PV modules fell dramatically as production capacity significantly outpaced installation. Rock bottom was reached in 2012/13, when very few of the production players throughout the value chain were still profitable, which forced the various players into the systems business. As of today, average sales prices of c-Si PV modules are of the order of €ct50/Wp in Europe and slightly above $ct60/Wp in the USA. Direct production costs for PV in the range $ct50–60 for a PV module using standard solar cells (p-type silicon, anti-reflective coating, back-surface field, Al rear-side metallization, Ag front-side metallization) can be considered feasible, at least in China. Jinko published production costs of $ct50/Wp and Yingli reported $ct55/Wp last year. In 2011 the costs were still in neighbourhood of $1, which means they have decreased 50% in two years. However, it is not within the scope of this article to analyse what has led to this development. Technology road maps and PICON Solar's investigation [1] moreover reveal that there is still cost-reduction potential for standard technology.

> "In the wake of all the c-Si turmoil, new and potentially large players began to appear on the CIGS scene."

In the wake of all the c-Si turmoil, new and potentially large players began to appear on the CIGS scene. TSMC licensed the technology from Stion to further develop it on its own, recently reporting a module efficiency of 15.7% (corresponding module power 171Wp) in 2013 and a production capacity increase from 40MWp to 120MWp in 2014. Hanergy went on a shopping trip and ended up with Solibro, MiaSolé and Global Solar Energy in its trolley. The record module efficiency (at the time) of 14.7% (138Wp) had already been achieved in 2011. Hanergy announced plans to ramp up the production capacity to a cumulated 3GWp for both the Solibro technology (currently 135MWp) and the MiaSolé technology (currently 150MWp). Equipment for an annual production 600MWp was ordered at beginning of 2014.

This new configuration – with at least three CIGS players having the potential financial resources to go all the way – calls for the previous cost of ownership calculation (CoO) of Schuler, Luck & Berghold [2] to be revisited in order to check whether the current status of the technology and its future potential would justify these moves. No such activities can be identified for c-Si: large players would rather back out than boost new technology steps, as the example of Bosch and GE shows. In the remainder of this paper the CIGS CoO result will be analysed for its main cost drivers and a brief comparison made with its fellow competitor c-Si.

Basic assumptions and CoO result

For the direct cost of ownership calculation, the costs are broken down into blocks, specifically material, equipment depreciation, facility depreciation, energy, labour, maintenance and consumables. The basic assumptions for the calculation are:

- A fictitious 143Wp CIGS glass/glass module with a total area of 1.1m^2 and 13% efficiency. These values are derived from the data sheets for the CIGS modules from Solar Frontier, Solibro and TSMC. This represents today's feasibility in mass production.

- The absorber layer (1.6µm) preparation used is the coevaporation of the elements method. An average metal evaporation coefficient of 40% is assumed.

- Today's metal prices are taken from internet sources (e.g. www.metalprices.com).

- The molybdenum back contact (0.3µm), the sodium diffusion barrier and the zinc oxide front contact (1µm) are deposited by sputtering without material recycling. An average rotatable target utilization rate of 75% and an average sputter material transfer coefficient of 55% are assumed.

- The CdS buffer layer (50nm) is applied using a wet chemical deposition step.

- EVA is used for encapsulation. A tape is used for edge sealing.

- The series interconnection of the cells is realized by monolithic integration.

- The nameplate capacity is 1000MWp, which allows economy-of-scale savings in raw material procurement comparable with that of c-Si fellow competitors. From a production point of view, a reasonable production capacity might be lower; in this case, however, several such production lines should be in operation.

- The production line operates 24/7/360 with an overall yield of 95%. No production drops occur due to seasonal markets.

- The production line operates in Europe, with corresponding costs for labour, building and technical infrastructure. Overheads are not considered.

- Equipment investment and the corresponding depreciation are taken from the latest press release of Solar Frontier, in which the company states that it spends $125m on 150MWp production capacity. This is even below the equipment expenditure reported for their previous 900MWp nameplate capacity. A currency exchange rate of €/$1.35 is assumed. Depreciation period is six years. The technical infrastructure is written off entirely in this time period, while the building is written off to 50% of its initial value.

- Yearly maintenance and consumables are kept at 5% of the initial equipment invest.

- The impact of any subsidies and capital costs is not taken into account.

The CoO assumptions result in €0.44/Wp production costs for a CIGS-based thin-film PV module (Table 1). An aluminium frame would add €0.04–0.05/Wp to the calculation. The cost structure is dominated by materials, with an overwhelming 44%, and depreciation holds a significant 25% share (Fig. 3). Other large cost drivers are energy at 11% and labour, which contributes 9%.

"Compared with previous CoO calculations, CIGS production costs have fallen by €0.14/Wp."

Compared with previous CoO calculations [2], CIGS production costs have fallen by €0.14/W_p – a reduction

Cost structure	[€/Wp]	
Total material cost	0.193	44%
Equipment depreciation	0.109	25%
Facility depreciation	0.018	4%
Energy cost	0.049	11%
Maintenance cost	0.016	4%
Consumables cost	0.016	4%
Labour cost	0.039	9%
Total cost	0.440	

Table1. Absolute and relative cost contributions of various segments to CoO.

Thin Film

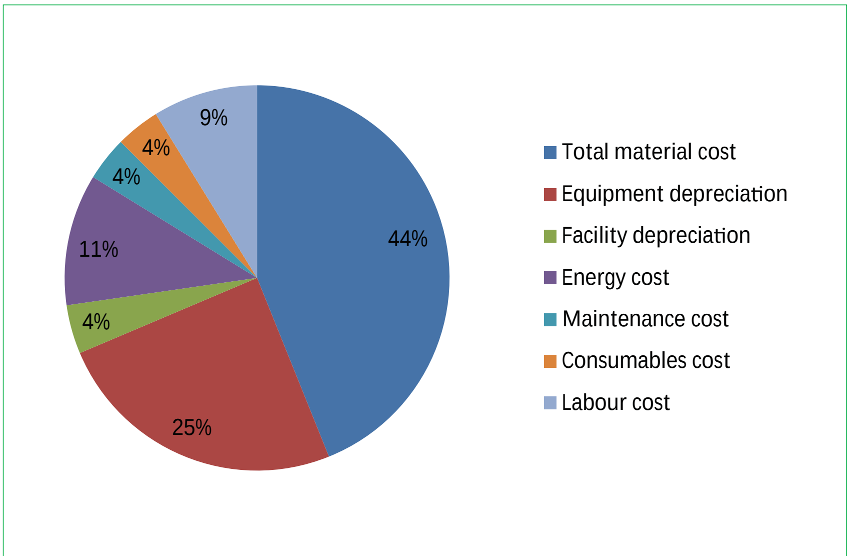


Figure 3. Relative cost contributions of various segments to CoO.

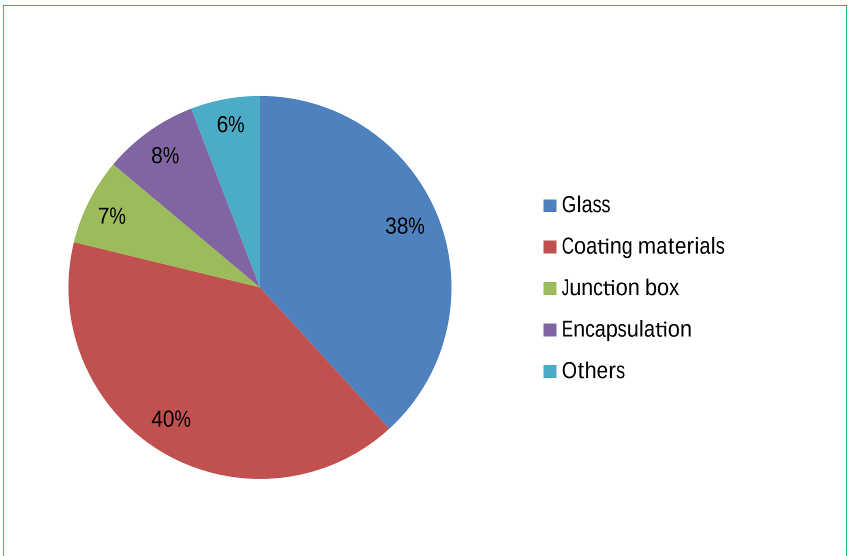


Figure 4. Relative contributions of the different material sections.

of more than 20% over the last two years. Materials have held their ground as the dominating segment in the cost structure, and equipment depreciation is still by far the second-largest position. Everything else (facility depreciation, energy, maintenance, consumables and labour) can be regarded as more or less stable. The overall decrease in production costs is attributable to two main factors:

1. An increase in module efficiency (total area) of 1%, from 12% to 13%.

2. A significant fall in equipment investment of almost 40%.

An analysis of the materials segment of the CoO reveals that the €0.19/Wp contribution is mainly made up of the glass and the coating material costs. Together these constitute almost 80% of total material cost (Fig. 4). Other noticeable shares come from the junction box and the encapsulation material.

CIGS compared with c-Si

Before continuing with sensitivity analyses of the CoO calculation, it is useful to take a quick look at the production costs of the fellow competitor c-Si. As mentioned in the introduction, these costs are around $ct50–55/Wp, which correspond to €0.37–0.41/Wp. This means that the fictitious CIGS factory would produce CIGS thin-film PV modules at either significantly or slightly higher costs. While costs have come down by 50% in c-Si module manufacturing in two years, only a 20% cost reduction has been achieved for CIGS within the same time frame. When comparing these two developments, one should keep in mind that the collapsing silicon prices have helped a lot in the case of c-Si. However, the question immediately arises as to where the difference in production costs comes from.

The impact of investment/depreciation is obvious: while €620,000 must be paid per MWp production capacity for CIGS, a c-Si cell/module fab can be constructed for anything between €90,000 and €110,000 per MWp. The impact on the cost structure is radical, to such an extent that depreciation becomes an insignificant portion of the cost structure. The high investment also imposes a very effective market-entry barrier, thus preventing CIGS module production reaching critical mass.

The lower module efficiency of 13% for CIGS, compared with at least 16% for c-Si, influences the cost structure in a similar fashion. The efficiency aspect can simply be translated into throughput: the higher the efficiency, the lower the investment for a certain production capacity. The other way to look at it is that you get more production capacity for your money. In either case, the depreciation per Wp decreases. The lower efficiency of CIGS is also a disadvantage when per item cost factors are considered; items such as junction boxes and sealing are required per module, not per Wp. The lower the module power, the higher the impact of these items on the cost structure. The third area where the low efficiency is undoubtedly disadvantageous is the balance-of-system (BOS) costs in PV systems engineering: this evaluation, however, is beyond the scope of this paper.

Depending on the particular estimates being considered, the raw material c-Si wafer, which corresponds to the coating material in the CIGS module, makes up anything between 32% [3] and 41.2% [4]. However, the coating materials in CIGS make up 40% of the materials costs, which equates to only 20% of the total costs. In absolute numbers, that translates to around €0.07/Wp, which is significantly lower than what must be paid for a wafer. With respect to the cost of the absorber (coating) material at least, CIGS technology has clearly met expectations.

"With respect to the cost of €0.07/Wp for coating material, CIGS is highly competitive and beats c-Si impressively."

Summary and outlook

The CoO calculation has demonstrated that the production of CIGS thin-film PV modules is currently more costly than the production of c-Si modules – even under best-case assumptions, such as a very high overall production yield. Production costs for CIGS are at €0.44/Wp, with materials and equipment depreciation being the main cost drivers (70% of the total costs). However, with respect to the cost of €0.07/Wp for coating material, CIGS is highly competitive and beats c-Si impressively.

To evaluate what needs to be done in order to bring the costs down further, sensitivity analyses with a careful interpretation of the results need to be carried out. These will be the topic of discussion in a follow-up paper, which will look into the impact of varying efficiency, investment costs, material pricing, production yield, energy and labour. The likelihood of certain variations occurring or being achieved will also be commented on.

Acknowledgement

I would like to thank my colleagues Dr. S. Schuler and Ms. E. Benfares, without whose support the writing of this paper would not have been possible. I also acknowledge the companies centrotherm photovoltaics, Plansee and Solibro for their much-appreciated help in re-evaluating the basic assumptions.

References

[1] Schuler, S. & Luck, I. 2014, "Cell metallization by screen printing: Cost, limits and alternatives", *Photovoltaics International*, 23rd edn, pp. 46–52.

[2] Schuler, S., Luck, I. & Berghold, J. 2012, "Total cost of ownership for thin film PV module production – status, limits and future potential for CIGS based technology – a bottom up calculation model", Thin Film Forum Berlin, Germany.

[3] SEMI PV Group Europe 2014, "International technology roadmap for photovoltaic (ITRVP): Results 2013", 5th edn (March) [available online at http://www.itrpv.net/Reports/Downloads/].

[4] GTM Research 2013, "PV technology and cost outlook 2013–2017", webinar.

About the Author

Dr. Ilka Luck founded PICON Solar GmbH in 2008 to provide consultancy services for the PV industry. Prior to that she was managing director of Global Solar Energy Deutschland GmbH and founder and general manager of Sulfurcell Solartechnik GmbH. She has also co-founded several other companies in the renewable energy sector. She holds a doctorate and diploma in solid-state physics and an MBA.

Enquiries

Dr. Ilka Luck
PICON Solar GmbH
Wrangelstraße 100
D-10997 Berlin
Germany

Tel: +49(0)30 8145264-502
Email: luck@picon-solar.de
Website: www.picon-solar.de

PV Modules

Suntech module warranty pledge

Module manufacturer Wuxi Suntech has promised to honour existing warranties despite the company's recent change of ownership. Shunfeng Photovoltaic International concluded its purchase of Wuxi Suntech in early April 2014 following Shunfeng shareholder approval. Shunfeng bought the company for RMB3 billion (US$483 million) through the bankruptcy court of Wuxi.

Wuxi Suntech said it had been fielding questions from customers about the validity of their old warranties.Wuxi Suntech CEO Eric Luo said: "We will continue to underwrite all the product and performance warranties for the products manufactured in the past and contracts entered no matter before or after the start of its restructuring phase on March 20th, 2013."

Early in that phase, Suntech Power Holdings' liquidators brokered a deal with Wuxi Suntech, operated by Shunfeng, for the former owner to act as intermediaries for the sale of modules in the US and Europe.

Suntech Power Holdings distribution subsidiaries in the US and Europe will benefit from earning commission from selling Wuxi Suntech's products in a deal to initially run for one year.

Warranties for Suntech modules will be honoured under new ownership.

Domestic content woes in India

Solar cell price rises 'putting Indian domestic content projects at risk'

Developers who have bid for projects under the domestic content part of India's JNNSM national solar programme may not sign power purchase agreements, industry body the National Solar Energy Federation of India (NSEFI) has warned. The NSFEI wrote a letter 24 March, to India's Ministry of New and Renewable Energy (MNRE) and its national solar mission departmental organiser, the Solar Energy Corporation of India (SECI), stating the DCR has made projects "economically unviable".

The letter accuses India's manufacturers of using the DCR to raise solar cell prices "by a whopping US$0.06-08 per watt, within a few days of award announcement," calling price rises "completely unethical".

NSEFI concludes manufacturers' price rises have made it "impossible" for developers to execute DCR projects, and the movements are a "serious threat to the solar mission," and could deter developers from future DCR projects. NSEFI predicted a maximum of only 35% of the current pipeline for DCR projects could be completed as a result of low manufacturing capacity. In turn with cell prices rising, module manufacturers have increased prices by up to 16% more than the quotes produced prior to developers' bids, NSEFI claims.

SunEdison drops domestic content project in India

SunEdison has dropped a 20MW project following concerns about domestic manufacturing supply in India. The project was selected to go ahead under the 375MW domestic content batch of India's JNNSM solar mission. All projects under the domestic content requirement (DCR) policy have to source equipment from local manufacturers.

SunEdison is thought to have dropped the project because of a local supply shortage and concerns over unviable pricing. SunEdison put down a INR20 million (US$332,000) deposit to develop the project, which now may be lost. The US has also filed complaints to the World Trade Organization (WTO) stating that the DCR is not fair to international module suppliers.

Big hitters

Trina Solar develops p-type monocrystalline module with record 326.3W performance

Trina Solar claims to have set a new performance record for a module using p-type monocrystalline wafers of 326.3W, an output independently verified by TUV Rheinland.

The cell uses Trina's 'Honey' cell technology, which the company noted in its recently released 2013 Annual Report

Source: SunEdison

SunEdison has dropped a 20MW project in India.

had reached an average module power of 283.5W, and a maximum module power of 285.5W on its dedicated pilot production line.

The latest world record for p-type monocrystalline modules, dubbed 'Honey Ultra' employs a second-generation 'Honey' cell technology that includes back surface passivation technology and low-resistance connection technology, along the lines of a typical PERC (Passivated Emitter and Rear Cells) solar cell design.

Development of the cell and module were undertaken at Trina Solar's State Key Laboratory of PV Science and Technology and the company hinted that the Honey Ultra was "suitable for rapid roll-out to large-scale production".

JA Solar bucks trend on guiding higher Q1 shipments

In contradiction to its nearest rivals, JA Solar has revised upwards its first quarter 2014 shipments that the company said was based on "solid execution", compared to recent downward shipment revisions by both Yingli Green and Trina Solar.

The company noted that it expects total shipment volume in the first quarter to exceed 620MW, compared to previous guidance of 580MW to 610MW. However, in line with rivals, JA Solar said that it also expected sequential gross margin improvement in the first quarter of 2014, though did not specify a percentage range.

JA Solar had reported a gross margin increased from 11.3% in the third quarter of 2013 to 15.5% in the fourth quarter.

The company also reiterated its full-year solar cell and PV module shipments guidance of between 2.7GW and 2.9GW, which still includes 200MW of module shipments for its downstream PV projects.

Yingli Green targeting over 4GW of shipments in 2014

Yingli Green Energy has reported fourth quarter results in line with its recently revised guidance, while targeting shipments in 2014 of between 4GW and 4.2GW. The company reported total net revenues in 2013 of US$2.2 billion, up from US$1.82 billion in the previous year. Overall gross profit was US$241.0 million, while the net loss was US$321.2 million, down from just over US$500 million in 2012. Yingli Green reported total PV module shipments of 3,234.3MW in 2013, up 40.8% from 2,297.1MW in 2012.

Yingli Green reported fourth quarter net revenue of US$613.0 million, up from US$596.3 million in the previous quarter. However, revenue only increased by 2.8% from the previous quarter while module shipment increased by 11.4%, indicating continued ASP declines, which could be attributed to higher shipments within China. Yingli Green expects PV module shipments to be in the range of 4GW to 4.2GW in 2014, representing an increase of up to 32.6% compared to 2013.

Source: LEDICO

Yingli modules in Israel. The company is targetting shipments of up to 4.2GW in 2014.

Canadian Solar's shipments near 2GW on return to profitability in 2013

A strong spike in PV module shipments in the fourth quarter of 2013 supported Canadian Solar closing in on 2GW of shipments for the year and secured a return to profitability in 2013. Canadian Solar reported full-year net revenue of US$1,654.4 million, compared to US$1,294.8 million in 2012. The company reported a gross profit of US$275.6 million and a net income of US$45.5 million in 2013.

Benefiting from the rush to complete PV power plant projects in China, Canadian Solar's shipments to the Chinese market amounted to 42.9% of total shipments in the quarter, an undisputed transformation from the prior quarter when shipments failed to account for 1% of the total and just below 10% when compared to the same quarter of 2012.

Emerging markets

BYD supplies modules for Rwanda's first grid PV project

BYD, the Chinese solar and storage manufacturer partially owned by investor Warren Buffet, is to supply modules for the first large-scale PV power plant in Rwanda. The 8.5MW grid-connected project is being built by Norway's Scatec Solar under a 25-year power purchase agreement with the Rwanda Energy, Water and Sanitation Authority.

BYD and Scatec Solar have already collaborated on the 75MW Kalkbult project in South Africa, with BYD again supplying modules.

Their latest project is being built at the Agahozo-Shalom Youth Village, 60km from Rwanda's capital, Kigale.

The company said Rwanda was one of Africa's "strongest emerging markets", given its plans to increase total generation capacity more than five-fold by 2017. Overall the country is expecting to have 40MW of solar generation capacity in place by 2017.

Hanwha SolarOne delivers 6.2MW of PV modules to Guatemala

PV module manufacturer Hanwha SolarOne has supplied 6.2MW of its 72-cell solar modules (HSL72) to Spanish-based companies Cobra and Gransolar for a new solar park located in Rio Hondo, Las Cruces, Guatemala.

Maengyoon Kim, managing director of Hanwha SolarOne said: "We see many opportunities in Latin America, and our company is taking the necessary steps to strengthen our presence in the region. In addition to serving EU-based customers active in Latin America from our European offices, the Hanwha Group's global sales network provides local representation in the region."

This is not the first time that Hanwha has collaborated with both Cobra and Gransolar, as the two PV developers installed 155MW of Hanwha SolarOne modules in the Letsatsi and Lesedi solar parks in South Africa last year.

Trina signs 36MW Chile module supply deal

Module manufacturer Trina Solar has signed an agreement to supply its modules to an unspecified 36MW project in Chile.

Trina Solar will supply its high efficiency TSM-PC14 modules to the project, which is expected to produce an estimated 97,000MWh a year. The shipment is scheduled to be complete by the end of the second quarter of 2014.

According to Trina Solar the modules are IEC certified and specifically tailored for the desert conditions in some parts of Chile.

The completion of projects in Chile's massive PV project pipeline is finally gathering momentum.

Product Reviews

teamtechnik

teamtechnik boosts throughput of single track TT1600 stringer system

Product Outline: PV module stringer specialist, teamtechnik, has claims to have reduced cell-to-cell soldering cycle-times to below 2.25 second, boosting overall throughput of its single-track TT1600 stringer system to an annual output of 45MWp, inline with dual stringer systems.

Problem: Improvements in throughput and productivity lower production costs. Only stringer systems with dual soldering lines have previously offered high throughput speeds but are more costly than single track systems.

Solution: With 1600 cycles per hour on one track and with a reliable 24/7 production, the Stringer TT1600 guarantees output at a level that has never been achieved before, according to teamtechnik. At the same time, far fewer spare parts and operators are required than for dual-track systems. This also cuts production costs.

Applications: String soldering of conventional c-Si solar cells with Cell thickness > 160 µm and 2 and 3 bus bars.

Platform: teamtechnik uses a hold-down device in its systems to separate the soldering process from the cell handling process. This guarantees 1,600 cycles per hour on a single-track. At the same time the device ensures safe and reliable process steps and minimal breakage rates as well as precise positioning and alignment of cell and ribbon. The resulting strings offer impressive geometrical quality, linearity, length tolerance and cell gaps with excellent cell and ribbon positioning (± 0.2 mm position accurancy).

Availability: May 2014 onwards.

FRAMOS

FRAMOS offers Datalogic embedded systems for maximum image processing

Product Outline: FRAMOS is now adding vision processors from the Italian automation supplier, Datalogic to its portfolio, and will sell these through its German and international network that can provide low-cost high-resolution image analysis for solar PV panel checks and quality assurance applications.

Problem: In order for companies to benefit more from the use of image processing in production automation and quality assurance, barriers such as high development and integration costs must be lowered. Above all, the cost of algorithms and software development is a risk that frightens many company decision-makers off the idea of image processing. Here, the simple configuration of complex tasks is the key requirement for users.

Solution: With Datalogic vision processors, customers can develop complex systems with several cameras, without needing any knowledge of programming languages. 'IMPACT,' Datalogic's graphic programming environment, offers a huge and diverse number of image processing algorithms. Complex image processing solutions are created within minutes, rather than hours. In addition, when combined with industrial standard cameras, vision processors from Datalogic offer a clear cost advantage over so-called smart cameras.

Applications: System integrators can implement a huge variety of image processing projects, such as high-resolution image analysis for solar PV panel checks.

Platform: Datalogic offers an image processing PC in a performance class to suit the application, with Intel GPUs and multi-core CPUs from dual-core 1.9 Ghz to quad-core 2.1 GHz, and with up to four GigE camera ports with Power over Ethernet (PoE), or up to six USB2.0/USB3.0 ports.

Availability: March 2014 onwards.

Komax Solar

Komax Solar's Xcell X3 high-speed Stringer achieves 1800 cell per hour throughput

Product Outline: Komax Solar has launched its new next-generation solar cell stringer system, the Xcell X3. Key features include throughput of 1800 cells/hour and up to five busbar and half-cell capabilities.

Problem: As PV module manufacturing expands and the demand for reliable production processes increases, it is essential to have proficient automated interconnection equipment with high throughput, low energy consumption and easy integration into any new or existing manufacturing line.

Solution: The Xcell X3 was designed with the user in mind to ensure the lowest possible cost of ownership in the industry. The Xcell X3 is ready to process any solar cell with up to 5 busbars, PERC, p-type, n-type, and/or half-cells. A powerful and efficient induction soldering process ensures a reliable, repeatable, and controllable soldering process. With a high throughput of 1800 cell/hour or 50 MW per stringer, a compact design enables reduced floor space and provides an expandable platform.

Applications: Xcell X3 can handle full or half-cells with 2, 3, 4, or 5 busbars, PERC, p-type cells, n-type cells and ribbon widths as low as 0.8 mm.

Platform: Xcell X3 uses a streamlined AccuTrack system with an efficient closed loop soldering technology to reduce processing time without compromising soldering excellence. It easily integrates with various offloading/layup systems and is ideal for manufacturers looking to expand existing production lines, create new production lines, or transition to automatic module manufacturing. Komax Solar also offers layup and inspection solutions to further enhance module manufacturing.

Availability: May 2014 onwards.

Fraunhofer PV Durability Initiative for solar modules: Part 2

Claudio Ferrara[1], Sandor Stecklum[1], Cordula Schmid[2], Cameron Stark[3] & Geoffrey S. Kinsey[2]

[1]Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany
[2]Fraunhofer Center for Sustainable Energy Systems CSE, Boston, Massachusetts, USA
[3]Fraunhofer Center for Sustainable Energy Systems CSE, Albuquerque, New Mexico, USA

ABSTRACT
The potential for PV modules to fail before the end of their intended service life increases the perceived risk, and therefore the cost, of funding PV installations. While current IEC and UL certification testing standards for PV modules have helped to reduce the risk of early field (infant mortality) failures, they are by themselves insufficient for determining PV module service life. The goal of the Fraunhofer PV Durability Initiative is to establish a baseline PV durability assessment programme. PV modules are rated according to their likelihood of performing reliably over their expected service life. Modules are subjected to accelerated stress testing intended to reach the wear-out regime for a given set of environmental conditions. In parallel with the accelerated tests, modules are subjected to long-term outdoor exposure; the correlation between the accelerated tests and actual operation in the field is an ultimate goal of the programme. As understanding of PV module durability grows, the test protocols will be revised as necessary. The regular publication of durability ratings for leading PV modules will enable PV system developers and financiers to make informed deployment decisions. This paper provides summary data for eight module types from the two rounds of testing to date.

Introduction

Current IEC and UL certification testing is done on a pass/fail basis: assessment of the relative reliability risk, and the guidance provided to manufacturers for improvement, are therefore limited [1–5]. The tests also lack standard protocols for comparing the relative durability risks between different module designs. Without these benchmarks, financial models must instead depend on a patchwork of methods to create predictions for relative durability. This makes it difficult to quantify which solar modules are best suited to a particular installation. The uncertainty creates confusion that increases perceived risk, delays financing and ultimately raises the cost of building PV power plants.

First announced in 2011, the PV Durability Initiative is a joint venture between the Fraunhofer Institute for Solar Energy Systems ISE and the Fraunhofer Center for Sustainable Energy Systems CSE. The aim is to create an open-source durability assessment protocol that will eventually form the basis for an international industry standard. The first round of testing included five module designs [6]; data for three more module designs is reported here for the second round.

> “The accelerated test component is an extension of familiar reliability stress tests.”

The accelerated test component is an extension of familiar reliability stress tests [7–11]. Since the acceleration factors of most stress tests are not yet known, the protocol combines accelerated testing with long-term outdoor exposure testing. Until the acceleration factors for various stress tests are identified, the relative comparison of modules remains the best means of assessing (relative) module service life. To enable a comparison of different module technologies to be made, performance is converted to a rating on a scale of zero to five. The modules are rated for both performance and safety. Modules in group 1 (potential-induced degradation) are rated based on their performance at the end of the test, following light exposure. Modules in the remaining groups are rated based on their ‘weighted normalized performance’. The weighted normalized performance is a piecewise integral of their performance in each test interval, weighted by the final performance value and normalized by the initial value. Weighting by the final performance value is intended to give a higher rating to modules that show the least degradation under the tests with combined stress effects. In the years ahead, outdoor measurements of the modules under test will be used to allocate the proper acceleration factors for the accelerated test sequences.

The programme requires that, where possible, commercial modules be purchased on the open market, to avoid selection bias. If the module design is not available on the open market, the module ID label is annotated by an asterisk to indicate how the modules were acquired.

The manufacturers of modules tested in the programme have the option of withholding their identity from reports. However, the data generated remains (an anonymous) part of the dataset, for continuing comparison with the rest of the field. As the PV Durability Initiative continues, a background of prior results is available for comparison with the recent additions. Testing to this protocol has been completed in two rounds to date, on eight commercial module types. One module manufacturer has attached the identification to the results: PVDI01* is the SunPower E20 module, manufactured by SunPower, Inc.

Test sequences and results

The test protocol is broken down into five test groups (Fig. 1). A minimum of sixteen modules is currently required to complete the tests. Modules are initially characterized, then assigned to a particular test sequence. The modules assigned to the control set are stored in a temperature-controlled environment and are used to confirm the consistency of the power measurement systems. As each module progresses through its

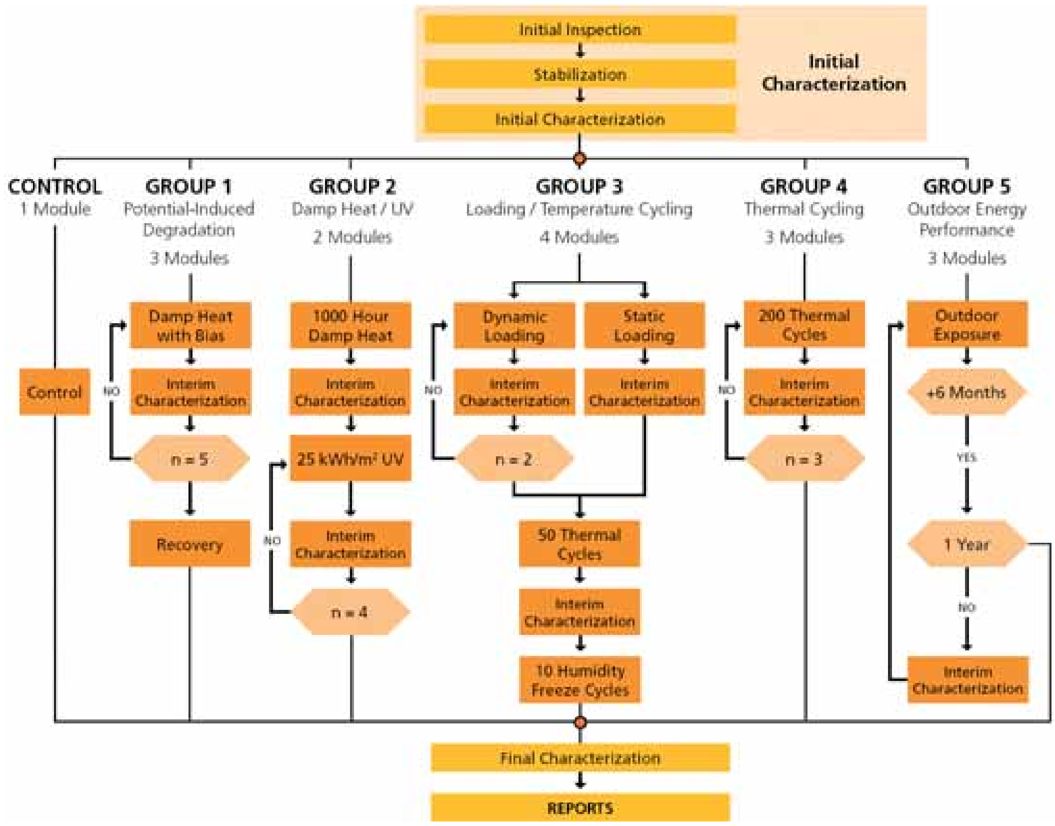


Figure 1. The PV Durability Initiative test sequences.

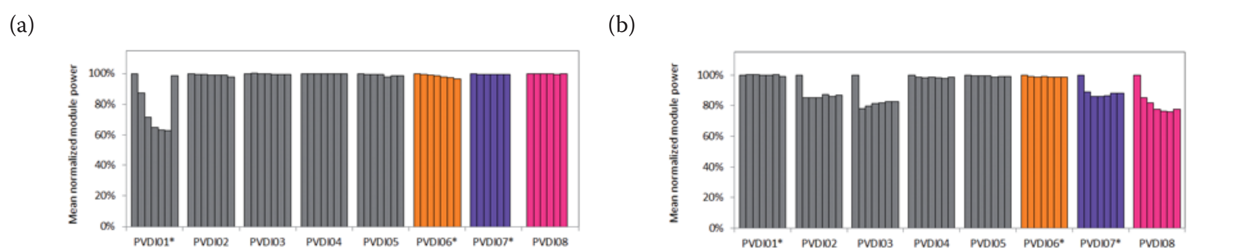


Figure 2. PID tests under (a) positive bias and (b) negative bias. To determine the PID rating, the final performance value after light soaking is used. If the module design was not acquired on the open market, the module ID label is annotated with an asterisk.

assigned test sequence, it is repeatedly characterized: for example, in group 4, each module is characterized after every set of two hundred thermal cycles. At each interim test point, electrical performance is determined, and electroluminescence and infrared images are collected. In some instances, wet leakage current and insulation resistance are also measured.

Initial characterization and stabilization

Commercial modules purchased on the open market arrive at the test facility in their standard shipping container and will have undergone typical shipping stresses. The modules are unpacked and visually inspected for any manufacturing defects or for damage suffered during shipping.

Following the visual inspection, the modules are light soaked to allow any light-induced degradation to occur. Light soaking requires a minimum of 60kWh/m^2, and may take upwards of 600kWh/m^2 to complete. The time to complete this pre-conditioning is technology dependent: thin-film technologies generally take longer to stabilize than crystalline or polycrystalline silicon technologies. During light soaking, the modules are maintained at their maximum power point and *I-V* curves are collected periodically. Light soaking is completed once the modules have reached a stable performance level. Stability is determined by taking measurements from three consecutive periods to see if they satisfy the condition $(P_{max}-P_{min})/P_{mean} < 2\%$.

Once stabilization is complete, the initial characterization is performed, consisting of light current-voltage (LIV) measurements at standard test conditions (STC), electroluminescence imaging, infrared imaging, and measurements of wet leakage current and insulation resistance.

The initial performance data is used throughout the test sequence to normalize successive performance measurements. It is also used in the comparative analysis of the nameplate performance ratings.

Group 1: potential-induced degradation

The group 1 test sequence is designed to assess a module's ability to perform under the stress of high electrical potential. The class of degradation mechanisms caused by a high potential between internal and external components is collectively referred to as potential-induced degradation (PID) [12,13]. Since PV modules may be installed where the electrical potential between the module and the earth ground can be positive or negative, modules are tested at both positive and negative electrical biases. The magnitude of the electrical bias during testing is set to the module's rated maximum system voltage.

The test begins by mounting the module in a vertical orientation (to reduce condensation accumulation) in a heat and humidity chamber. The electrical leads of the module are shorted together and connected to the biasing power supply. The opposite polarity of the power supply is connected through a sensing resistor to the frame of the module or to other conductive mounting points. Since the most common PID mechanisms occur under negative bias, the current procedure requires that two modules be negatively biased and one positively biased. In order to represent operating conditions, a light bias (illumination) should also be applied during voltage biasing. Since the configuration of most heat and humidity chambers precludes this, the modules are currently exposed to light soaking after heat and humidity exposure, to assess for recoverability of performance.

Depending on the module design and the failure mechanism involved, some module designs will recover their power performance when the high electrical bias is removed or reversed. Other modules have exhibited resistance to, and recovery from, PID when operated near their maximum power point under light exposure [2] or by raising the cell temperature to the normal operating cell temperature. For such modules, PID is not expected to have an impact in operation.

The results of the PID testing are summarized in Fig. 2. PVDI01* showed power degradation followed by recovery under light soaking. Since bias without illumination is unlikely for modules in operation, this illustrates the need for 'combined effects' testing that better mimics field operating conditions. PVDI01* has a low probability of exhibiting PID degradation under field operating conditions. To date, four out of the eight tested module designs exhibit PID under negative bias.

"To date, four out of the eight tested module designs exhibit PID under negative bias."

Group 2: damp heat and UV

The group 2 test sequence is designed to assess a module's susceptibility to high-moisture conditions, elevated temperatures and high levels of UV radiation. The damp heat and UV procedures were combined into a single test sequence to provide a means of evaluating the effects of UV on modules in damp environments. The damp heat conditions represent a harsher environment, which is expected to accelerate degradation due to UV exposure [10].

The test begins by mounting the module in a vertical orientation in a heat and humidity chamber. Each module receives a small bias current to monitor the continuity through the module during the test. Following heat and humidity exposure, the modules are placed in a UV chamber, where they are subjected to high-intensity UV light for a total dose of $100 kWh/m^2$. The exposure is carried out in four steps, with characterization and re-saturation of the modules between iterations. The

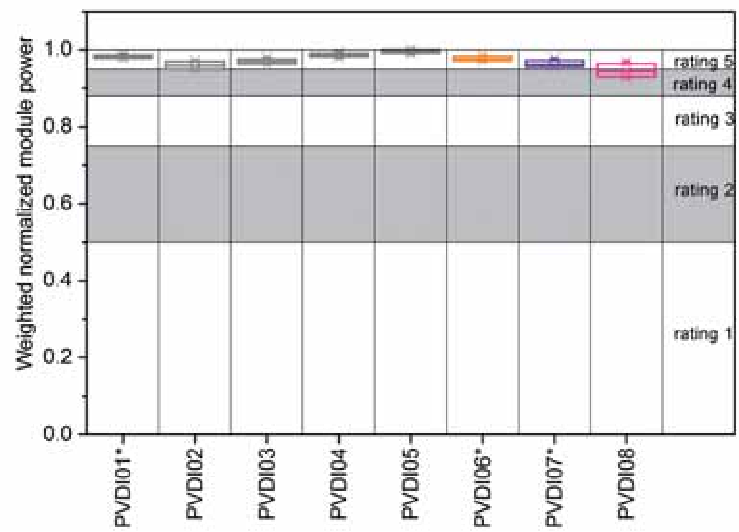


Figure 3. Normalized performance following damp heat and UV exposure.

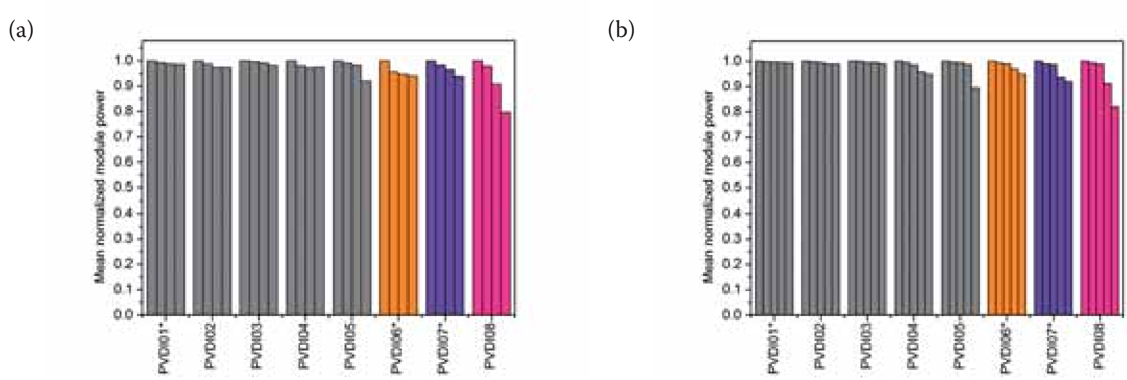


Figure 4. Mean degradation of two modules at the various test intervals of (a) static and (b) dynamic mechanical loading. The specific intervals are: initial, after loading (2× for dynamic mechanical loading), after 50 temperature cycles and after 10 humidity–freeze cycles.

modules are re-saturated by exposing them to damp heat for forty-eight hours to counter the drying effects of the UV light.

The current damp heat UV test sequence did not demonstrate significant degradation in any of the modules tested (Fig. 3). The wear-out regime for these conditions had therefore not yet been reached, and no conclusions can be drawn at this point with regard to relative susceptibility to damp heat and UV stress. This test will be revised in the future in order for the wear-out regime for UV exposure to be reached.

Group 3: static and dynamic loading, thermal cycling, and humidity freeze

The group 3 test sequence is designed to assess the effect of both static and dynamic loading on a module's performance and package integrity.

A module's ability to withstand static mechanical loads for prolonged periods is significant primarily for regions where snow loads are present. The test is performed at a temperature of –40°C in order to increase the stress in and between materials [14,15].

The static test is performed with the module loaded in a downward direction (opposite the normal of the sunward module surface) under a force of 5.4kPa for three one-hour periods, with a rest period between these loading periods.

The dynamic loading portion of the test is designed to assess the effects of intermittent loads, such as wind loads. This test is carried out at a low temperature, at which the effects are expected to be most severe. The modulus of many encapsulants will increase dramatically as the module temperature approaches the encapsulant's glass transition temperature. This stiffening of the encapsulant results in greater stress transmission to the cell and interconnects, which may lead to cell cracking and interconnect failure, for example.

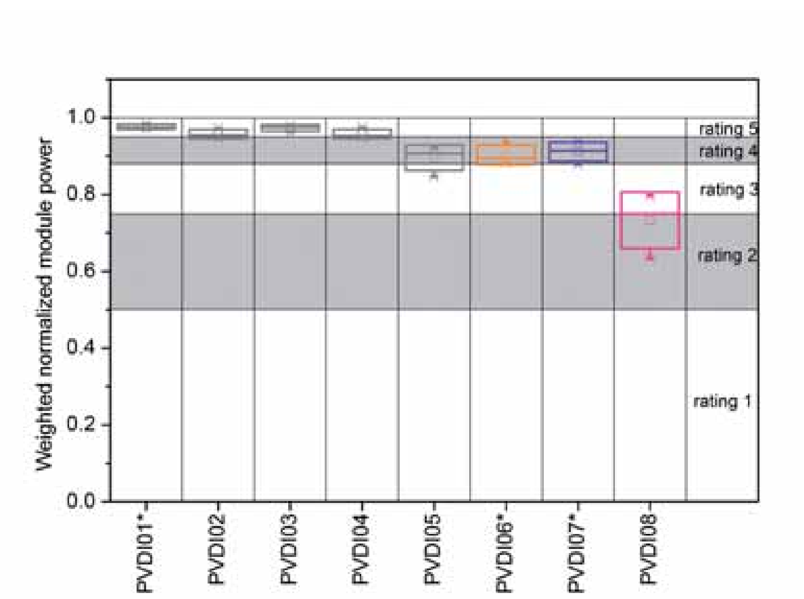


Figure 5. Normalized performance under static loading.

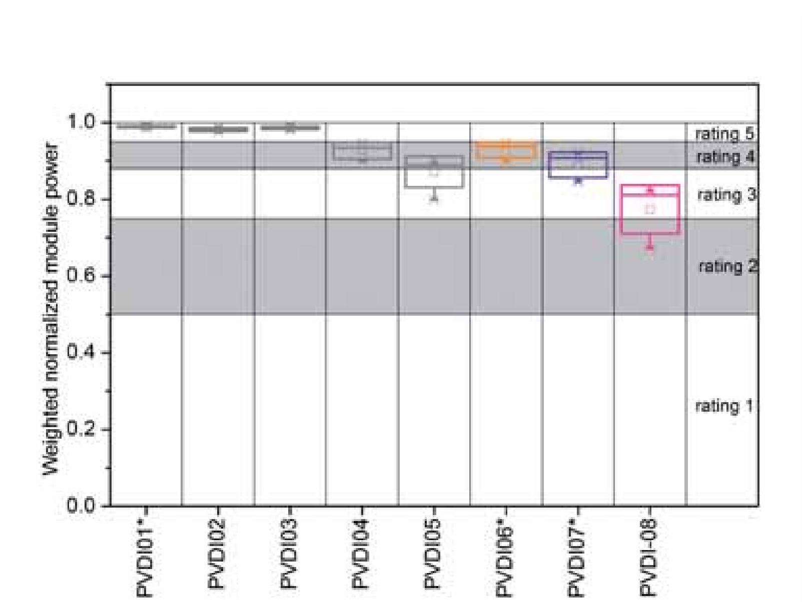


Figure 6. Normalized performance under dynamic loading.

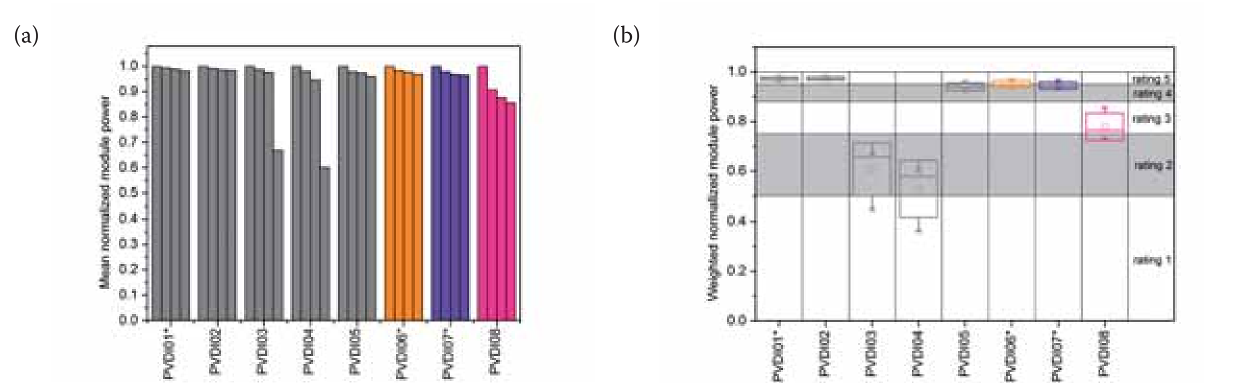


Figure 7. Performance degradation in thermal cycling: (a) results at each interval of 200 cycles; (b) normalized performance.

EU PVSEC 2014

29th European Photovoltaic Solar Energy Conference and Exhibition

The most inspiring Platform for the global PV Solar Sector

Conference Programme Available - Register Now

RAI Convention & Exhibition Centre
Amsterdam, The Netherlands

Conference 22 - 26 September 2014
Exhibition 23 - 25 September 2014

www.photovoltaic-conference.com
www.photovoltaic-exhibition.com

The dynamic load, to a maximum force of 2.4kPa, is applied normal to the module surface, in directions both positive and negative with respect to the plane of the module at rest. This is performed twice, with an interim characterization to record any change in performance and to inspect for the appearance of cell cracks and damaged interconnects.

Following load testing, the modules are subjected to thermal cycling and humidity–freeze stresses: this is done to amplify crack propagation initiated during the load tests (Figs. 4–6).

Group 4: thermal cycling

The group 4 test sequence assesses a module's ability to withstand the effects of shade-induced, diurnal and seasonal temperature changes. Under normal operating conditions, a module will be subjected to daily temperature excursions as well as more rapid temperature changes due to transient cloud cover. When temperature transients occur, stresses can be induced inside the modules as a result of the different thermal expansion characteristics of the various materials [16].

To simulate the heating effects due to current flow under normal operating conditions, the modules are biased with a current equivalent to their short-circuit current. The chamber is cycled between –40°C and +85°C at a constant rate, with a dwell of 10 minutes at both temperature extremes. Each module undergoes a total of 600 cycles; characterizations are performed after every 200 cycles.

The results of the thermal cycling tests are shown in Fig. 7.

Group 5: outdoor energy performance

The group 5 test sequence is designed to assess a module's performance under real-world (non-accelerated) operating conditions [17]. Three modules of each type are installed on an outdoor test station and monitored for long-term degradation effects. One module is instrumented with a power supply that maintains the module at its maximum power point and sweeps *I-V* curves at preset intervals; this data is used to calculate the performance ratio of the module. The other two modules are maintained at a fixed load near the maximum power point.

All three modules are removed from the test rack at six-month intervals, visually inspected and tested at STC, then returned to the outdoors. Modules will be monitored on an ongoing basis for several years. The outdoor data will be compared with the accelerated test data, as well

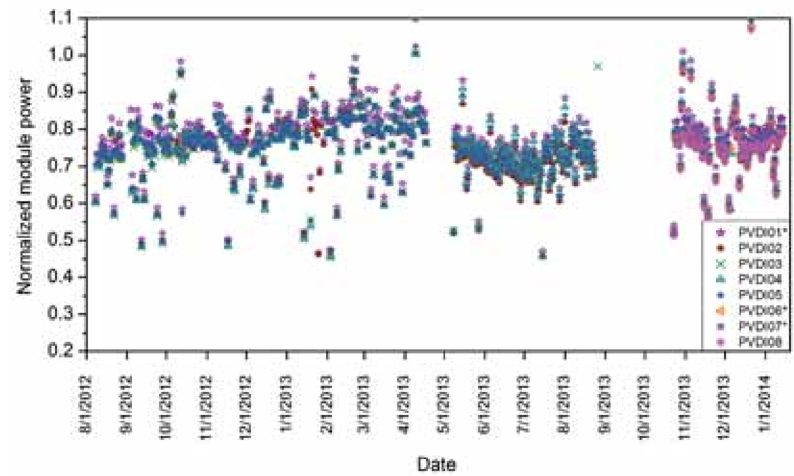


Figure 8. Outdoor performance to date.

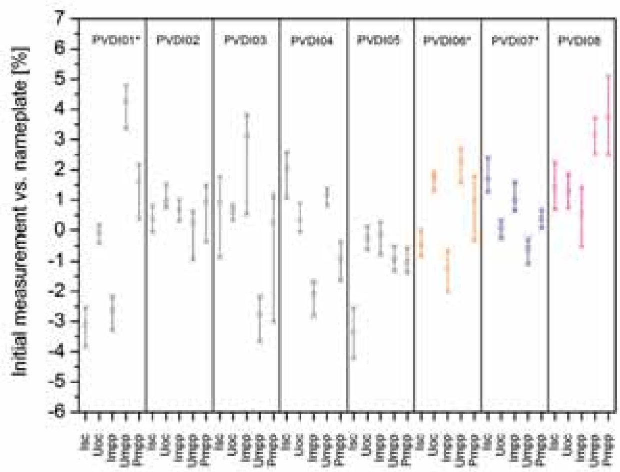


Figure 9. Baseline performance parameters with respect to nameplate rating.

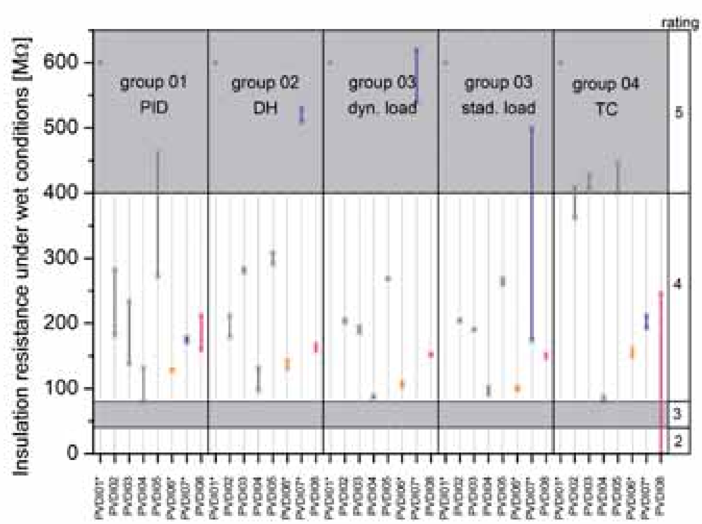


Figure 10. Wet leakage resistance results for all modules by project and test group.

as with outdoor data from analogous module designs at other sites around the world. The ultimate goals are to understand long-term wear-out, identify new failure modes and determine the acceleration factors that are necessary to correlate the accelerated test results to outdoor operating lifetime (Fig. 8).

Nameplate rating comparison

Fig. 9 illustrates initial module (STC) performance relative to the nameplate rating. Manufacturers may intentionally rate their modules below their expected initial performance in order to provide a performance buffer and reduce the risk of warranty claims. The results shown in Fig. 9 indicate that all of the module designs are within the manufacturers' specified power tolerance limits.

> "All of the module designs are within the manufacturers' specified power tolerance limits."

Rating	Rating criteria
5	$P \geq 0.95$
4	$0.88 \leq P < 0.95$
3	$0.75 \leq P < 0.88$
2	$0.50 \leq P < 0.75$
1	$P < 0.5$
0	$P = 0$

Table 1. Module performance rating ranges.

	Environmental conditions				
ID	PID	Damp heat/UV	Static load	Dynamic load	Thermal cycling
PVDI01*	5	5	5	5	5
PVDI02	4	5	5	5	5
PVDI03	4	5	5	5	2
PVDI04	5	5	5	4	2
PVDI05	5	5	4	3	4
PVDI06*	5	5	4	4	5
PVDI07*	4	5	4	4	4
PVDI08	3	5	2	3	3

Table 2. Module performance ratings based on mean weighted normalized power measurements.

Module ratings: performance and safety

Modules are given a rating on the basis of both performance and safety. The module's performance is based on the measured electrical performance at STC, for which the mean of the weighted normalized module power is used. The safety rating is based on module package integrity; wet leakage resistance and insulation resistance measurements are used for this evaluation.

Module performance ratings

The rating categories are:

1. **PID:** This category indicates a module's probability of surviving in an environment where there are large potentials (600–1000V_{DC}) between the active circuit of the module and ground.

2. **Damp heat/UV:** This category indicates a module's probability of surviving and performing as specified in environments where high humidity is expected to be a dominant environmental condition.

3. **Static and dynamic loads:** The static load category indicates a module's probability of surviving in an environment where it will be regularly subjected to static mechanical loads, such as heavy leaf-fall, snow or ice. The dynamic load category indicates a module's probability of surviving and performing as specified in environments where it will be subjected to constantly changing mechanical loads, such as wind.

4. **Thermal cycling:** This category indicates a module's probability of surviving and performing as specified in environments where there are temperature extremes and an expectation that the temperature will vary widely diurnally and annually.

Table 1 summarizes the performance rating criteria, and Table 2 shows the performance ratings for the modules tested. The mean of the weighted normalized module power P is determined from the equation:

$$P = \frac{\bar{P}_{n,n}}{n} \cdot \sum_{i=1}^{n} \bar{P}_{n,i} \qquad (1)$$

where n = the number of performance measurements within a test sequence, and $\bar{P}_{n,i}$ = the mean power, normalized with regard to the initial measurement, of all modules in a test group at the measurement step i. In the determination of P for test group 1 (PID), only the values of the initial and final measurements are used – this is because of the recovery process after the PID stress test.

Rating	Rating criteria
5	$R \geq 400M\Omega$
4	$80M\Omega \leq R < 400M\Omega$
3	$40M\Omega \leq R < 80M\Omega$
2	$400k\Omega \leq R < 40M\Omega$
1	$200k\Omega \leq R < 400k\Omega$
0	$0 < R < 200k\Omega$

Table 3. Module safety (package integrity) rating ranges.

Module safety rating: package integrity

The integrity of the package determines the safety of the module. Package integrity is determined by the leakage resistance density at the conclusion of a test sequence.

> "Package integrity is determined by the leakage resistance density at the conclusion of a test sequence."

The magnitude of the leakage resistance density is dependent on the voltage applied, the area of the module and the resistance of the module's insulating materials. To normalize the leakage resistance for the comparison ratings, the measurements are normalized for area to yield resistance per square metre. The resistances are then binned according to the IEC leakage resistance limits and an equivalent resistance for the OSHA ground fault leakage current of 5.0mA [18]. The equivalent resistance at 5.0mA is 200kΩ for a system voltage of 1kV_{DC}. This method ensures that no module receives a rating above zero if it has a leakage current greater than 5.0mA.

Table 3 summarizes the module safety (package integrity) rating criteria, and Table 4 shows the safety ratings of the modules tested. The normalized leakage resistance density R is given by the equation:

$$R = \frac{1}{k} \cdot \sum_{i=1}^{k} R_{M,i} \qquad (2)$$

where k = the number of modules in a test group, and $R_{M,i}$ = the insulation resistance under wet conditions of the final measurement of a module in a test group. R is therefore the mean of all insulation resistances from the final measurements of all modules in a test group.

Wet leakage resistance results for

ID	Environmental conditions				
	PID	Damp heat/UV	Static load	Dynamic load	Thermal cycling
PVDI01*	5	5	5	5	5
PVDI02	4	4	4	4	4
PVDI03	4	4	4	4	5#
PVDI04	4#	4#	4#	4#	4#
PVDI05	4	4	4	4	5#
PVDI06*	4	4	4	4	4
PVDI07*	4	5	5	4	4
PVDI08	4	4	4	4	4

Rating has changed from the 2013 publication [6] because of a modification of the rating procedure.

Table 4. Module safety ratings based on wet leakage resistance measurements.

all modules, along with the rating thresholds, are shown in Fig. 10.

References

[1] Ferrara, C. & Philipp, D. 2012, "Why do PV modules fail?", *Energy Procedia,* Vol. 15, pp. 379–387.

[2] Wohlgemuth, J.H. et al. 2008, "Using accelerated tests and field data to predict module reliability and lifetime", *Proc. 23rd EU PVSEC,* Valencia, Spain, p. 2663.

[3] Wohlgemuth, J.H. et al. 2006, "Long term reliability of photovoltaic modules", *Proc. IEEE 4th World Conf. PV Energy Conver.*, Waikoloa, Hawaii, pp. 2050–2053.

[4] Wohlgemuth J.H. & Kurtz, S. 2011, "Using accelerated testing to predict module reliability", *Proc. 37th IEEE PVSC*, Seattle, Washington, USA, pp. 3601–3605.

[5] TamizhMani, G. et al. 2008, "Failure analysis of design qualification testing: 2007 vs. 2005", *Proc. 33rd IEEE PVSC*, San Diego, California, USA, pp. 1–4.

[6] Meakin, D. et al. 2013, "Fraunhofer PV Durability Initiative for solar modules", *Photovoltaics International*, 20th edn, pp. 77–87.

[7] Wohlgemuth, J.H. 2010, "Overview of failure mechanisms and PV qualification tests", *Proc. PV Mod. Rel. Worksh.*, Golden, Colorado, USA.

[8] Wohlgemuth, J.H. et al. 2010, "Failure modes of crystalline Si modules", *Proc. PV Mod. Rel. Worksh.*, Golden, Colorado, USA.

[9] Osterwald C.R. & McMahon, T.J. 2009, "History of accelerated and qualification testing of terrestrial photovoltaic modules: A literature review", *Prog. Photovolt.: Res. Appl.*, Vol. 17, No. 1, pp. 11–33.

[10] Winter M.R. & Aeby, I. 2011, "Testing for lifetime reliability", *Proc. 37th IEEE PVSC*, Seattle, Washington, USA, pp. 1014–1018.

[11] Wirth, H. & Ferrara, C. 2012, "PV module technology and reliability – status and perspectives", *Green*, Vol. 2, No. 4, pp. 159–169.

[12] Hoffmann, S. & Koehl, M. 2012, "Effect of humidity and temperature on the potential-induced degradation", *Prog. Photovolt.: Res. Appl.*, Vol. 22, No. 2, pp. 173–179.

[13] Hacke, P. 2012, "Considerations for a standardized test for potential-induced degradation of crystalline silicon PV modules", *Proc. PV Mod. Rel. Worksh.*, Golden, Colorado, USA, pp. 1–30.

[14] Wendt, J. et al. 2009, "The link between mechanical stress induced by soldering and micro damages in silicon solar cells", *Proc. 24th EU PVSEC*, Hamburg, Germany, pp. 3420–3423.

[15] Barkaszi S. & O'Brien, C. 2010, "Wind load calculations for PV arrays", Solar American Board for Codes and Standards Report.

[16] Sorensen, N.R. et al. 2009, "The effect of metal foil tape degradation on the long-term reliability of PV modules", *Proc. 34th IEEE PVSC*, Philadelphia, Pennsylvania, USA, pp. 923–928.

[17] Koehl, M. et al. 2008, "Indoor and outdoor weathering of PV-modules", *Proc. SPIE Vol. 7048*, San Diego, California, USA, p. 704806.

[18] Underwriters Laboratories Incorporated 1993, Ground-Fault Circuit-Interrupters, UL 943. Northbrook, IL: Underwriters Laboratories.

About the Authors

Claudio Ferrara is currently the head of the weathering and reliability department at Fraunhofer ISE in Freiburg. In addition he holds the position of head of the TestLab PV Modules, which provides services as an accredited test laboratory. Claudio has over 20 years of research experience in the area of renewable energies and sustainable development of energy systems, especially photovoltaic energy, for buildings and cities.

Sandor Stecklum studied physical technology at the University of Applied Sciences Ravensburg-Weingarten, and has been working as a test engineer in the TestLab PV Modules at Fraunhofer ISE since 2012. Previously, Sandor spent four years as a scientific assistant in the Materials – Solar Cells and Technologies Department at Fraunhofer ISE, where he worked on new concepts for concentrator photovoltaic systems and conducted characterization measurements on concentrator cells and modules.

Dr. Cordula Schmid has been with the Fraunhofer CSE PV Technologies team since 2010. She specializes in the assessment of module packaging materials and the mechanical and electrical testing of modules. Prior to that, Cordula worked at the Fraunhofer Institute for Mechanics of Materials (IWM), where she focused on identifying and mitigating mechanical and thermal loads in solar cells and modules. She has also carried out consulting work in the area of failure analysis.

Cameron Stark has served since 2010 as a primary technical member of staff at Fraunhofer CSE in Albuquerque, where he focuses on outdoor testing. He previously worked as the primary production test engineer and a cell R&D engineer for Advent Solar. He later became the senior PV designer for a commercial-scale PV integrator, where he designed and commissioned systems throughout the USA and Latin America.

Geoffrey S. Kinsey is Director of Photovoltaic Technologies at Fraunhofer CSE. He was previously Senior Director of Research and Development at Amonix, where his group was the first to demonstrate a module outdoor operating efficiency rating over 30% and, successively, over 33%. He received his B.S. from Yale University and his Ph.D. from the University of Texas at Austin. He has two patents issued and over eighty publications in optoelectronics.

Enquiries

Claudio Ferrara
Head of Department Weathering and Reliability
Head of TestLab PV Modules
Division Photovoltaic Modules, Systems and Reliability
Fraunhofer Institute for Solar Energy Systems ISE
Heidenhofstrasse 2
79110 Freiburg
Germany

Email: claudio.ferrara@ise.fraunhofer.de

Geoffrey S. Kinsey, Ph.D.
Director, Photovoltaic Technologies
Fraunhofer Center for Sustainable Energy Systems CSE
5 Channel Center Street
Boston, MA 02210
USA

Tel: +1-617-575-7258
Email: gkinsey@fraunhofer.org

Power Generation

Ukraine solar energy in jeopardy through political turmoil

Austria-based solar developer, Activ Solar, accounting for most of Ukraine's installed solar capacity, has warned the continuing political situation in Ukraine is jeopardising its current and future energy investments.

The state electricity distributor, Energorynok, has stopped paying for all the energy installations in Crimea "including PV, wind, gas, coal, biomass. Hence, the park owners are not receiving the (FiT) for the energy the parks are producing. The owners of the parks will have to decide what to do".

Advisor to the Analytical Center for the Government of the Russian Federation, Yevgeny Gasho said: "The situation in Crimea is certainly difficult considering that only 12-13% of the consumed energy is covered by its internal production."

Ukraine's current feed-in tariff, set by ousted former president, Viktor Yanukovych, stands at €0.34/kWh (US$0.47/kWh).

Source: Activ Solar

The future of solar in Ukraine looks uncertain as a result of ongoing political turmoil.

Government Programmes

Saudi Arabia to launch 1GW solar tender 'by end of the year'

Saudi Arabia will put 700-1000MW of solar power out to tender by the end of the year, according to Vahid Fotuhi, president of the Middle East Solar Industry Association (MESIA).

The country has long-term ambitions to invest more than US$109 billion in solar energy but scepticism has been building with little tangible progress being made for outside observers to see.

"They [the Saudi government] want to come out with something this year," Fotuhi said. "If everything holds, then we will have the introductory round of projects unveiled by the end of the year. This will be roughly 1000MW, between 700-1000MW. They are targeting 40-42GW; 1GW is not that big in the grand scheme of things."

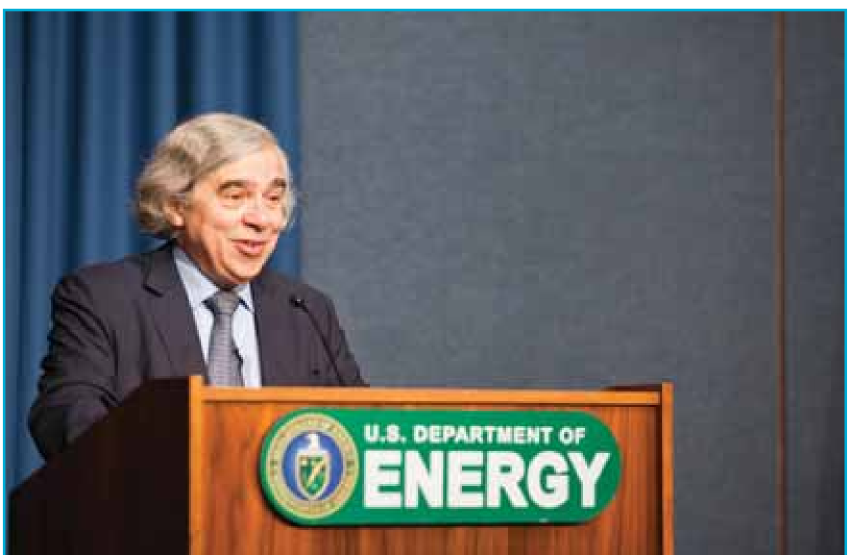
South Africa to add more renewables to next procurement round

Additional renewable energy capacity, including onshore wind and photovoltaic power generation projects, will be granted approval under the third round of South Africa's Renewable Energy Independent Power Producer Programme (REIPPP).

The country's Department of Energy (DoE) will consider allocating additional megawatts for renewable energy projects because bidding prices were competitive in the REIPPP.

According to the announcement, the fourth round of the REIPPP is "on track" to close in August 2014. The fourth round will see a tender process open for bidding on 1,000MW of renewable energy projects.

In total the DoE announced details of seven infrastructure programmes including the REIPPP.



US energy secretary Ernest Moniz has announced a boost for commercial solar in America.

Norway's sovereign wealth fund renews commitment to renewable energy investment

Just a few weeks after news broke that Norway's oil-generated sovereign wealth fund, Government Pension Fund Global (GPFG), would focus 5% of its NOK5 trillion (US$800 billion) on the renewables sector, a new report was published to the Norwegian parliament on 4 April that expands on the new mandate.

The report states that the fund will nearly double its investments in renewable energy from US$5 billion to 8.4 billion. The set allocation to environmental mandates will rise from NOK20-30 billion (US$3.3-5 billion) to 30-50 billion (US$5-8.3 billion). Norges Bank, the central bank of Norway, will also report separately on the Fund's investments in both emerging sectors and renewable energy.

US government announces boost for commercial-scale solar

In mid-April, the US government announced plans to smooth the path for the development of commercial-scale solar with US$15 million being set aside for community-lead projects.

The new Solar Market Pathways project, part of the SunShot Initiative to reduce the cost of solar, will focus on

SMA has introduced a battery backup function for its inverters.

removing red tape to allow communities to establish solar schemes for installs on the roofs of homes and businesses.

"As part of the President's all-of-the-above energy strategy, solar energy is helping families and businesses throughout the US access affordable, clean renewable power," said energy secretary Ernest Moniz.

The project will enable new financing models for communities such as shared solar where families and businesses own or lease part of, or simply buy electricity from, a larger solar installation.

Japan's 2014 FiT rates set

Japan's 2014 feed-in tariff (FiT) rates came into effect from 1 April, including solar FiTs set at ¥32/kWh (US$0.32) for commercial customers and ¥37/kWh (US$0.36) for residential PV system owners.

Residential solar is defined as anything under 10kW in capacity and commercial solar as anything above that. Non-residential FiTs will be paid over 20 years, with residential FiTs lasting half of that duration.

The new FiTs show a decline of around 11% in commercial rates and a drop of around 2.6% for residential.

Inverters & Microinverters

SMA introduces inverter battery backup function

SMA Solar Technology is now offering a battery backup function for some of its inverters. The new function is for SMA's 'Sunny Island' 6.0H and 8.0H inverters.

The battery backup function, part of firmware version 3.0, provides reliable energy during power outages and is "future-proof and self-sufficient", according to SMA.

All 6.0H and 8.0H inverters will now include firmware version 3.0, and it is also available as a retrofit for existing installations.

The system can provide data on self consumption and sufficiency with system planning capabilities. The three-phase battery backup and self-consumption system can now be used with Sunny Island inverters so installations can be planned to an industrial scale, SMA said.

PV inverter supplier rankings continue shift, says IHS

Market research firm IHS has disclosed the top 10 PV inverter suppliers for 2013, which highlights the continuing market share gains by Asian-based suppliers at the expense of European rivals.

IHS revealed that four of the top ranked firms came from China and Japan, a direct consequence of end market demand shifts to the two leading countries for PV installations last year.

China-based Sungrow Power Supply Co was picked out as a notable example of the rapidly shifting PV inverter market, which shipped over 2GW in 2013, shipping more inverters in megawatt terms in the final quarter of 2013 than any other supplier. Sungrow was said to have not appeared in the top 10 rankings during any other single quarter in 2013.

However, the inclusion of Japanese firms Omron, TMEIC and Tabuchi in the rankings is further confirmation of market share shifts, becoming the third, fourth and seventh largest suppliers in the world, respectively. Higher ASPs compared to those of Sungrow in China also played a part in their ascent.

SolarBridge riding microinverter wave with US$42 million new funding round

US-based microinverter firm, SolarBridge Technologies, has secured US$42 million in a new funding round led by Constellation Technology Ventures.

SolarBridge said that the latest funding would be used to expand operations across North America and Australia, while supporting further R&D activities.

Other investors that contributed to the latest funding round included Shea Ventures, Rho Ventures and Prelude Ventures. Bill Mulligan, president and CEO of SolarBridge said: "AC modules are changing the way distributed PV is sold, designed and installed."

Sungrow's SG1000TS central inverter passes TÜV Rheinland certification

In early April, Sungrow Power Supply announced that its 1MW 'SG1000TS' central inverter had passed TÜV Rheinland certification for harsh environment testing.

Sungrow said that the containerized inverter used in utility-scale projects was equipped with patented air inlet and outlet features that provided efficient integrated heat dissipation, while ensuring effective dust-proofing.

TÜV Rheinland's testing included the containerized inverter's ability to effectively operate in both high-and-low temperature environments as well as in harsh humid and desert conditions.

According to the company the 1MW containerized central inverter integrates two sets of 500kW inverters as well as power distribution, monitoring and security features and has a footprint of 7 square metres.

SolarMax supplies 65MW of PV inverters in UK

Supporting the rush to complete PV power plant projects in the UK by the end of the first quarter of 2014, Sputnik Engineering, the Swiss manufacturer of SolarMax inverters, said that over 65MW of its inverters had been installed before the ROC subsidy change on April 1.

SolarMax 720TS-SV Compact Stations were said to have been used in five ground-mounted projects in the quarter, which included support engineers from the company to meet schedules.

Martin Allman, UK regional manager for Sputnik Engineering, said the company was "delighted" the projects had been completed "in spite of the usual problems with adverse weather and difficult site conditions".

Chinese Giants Moving Downstream

Trina Solar sells first Chinese PV power plant

Having only gained approval to build a 50MW PV power plant in Wuwei, Gansu province, China in January, 2014 Trina Solar said that Huadian Fuxin Energy Corporation has acquired the project, the first the module manufacturer has sold in China.

The semi-desert region in north-west China is said to be well suited for solar energy, with high irradiance and the ability to sell surplus power to other parts of the country as well as supply its own needs.

Trina Solar noted in a recent earnings conference call that its PV project pipeline stood at around 400-500MW, with 70-80% located in China.

Hanwha SolarOne signs MoU to expand China downstream business

Tier-one manufacturer Hanwha SolarOne has begun establishing a "long-term strategic partnership to develop downstream PV

Source: Hanwha SolarOne

Hanwha SolarOne has a established a new partnership to develop its downstream project business in China.

projects" with the Wuxi New District Administrative Committee in China.

Wuxi New District is on the eastern coast of China and was designated an industrial zone in the early 1990s, aimed at attracting investment from abroad. Hanwha SolarOne and the regional committee have signed a memorandum of understanding (MoU) to the effect that the administrative committee will provide rooftop space for PV projects, facilitate approvals from local government and ensure grid connection.

Wuxi New District Administrative Committee will also assist Hanwha SolarOne in gaining preferential tax treatment as well as project financing.

The deal is planned to ultimately result in Hanwha SolarOne becoming the owner and operator of 100MW of distributed generation of projects in the district.

GCL-Poly China PV plans get US$800 million boost

Polysilicon producer GCL-Poly's move into PV project development has received a boost in the form of a CNY5 billion (US$805 million) credit line from the China Development Bank.

The news followed an announcement in March that GCL's holding company would be changing its name to GCL New Energy to reflect the company's increasing involvement in downstream business. GCL-Poly said the credit line would be available to enable the company to build up its solar farm business in China.

ReneSola completes 60MW PV sale in Western China

At the end of March module manufacturer ReneSola said it had completed the sale of three utility-scale PV projects in Western China.

The three grid-connected projects total 60MW and were sold to solar equipment and services company, Jiangsu Akcome Solar Science and Technology.

The deal was competed on 31 March, fulfilling memorandum of intent signed by ReneSola and Akcome in December 2013.

"We remain optimistic about China's market for solar projects over the longer term, and we will continue to participate in China projects and explore related opportunities," said Xianshou Li, ReneSola's CEO.

Big Investment

European Investment Bank earmarks €750 million for French renewables projects

The European Investment Bank is to provide €750 million (US$1 billion) to support renewable energy development in France over the next two years.

EIB will cover 50% of the funding needed for selected solar, wind and other renewable energy projects with a capital cost of €50 million (US$68.8 million) or less.

The EIB will deliver the programme through partner banks, Société Générale, Credit Agricole and BPCE, which will be responsible for choosing projects and structuring their financing.

Public or private entities will be able to take advantage of the funding.

EIB said last year it decided to target some €19 billion (US$26 billion) on energy transition projects. France is one of the first beneficiaries of this new focus.

SunEdison secures US$250 million from first yield co

SunEdison has completed its first yield co securitization with Goldman Sachs Bank USA, acting as the single lead arranger.

SunEdison recently noted that it plans to increase its PV project business to a scale that would require up to US$15 billion a year in project finance capital. The company had noted that yield co vehicles as well as debt and equity deals would be used.

Carlos Domenech, CEO of SunEdison Capital said: "SunEdison's yield co will utilize proceeds from the US$250 million facility to acquire projects from third party developers as well as projects developed by SunEdison."

Northland secures loan for final phase of 130MW PV programme

Canadian independent power producer Northland Power has closed financing for the final phase of a programme to build 130MW of PV generation capacity in Ontario, by securing a CAN$240 million (US$217.81 million), 18-year loan. The 18-year term loan takes the form of a construction credit facility.

The 50MW fourth phase will consist of five plants, each of 10MW, split between northern Ontario, near the town of Cochrane and in central Ontario, near the town of Huntsville.

The projects are expected to begin commercial operation during this year and the first half of next year.

The financing deal was managed by three major Japanese financial institutions, with Siemens Financial and Norddeutsche Landesbank as lead arrangers. Other institutions were also involved in the financing process.

Source: SunEdison

SunEdison has completed securitization of its first yield co.

News

Product Reviews

JA Solar

JA Solar's 'PERCIUM' mono-Si modules surpass 20% conversion efficiencies

Product Outline: JA Solar is rolling out globally a new series of high performance solar cells and modules in 2014. Highlights include its monocrystalline silicon (mono-Si) solar cell (156x156 mm2), 'PERCIUM', with 20%-plus conversion efficiency.

Problem: Residential and light commercial PV installations continue to require high-efficiency but cost-competitive PV modules in markets with feed-in tariff regression, as well as unsubsidized emerging markets.

Solution: JA Solar claims its PERCIUM cell has surpassed a conversion efficiency of 20.3%, 1.3% higher than average mono-Si solar cells by 20W. The cell efficiencies have been independently confirmed and certified by the Fraunhofer ISE's photovoltaic calibration laboratory (CalLab) in Freiburg, Germany, and sets an industry-leading mark for industrial size (156x156 mm2) solar cells using p-type mono-Si wafers. The PERCIUM module is claimed to produce 8% more power output per unit area than the average. It is claimed to produce 1% more power due to improved yield in low-light conditions. The company claims a reduction in transportation, installation and BOS costs.

Applications: The PERCIUM module is suitable for residential and commercial rooftops (small and medium-sized).

Platform: All JA Solar's products are manufactured in-house, a procedure certified by PI-Berlin and Solar-IF. Apart from PID test, products of the company also pass long-term reliability tests, harsh climate environment endurance tests, and others. The PERCIUM cell employs a passivated, local back surface field (BSF).

Availability: Already available.

Nextronex

Nextronex 'Power Podium' offers plug-and-play inverter operation

Product Outline: Nextronex has launched the 'RAY-MAX' Power Podium, which integrates the RAY-MAX Inverters, MV Load Centers, DC Bus Power Strip and the Smart Controller on a factory-installed platform, allowing for simple and fast-track field installation. Nextronex Distributed Architecture is claimed to deliver up to 8% more energy output.

Problem: Large-scale PV power plants are under constant pressure to reduce installations cost for key capital equipment such as PV inverters. Adopting systems that provide fast installation times and increased efficiency, while maintaining IRR are essential for any projects success.

Solution: The RAY-MAX Power Podium simplifies on-site wiring, facilitates construction scheduling and reduces field concrete and labor expenses. All equipment is pre-assembled onto the platform, fully wired and pre-tested. The 'Power Podium' offers a plug-and-play solution that requires only simple AC and DC connections in the field. Nextronex is able to offer the Power Podium configurations to matches the specific design needs of the client and the site.

Applications: PV arrays of 150kW-plus.

Platform: The Power Podium maintains the advantages of the Nextronex Distributed Architecture with greater energy production, higher reliability and increased longevity. The Smart Controllers handle all master/slave coordination, control, telemetry functions and real-time monitoring. Additionally, the design facilitates centre array inverter placement, minimizing shading and providing wiring savings.

Availability: April 2014 onwards.

Soitec

Soitec's Plug&Sun+ CPV system offers improved off-grid performance

Product Outline: Soitec has introduced the Plug&Sun+, a new higher capacity version of its off-grid concentrator photovoltaic (CPV) product. The new Plug&Sun+ can be coupled with batteries and/or a diesel generator to provide electricity 24/7 and is designed to address the needs of medium-scale solar-energy installations at remote sites.

Problem: The original Plug&Sun, launched in 2011, is a robust, reliable, easy-to-deploy CPV tracking system designed to meet the energy needs of small-scale isolated sites. The new, Plug&Sun+ provides an enhanced mix of technical and economic performance.

Solution: Plug&Sun+ uses three of the latest generation of CPV modules from Soitec and is linked to an energy management system. This allows the system to achieve a peak-power output of 7.3 kWp while providing hundreds of watts of power throughout the day and night. Additionally, when Plug&Sun+ is used in hybrid installations, it provides a renewable energy source that complements existing power generators. This can help reduce diesel consumption and maintenance costs.

Applications: The Plug&Sun+ system is configurable to meet the installation requirements for different applications including housing, industrial sites, outdoor lighting, water treatment and telecommunications base stations.

Platform: By combining several modules on biaxial trackers, which use a proprietary algorithm to automatically optimize their position based on the path of the sun, Soitec's technology maximizes energy generation throughout the day.

Availability: Currently available.

Large-area solar irradiance mapping

Dazhi Yang, **André Nobre**, **Rupesh Baker** & **Thomas Reindl**, Solar Energy Research Institute of Singapore (SERIS), National University of Singapore, Singapore

ABSTRACT

As PV systems proliferate and become an important part of the global energy mix, it is increasingly important to forecast their energy output in order to ensure a safe and reliable integration of their variable output into electric power grids. One of the main prerequisites for that is the detailed recording and interpolation of the actual irradiance in a spatially resolved way. Such 2D irradiance maps would also allow the assessment of the performance of the many PV systems that do not have irradiance sensors installed at the site. The maps are ideally based on a dense network of irradiance sensors; however, in many cases the costs of high-precision pyranometers, real-time monitoring and frequent maintenance are prohibitive for such operational forecasting systems. On the other hand, many PV installations are in fact equipped with reference cells in the plane of array (POA) for evaluating and monitoring the performance of the systems. Adding this network of reference cells to existing pyranometer networks (from meteorological services or research institutes) would substantially help in improving the accuracy of the irradiance maps. This paper introduces an irradiance conversion technique that allows POA irradiance measurements from an on-site reference cell to be converted to global horizontal irradiance data, which can then collectively be used to generate large-area irradiance maps.

Introduction

There are two main reasons for the development of accurate solar irradiance mapping, namely to calculate the so-called *performance ratio* (PR, in %), and to use it as a critical input to perform solar irradiance forecasting. Many owners of PV systems do not know how well their installations perform because they have no on-site readings from an irradiance measurement device. They would only be able to gauge the quality of the systems if they had at least a close estimation of the irradiance values at their respective locations, which would then enable them to calculate PRs. The sheer solar energy generated over time, even if it is related to the installed capacity (so-called *specific yield* in kilowatt hour per kilowatt peak – kWh/kWp), is not sufficient for judging the performance, since the baseline reference is missing and the output also fluctuates because of the year-on-year variability of the irradiance (there are 'good' and 'bad' solar years). So without the on-site irradiance, the PV system owner would not know whether the system 'could do better' or if the PV modules were possibly degrading faster than what had been guaranteed by the PV module manufacturer, for example.

Power system operators are often worried about the possible impact of the variability of energy generated from the increasing share of solar PV systems on the stability and resilience of the electric power grid. The solar power generation from PV modules naturally fluctuates with the available irradiance at the site, which is influenced by clouds and the absorbing or scattering constituents of the atmosphere. In order to support the power system operations, the ability to forecast the output of the PV systems would be helpful, probably not to the extent of advanced bidding as required from conventional power generators, but at least in terms of having a reasonable estimation of the solar power output over the next 15–30 minutes (typical dispatch cycles), intra-day (for ramping up or down of conventional capacities) or day-ahead (for futures trading). 'Reasonable' in that sense strongly depends on the climatic conditions and the forecasting horizon, but could go as low as less than 10% uncertainty. Forecasts (even long term) with greater than 50% accuracy are most probably not meaningful anymore.

Both the above-mentioned challenges could be addressed if (together with other techniques) there were a constantly updated, area-wide mapping of the solar resource available. Ideally, such a map is based on a dense network of irradiance sensors, but is restricted in many cases by the cost of high-precision pyranometers, real-time monitoring and frequent maintenance. However, many PV systems are in fact equipped with reference cells which are typically installed in the plane of array (POA) of the PV modules for evaluating and monitoring the performance of the PV system. Adding this network of reference cells to existing pyranometer networks (from meteorological services or research institutes) would allow the generation of large-area irradiance maps with improved resolution, which could then be used either to evaluate the performance of PV systems without an on-site irradiance reading capability, or to have a base for irradiance and solar power output forecasting for the grid operator. Since POA readings cannot be added to horizontal irradiance sensor data, this paper describes an irradiance conversion technique which allows POA irradiance measurements from an on-site reference cell to be converted to global horizontal irradiance (GHI). The converted GHI from each location can then be used for maps through spatial interpolation techniques, such as kriging – an interpolation technique which uses the spatial covariance to generate weightings.

Why and how to assess the performance of solar PV systems?

The performance of a PV system is usually assessed via two metrics: 1) the specific yield in kWh/kWp over a certain period of time (typically one year); and 2) the PR in %, which is a measure of how well a PV system converts the incoming solar flux into electricity, based on a) the amount of the solar resource reaching the POA of the PV installation, and b) the nominal system capacity at standard test conditions (STC). The latter measure gives the ratio of the actual AC energy yield to the 'theoretical' maximum DC yield, based on in-plane irradiance measurements and on the assumption of full DC-to-AC conversion.

> "The performance ratio is an internationally recognized metric for PV system performance assessment and is used for system evaluation all around the world."

Relatively independent of the irradiance on site, the PR is an internationally recognized metric for PV system performance assessment and is used for system evaluation all around the world. It has been adopted by the International Energy Agency (IEA) Photovoltaic

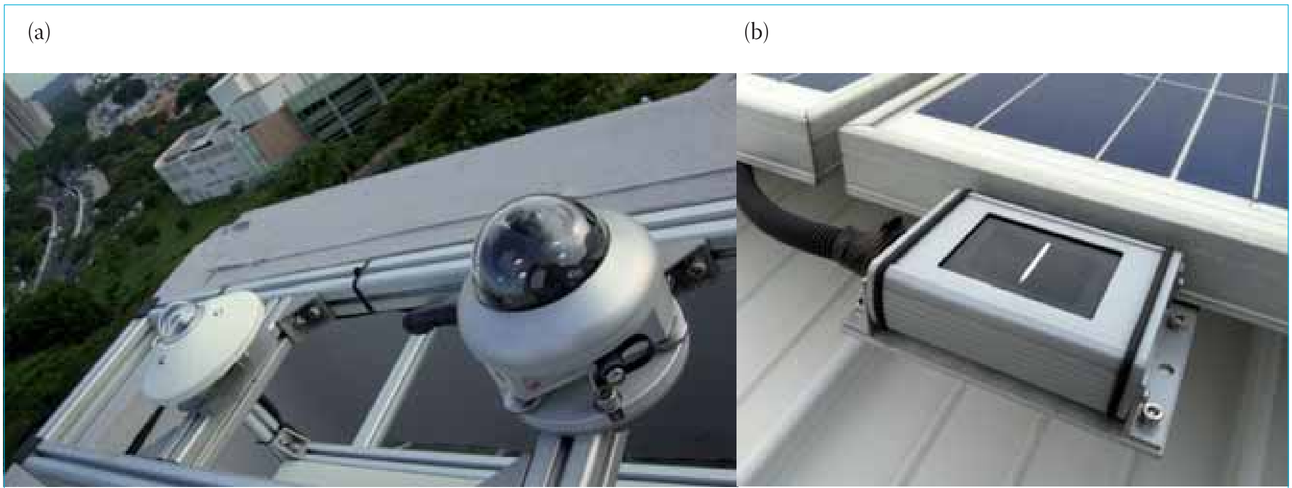


Figure 1. (a) Two pyranometers: a CMP11 from Kipp & Zonen (left), and an SPN1 from Delta-T (right); (b) a silicon sensor installed in the plane of array of a PV system.

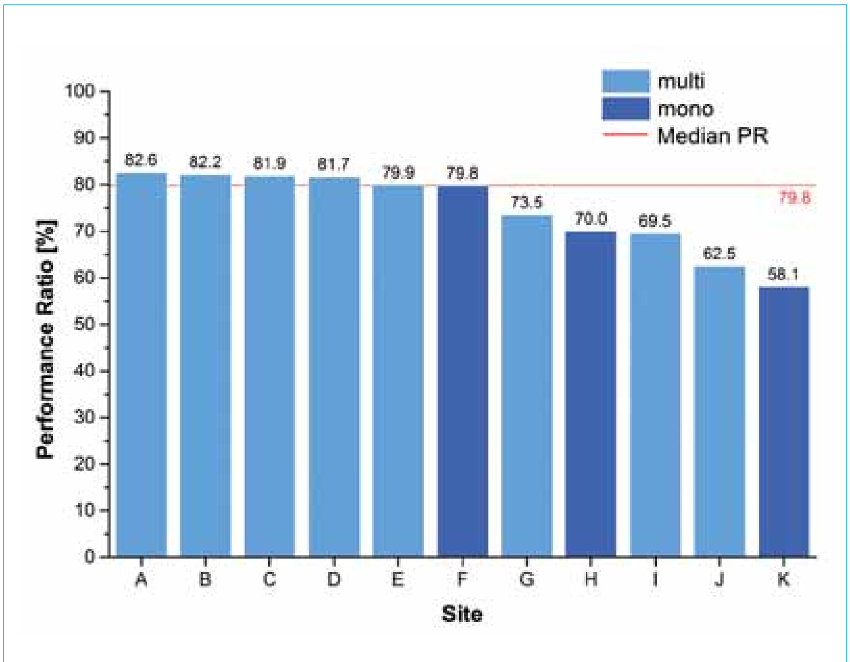


Figure 2. Measured PR of 11 silicon-wafer-based PV systems in tropical Singapore. The median performance value for the year 2011 was ~80%. (See Nobre et al. [1].)

Power Systems (PVPS) programme and is described in the IEC standard 61724 (1998).

In order to measure the irradiance, silicon-wafer-based reference cells ('silicon sensors') are normally used in PV system installations, while pyranometers or calibrated silicon sensors are commonly used for research-grade investigations (see Fig. 1). It should be pointed out that the irradiance readings from a calibrated pyranometer (used for solar radiometric measurement, see below) are ~3–4% higher than those obtained using reference cells (due to the fact that pyranometers absorb a larger fraction of the solar spectrum), which in consequence results in a lower PR. In a later section, some of the loss mechanisms (the deviations of the reference cell measurements from the pyranometer measurements) will be discussed in detail. These deviations, however, are well known and can be accounted for in the conversion of POA readings to GHI to enable the generation of large-area irradiance maps from a network of multiple measurements devices.

Fig. 2 shows the performance ratio of 11 silicon wafer-based PV systems in Singapore, assessed during 2011. PV systems in hotter climates will generally display a lower performance than in temperate climates.

Why and how to forecast solar irradiance?

Power system operation centres need to concurrently manage grid parameters (voltage, frequency, etc.), load flow, unit commitment, transient stability and transmission. A common goal of these operations is to meet the changing electricity demand and to minimize outages. Although highly complex, power system operation is well developed for conventional power generation, transmission and distribution. With the increasing penetration of distributed solar power into the electricity grids, the inherently introduced variability (i.e. from different irradiance levels because of cloud movements) potentially poses challenges for the power system operations. Despite there also being positive impacts on the power grid – such as the reduction of peak demand (especially in countries where the air conditioning load pattern matches the irradiance curve of the day) or reduced voltage drops in the distribution grid – the high ramp rates and sudden drops when clouds move over a PV installation are still seen as a threat by many grid operators. Apart from the more conventional approach of increasing the spinning reserves in the power system (which is a rather costly option), there are various other ways of managing this variability, some of which are:

- Suitable regulations for active and passive inverter reaction.
- Demand-side management (DSM) – advance notice in the range of hours.
- Direct load control – an extreme form of DSM for short notice periods (minutes).
- Energy storage – e.g. battery based, with instant reaction.

Complementary to the above-mentioned options, the forecasting of the solar power output on different timescales for a certain area is a very powerful tool, which brings solar PV one step closer to being 'dispatchable,' and thereby making it more compatible with the current power grid operation. Solar energy forecasting is also compliant with future smart grids, where various devices and communication gateways can make automated decisions with respect to energy flows (e.g. self-consumption) and economic considerations (e.g. selling to the grid at peak demand).

Among various timescales of solar energy forecasting, medium-term forecasting (15 minutes to 1 hour, depending on the local dispatch cycle) is particularly important, especially with regard to the operations of peaking and load-following power plants. However, these forecast models are less developed than long-term and very short-term forecasts.

For long-term (several hours to a few days) solar irradiance forecasts, satellite-based techniques are commonly adopted [2]. The forecasts are usually derived from the output of so-called *numerical weather prediction* (NWP) models; model output statistics are then used to post-process the forecasts. Depending on the location on the Earth, cloud motion analyses can be added in order to capture and project the dynamics of the clouds, from which the irradiance maps are then derived through a projection of the sky conditions. These prediction model methods can be traced back to the 1920s (when NWP was first proposed).

Very short-term (a few seconds to five minutes) irradiance forecasts can be separated into two classes of methods – one based on sky cameras and the other using high-spatial-resolution (a few metres apart) irradiance sensor networks. Both methods aim to provide a better understanding of cloud movements. Unlike NWP, these methods analyse cloud motion under local sky conditions. As the cloud motion is considered to be persistent within a small time window, these forecasts can accurately account for the up-and-down ramps in PV output [3].

Medium-term forecasting is a much more challenging problem, with no dominant strategies being available at the moment. Currently, spatio-temporal statistical models (such as time-forward kriging [4]), which use multiple irradiance sensors, or purely temporal statistical models [5], which use only one sensor, are usually adopted. In view of the effects of cloud propagation [6], spatio-temporal models are preferred over purely temporal models, which seek to identify the relationship between the points of forecast and past observations. In other words, past values are combined, either linearly or non-linearly, to form the forecasts through a regressive framework. In a spatio-temporal model, the past values from a particular station and from its neighbouring stations are used [7]. Space–time kriging and vector autoregressive models are examples of such spatio-temporal statistical models [8]. A common pre-requisite for applying these statistical models is a network of horizontally installed irradiance sensors, which measure the spatio-temporal irradiance distribution. Using the satellite-derived irradiance data for these statistical models may also be considered; however, satellite-derived irradiance usually has a higher uncertainty of ~8–25%. Moreover, it has low temporal resolution (typically 30 minutes to 1 hour) and low spatial resolution (1km to 10km), which may not capture the fast-changing irradiance random field. From a sampling point of view, a high spatial resolution of irradiance sensors is always desirable.

> "From a sampling point of view, a high spatial resolution of irradiance sensors is always desirable."

Irradiance measuring instruments

There are several accepted terms describing irradiance components (measured in W/m^2) used in modelling. Global horizontal irradiance (GHI) refers to irradiance measured on a horizontal surface. It can be decomposed additively into two components: the horizontal beam irradiance (HBI), i.e. the beam irradiance on a horizontal plane; and the diffuse horizontal irradiance (DHI). On a tilted surface, tilted global irradiance (TGI) can be decomposed additively into the tilted beam irradiance (TBI), the tilted diffuse irradiance (TDI) and the reflected irradiance (RI). Theoretically, if any two (out of seven) types of irradiance listed above are known, the others can be 'deterministically' calculated through transposition models (see details below).

To measure the above-mentioned irradiance, two types of device – namely thermopile-based instruments and PV reference cells – are used. Pyranometers and pyrheliometers are thermopile-based instruments that convert heat to an electrical signal which can then be recorded. A pyranometer is typically used to measure GHI; if equipped with an additional shadow band to block the direct irradiance, it can also record DHI. Pyranometers are often installed in larger PV systems to also measure TGI (and possibly TDI), but in this case need to be installed in the tilted module plane. However, each pyranometer only records one of the irradiance components mentioned above.

A pyrheliometer measures the beam irradiance with a solar tracking system that aims the instrument at the sun. HBI and TBI can then be calculated using the zenith angle and the incidence angle respectively. Pyranometers and pyrheliometers are often used for solar radiometric measurements [9]. The price range of industrial-grade pyranometers can reach a few thousand US dollars.

The alternative reference cell is a PV device, which converts a flux of photons directly into an electric current using an external circuit, working similarly to a PV system. Most reference cells are silicon wafer based; they are less accurate than thermopile-based devices (the major loss mechanisms are discussed

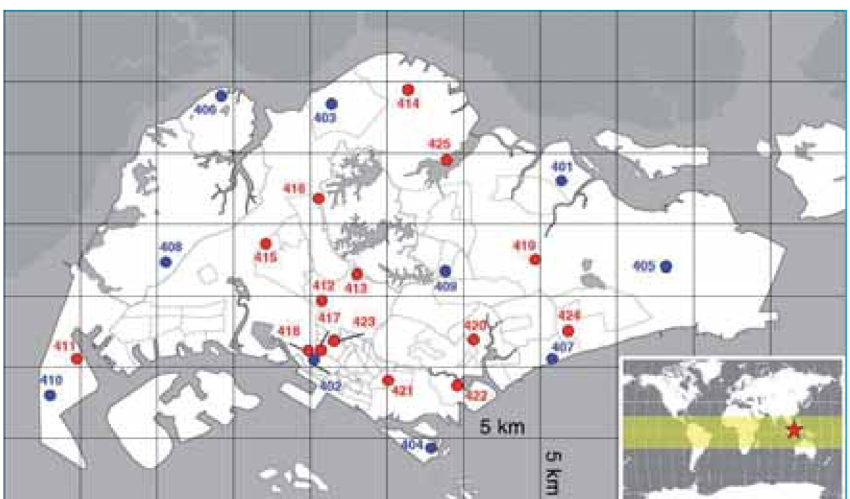


Figure 3. A network of 25 ground-based irradiance measurement stations in Singapore. The blue dots represent stations where both silicon reference cells and pyranometers are deployed. The red dots are stations where only reference cells are installed. The bottom right corner shows Singapore's position (red star) on the world map, as well as the 'sunbelt' region (yellow band) between the tropics of Cancer and Capricorn.

below). Hundreds of reference cell types are available on the market and are cheaper than pyranometers (a few hundred US dollars). This type of sensor is therefore often used to measure the POA irradiance at a PV site in order to assess the system performance [9]. A more detailed comparison of these instruments can be found in Meydbray, Emery & Kurtz [9].

In solar irradiance forecasting, solar radiometric measurements are preferred: hence high-precision pyranometers are typically used for this application [5]. Many research institutes – such as the Solar Energy Research Institute of Singapore (SERIS) – have taken the initiative to build irradiance measurement networks using pyranometers and/or reference cell devices [7,8]. Such an example is given in Fig. 3, which shows an irradiance network deployed in Singapore by SERIS.

In comparison to most networks currently available in the world, the network shown in Fig. 3 is rich in both temporal and spatial resolution for metropolitan-scale applications. Research has shown that the irradiance random process is extremely volatile [8]; a typical de-correlation distance of 1–10km is observed in many places of the world (a de-correlation distance is defined as the geographical distance over which cross-correlation between two irradiance time series is not observed anymore or is statistically insignificant). It should be noted that the de-correlation distance is a function of sampling frequency: a higher frequency corresponds to a smaller distance. With such considerations, an even denser network of irradiance sensors than the existing one described above would be desirable when the medium-term forecasts are performed at, for example, 15-minute intervals for grid utility management.

Tilt	MBE [W/m^2]	RMSE [%]	U95 [%]
10°	2.09	2.63	5.07
20°	–5.12	3.00	6.47
30°	–1.70	4.10	8.17
40°	–6.40	4.86	9.90

Table 1. Horizontal-to-tilt irradiance conversion errors using the Perez transposition model. The calculated TGI is compared with the actual TGI measured by reference cells tilted at four different angles. Mean bias error (MBE), root mean square error (RMSE) and the 95% expanded uncertainty (U95) are used as error metrics. All error terms include temperature, spectral loss and reflectance loss corrections.

Should reference cells be used for radiometric measurements?

As mentioned earlier, reference cells are typically used for PV efficiency and performance measurements. When they are used in solar radiometric measurements, three issues need to be addressed.

The temperature response of the silicon reference cells is similar to that of a PV system, but needs to be adjusted in order to obtain accurate solar radiometric measurements. Although the temperature coefficient is a function of irradiance and temperature, it is typically assumed to be linear with respect to temperature [10]. Some of these reference cells possess an on-board temperature sensor that provides real-time temperature measurements, enabling irradiance readings to be corrected (either at the sensor output level, or via post-processing in the data acquisition system). To optimize their performance, such reference cells need to be calibrated. The Fraunhofer Institute for Solar Energy Systems (Fraunhofer ISE), along with other leading solar research institutes, provides such calibration services, thereby reducing the uncertainty of reference cells to as low as 2% under indoor testing conditions.

Furthermore, reference cells have a narrower wavelength response than pyranometers. This is straightforward to deal with, as the spectral loss is considered to be linear with irradiance. The spectral loss is compensated during post-processing after the measurements are obtained.

The third loss mechanism is the reflectance loss. As the response to the angle of incidence falls off at angles greater than 80°, this loss can be regarded

Figure 4. The irradiance measurement station located on the roof at the Solar Energy Research Institute of Singapore (SERIS).

June 8-13, 2014 | Denver, Colorado

Early Registration Deadline

May 5, 2014

The PVSC brings together researchers, scientists, and technological leadership from industry, academia and government with the focused agenda on photovoltaic materials, devices, and systems. A host of cutting-edge topics will be addressed at the conference creating a stimulating and educational environment like no other scientific event. Topics include:

- Area 1. Fundamentals and New Concepts for Future Tech
- Area 2. Thin Film Polycrystalline Photovoltaics
- Area 3. III-V and Concentrator Technologies
- Area 4. Crystalline Silicon Photovoltaics
- Area 5. Thin Film Silicon Based PV Technologies
- Area 6. Organic Photovoltaics
- Area 7. Space Technologies
- Area 8. Characterization Methods
- Area 9. PV Modules and Manufacturing
- Area 10. PV Systems and Applications
- Area 11. PV Deployment
- Area 12. PV Reliability

OVER 1,100 TECHNICAL PRESENTATIONS ARE EXPECTED,
SO SUBMIT YOUR ABSTRACT NOW!

VISIT WWW.IEEE-PVSC.ORG
FOR MORE INFORMATION

BE A PART OF PVSC'S
ACTION-PACKED FLOOR SHOW

IEEE photonics SOCIETY | IEEE | Electron Devices Society | IEEE PES

as a function of incidence angle. The compensation for the reflectance loss is performed at various bands of incidence angle using linear regression, i.e. for each band:

$$\textit{Reflectance loss} = a + b \times \textit{angle of incidence} \quad (1)$$

where a and b can be determined empirically.

Once the loss mechanism issues are addressed, the reference cell can be used to approximate a solar radiometric measurement device. The remaining challenge is to convert the tilted reference cell measurements to horizontal so that they can be integrated in spatio-temporal irradiance maps.

Power Generation

"Once the loss mechanism issues are addressed, the reference cell can be used to approximate a solar radiometric measurement device."

Conversion from tilt to horizontal using two reference cells

Transposition is used to calculate TGI based on actual GHI and DHI measurements. There are two types of transposition models: isotropic and anisotropic. The isotropic transposition model does not include the azimuthal dependency of the DHI; in other words, the diffuse component is assumed to be homogeneous in all directions. However, in reality, the diffuse component is affected by two main anisotropic mechanisms – the circumsolar and horizon brightening effects. Both mechanisms are due to the scattering of solar radiation by aerosols in the atmosphere. For these reasons, anisotropic transposition models are proposed in order to account for such characteristics.

Among various scientific models, the Perez transposition model [11,12] is considered to be a very reliable and universal model. It separates the sky hemisphere into three parts: an isotropic background, the circumsolar disk and a band near the horizon. The circumsolar disk and the horizon band contributions can be expressed as fractions of the diffuse background radiation. These coefficients are determined empirically using irradiance measurements from a selection of geographical locations, mostly in the USA. The performance of the Perez model has been validated numerous times in the literature and can be considered to be robust, even for regions outside of the original training pool.

Table 1 shows the Perez model errors for various test cases that have been conducted for Singapore. In this experiment, four tilted silicon reference cells from Mencke & Tegtmeyer (±5% uncertainty) were installed at 10°, 20°, 30° and 40° respectively, with a common azimuth angle of 64° NE (see Fig. 4). A Kipp & Zonen CMP11 pyranometer (±3% uncertainty) was installed horizontally. In addition, a SPN1 sunshine pyranometer (±5% uncertainty) from Delta-T Devices measured the diffuse horizontal irradiance. The horizontal irradiance measurements were used to calculate the tilted irradiance at four different tilts; the results were then benchmarked with the reference cell measurements. During the conversion, all three loss mechanisms (temperature, spectral loss and reflectance loss) of a reference cell were accounted for. From Table 1 it can be seen that the Perez model errors are well within the measurement uncertainties, which indicates a good performance of the model in a tropical environment (in this case Singapore).

The horizontal-to-tilt irradiance conversion uses two horizontal irradiance components to construct the tilted measurements following the Perez model. What is not shown above is that the diffuse components on the tilt can also be readily calculated. This leads to the following conversion method: two tilted reference cells are used to 'back calculate' the GHI; the modelled irradiance is then benchmarked using the GHI measurements obtained from

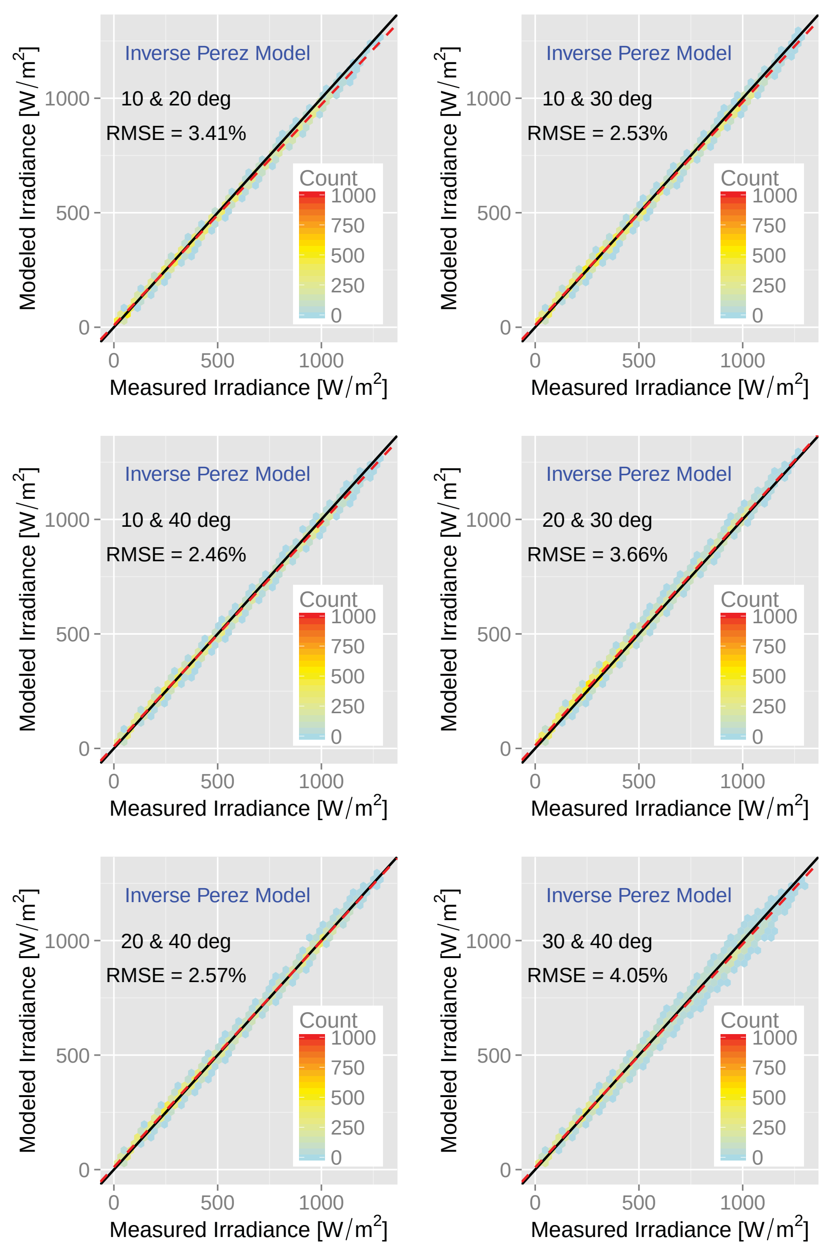


Figure 5. Scatter plots of the 'inverse Perez model' using various combinations of reference cells. A hexagon binning algorithm is used for visualization. The black solid lines are the identity lines, while the red dashed lines are the linear regression lines on the scatters.

Tilted reference cells used	MBE [W/m^2]	RMSE [%]	U95 [%]
10° and 20°	–9.08	3.41	5.60
10° and 30°	–4.22	2.53	4.71
10° and 40°	–3.82	2.46	4.61
20° and 30°	10.59	3.66	5.66
20° and 40°	4.23	2.57	4.79
30° and 40°	–3.71	4.05	7.82

Table 2. Tilt-to-horizontal irradiance conversion errors using the 'inverse Perez model'. The calculated GHI values are compared with the pyranometer measurements. Mean bias error (MBE), root mean square error (RMSE) and the 95% expanded uncertainty (U95) are used as error metrics. All error terms include temperature, spectral loss and reflectance loss corrections.

Credit: Photo courtesy of Phoenix Solar Pte. Ltd.

Figure 6. The first zero-energy house in Singapore: the east-facing roof is tilted at 18.3° (right side of the roof), while the west-facing roof is tilted at 6.1° (left side of the roof).

the horizontally installed CMP11. This conversion is called the 'inverse Perez model'. Fig. 5 and Table 2 show the performance of the inverse Perez model, demonstrating that the modelling errors are smaller than the measurement uncertainty, and that the model can therefore be considered to be robust.

Conversion from tilt to horizontal using one reference cell

One question that might arise is why is it necessary to use measurements from two different tilts to reconstruct the GHI values? The answer is because the global-to-diffuse mapping is non-injective, i.e. it is a one-to-many mapping. In other words, for a particular GHI value, for example 800W/m^2, the corresponding DHI can have a varying range because of different meteorological conditions. Therefore, the use of one reference cell to reconstruct GHI and DHI simultaneously equates to solving for two unknowns using one equation [13]. Including another set of tilt measurements, however, provides an additional equation, which is then sufficient for solving for the two horizontal irradiance components.

Despite the mapping from GHI to DHI being non-injective, the irradiance conversion from tilt to horizontal is still possible by means of a decomposition model. A decomposition model separates DHI and HBI from GHI in situations when the DHI or HBI measurements are not available. Fig. 6 shows the first zero-energy house in Singapore: it has an 18.3°-tilted

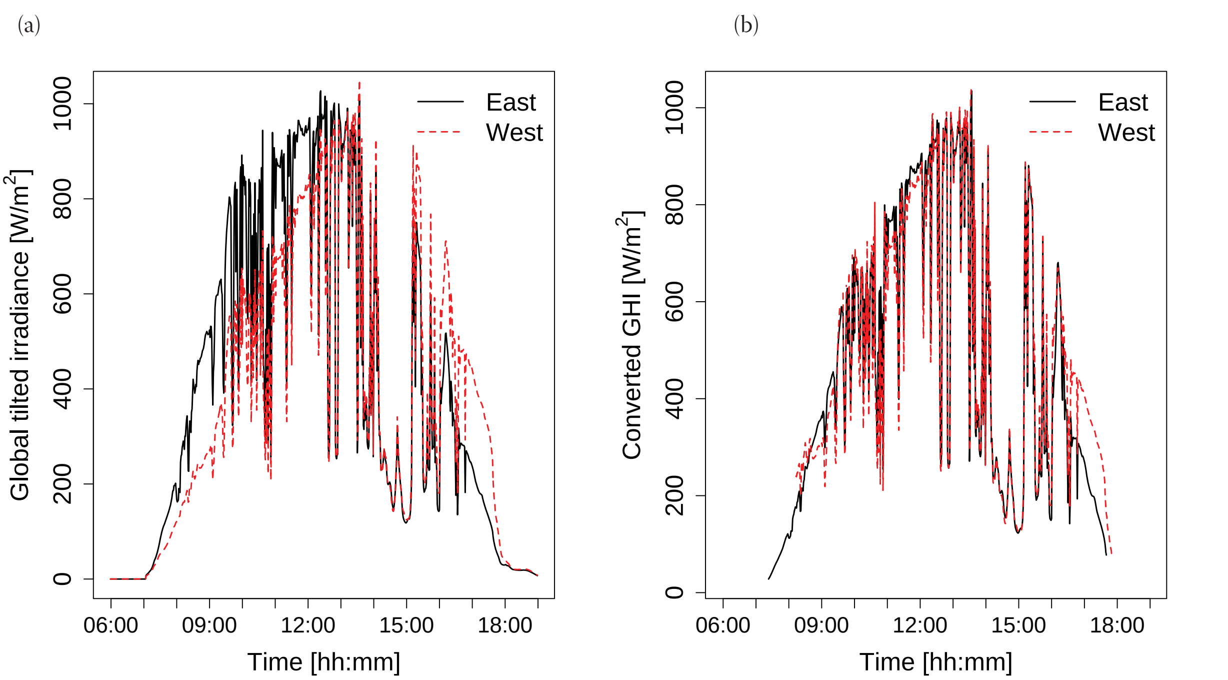


Figure 7. (a) Global tilted irradiance measurements on 5 July, 2011; (b) irradiance conversion from tilt to horizontal using only one reference cell. The converted GHI values using the east-facing and west-facing reference cells are in agreement.

Data	East MBE [W/m²]	East RMSE [%]	East U95 [%]	West MBE [W/m²]	West RMSE [%]	West U95 [%]
2011 Jan	–6.35	15.21	30.07	–1.87	9.65	18.96
2011 Feb	–15.66	12.00	24.40	–11.47	6.28	13.33
2011 Mar	–4.30	13.56	26.67	–4.78	9.29	28.39
2011 Apr	–9.14	12.80	25.44	–13.78	8.29	17.54
2011 May	–5.52	12.14	23.93	–12.90	8.10	17.16
2011 Jun	–5.18	13.45	26.51	–6.99	9.55	19.10

Table 3. Performance of the decomposition model of irradiance conversion from tilt to horizontal over a period of six months. TGI measurements from the individual reference cells are used as inputs; the outputs are benchmarked against the respective SPN1 GHI measurements. Mean bias error (MBE), root mean square error (RMSE) and the 95% expanded uncertainty (U95) are used as error metrics. All error terms include temperature, spectral loss and reflectance loss corrections. (Adapted from Yang et al. [13].)

east-facing roof and a 6.1°-tilted west-facing roof, and reference cells are installed in each of the two corresponding POAs. An SPN1 sunshine pyranometer is installed horizontally at the ridge of the roof (sensors are not visible in the photograph). The application of the decomposition model is demonstrated using this set-up.

As the aim of this section is to reconstruct GHI using only one reference cell, the two reference cells (at different tilts) are used to separately reconstruct GHI. In the following experiment, the diffuse irradiance component obtained by SPN1 was assumed to be an unknown. The TGI measurements from the east-facing roof reference cell were decomposed into TBI and TDI by applying decomposition models (see Erbs, Klein, & Duffie [14], for example). The decomposed tilted irradiance components were then used to reconstruct GHI. A similar experiment was conducted using the west-facing reference cell alone. Table 3 shows the error terms in these two experiments.

It is concluded from Table 3 that the reference cell with smaller tilt produces better GHI estimates. It is also observed that the RMSE varies with the months owing to the fact that the decomposition model is very sensitive to sky conditions. Lastly, the errors of the tilt-to-horizontal conversion using only one reference cell are larger than those using two reference cells.

To analyse the results further, the converted GHI values are compared. In principle, if the conversion is accurate within an acceptable range, the GHI values obtained using the east-facing reference cell should be similar to those obtained using the west-facing reference cell. Fig. 7 shows a visual comparison of the converted GHI. In Fig. 7(a), GTI measurements on 2011 July 5 are plotted: it is clear that in the morning, the east-facing reference cell received more irradiance than the west-facing reference cell, whereas in the afternoon, the west-facing reference cell received more. In Fig. 7(b), it can be seen that the converted GHI values using the east-facing reference cell agree with the conversion results using the west-facing reference cell. Although the tilt-to-horizontal conversion errors when using a single reference cell are larger than those when using two reference cells, the conversion accuracies are still in the range of ~10% RMSE, which is acceptable for both PR calculations of PV systems without on-site readings and irradiance forecasting for power systems operation.

Figure 8. An interactive tool developed by SERIS, showing a live irradiance map taken at 12:00 noon on 1 February, 2014. Locations of the 25 irradiance measuring stations (numbered 401–425) in Singapore are shown. (Map: Google Maps, retrieved 1 February, 2014.)

Generating area-wide irradiance maps

Using the conversion technique described above it is now possible to combine readings from both horizontal pyranometers and reference cells in the POA, which helps in the creation of a denser network of sensors. To generate a fully spatially-resolved 2D irradiance map, a suitable interpolation algorithm needs to be developed. Conventional interpolation techniques – such as inverse distance-weighted interpolation, various types of kriging and optimal interpolation – have strengths and weaknesses in different circumstances.

Application of the spatio-temporal interpolation model developed by SERIS for the case of Singapore, using the readings from 25 stations for an area of ~700km^2, resulted in a fully interactive irradiance map for the country, shown in Fig. 8. The map displays the irradiance at any point within this area, either via cursor movements or by entering zip codes. When the 2D irradiance maps are referenced with actual measurements from the 11 PV systems that were shown in Fig. 2, the uncertainties range from 6 to 31% for fine-time-resolution (<1 minute) irradiance interpolation, depending on the location and the spatial resolution. The higher values are naturally found in the outer areas of the island, where there are only one or two stations available for interpolation. This is less critical in larger countries, where the perimeter effect is less pronounced. The average uncertainty in the area with more sensors is 14%. This value can be significantly reduced through extending the sensor network, which would be possible by adding reference cell readings from existing – and future – PV installations and leveraging the conversion technique as described above.

> "Leveraging on the increasing number of PV systems that have irradiance measurement devices installed is a cost-effective method for improving the accuracy of forecasts."

Conclusion

Generating large-area irradiance maps would solve two challenges in today's PV industry: how to assess the performance of PV systems that do not have on-site irradiance measurement equipment installed, and creating a critical input for forecasting irradiance (and eventually the energy output of PV systems) in a spatially-resolved way for the grid operator to schedule the conventional power plants accordingly. Such irradiance maps require a dense network of irradiance sensors, which either is costly or does not necessarily provide the time or spatial resolution required (e.g. when using satellite data). Leveraging on the increasing number of PV systems that have irradiance measurement devices installed, typically in the plane of array, is therefore a cost-effective method for improving the accuracy of such forecasts. The technique described in this paper allows POA readings to be converted into GHI data, since the latter are required for a homogeneous, interpolated irradiance map. This has been successfully demonstrated in the case of Singapore.

References

[1] Nobre, A. et al. 2012, "High performing PV systems for tropical regions – optimization of systems performance", *Proc. 27th EU PVSEC*, Frankfurt, Germany.

[2] Dong, Z. et al. 2014, "Satellite image analysis and a hybrid ESSS/ANN model to forecast solar irradiance in the tropics", *Energy Conv. Man.*, Vol. 79, pp. 66–73.

[3] Yang, D. et al. 2013, "Block matching algorithms: Their applications and limitations in solar irradiance forecasting", *Energy Procedia*, Vol. 33, pp. 335–342.

[4] Gu, C. et al., "Spatial load forecasting with communication failure using time-forward kriging", *IEEE Trans. Power Syst.* [in press].

[5] Dong, Z. et al. 2013, "Short-term solar irradiance forecasting using exponential smoothing state space model", *Energy*, Vol. 55, pp. 1104–1113.

[6] Yang, D., Jirutitijaroen, P. & Walsh, W.M. 2012, "Hourly solar irradiance time series forecasting using cloud cover index", *Solar Energy*, Vol. 86, pp. 3531–3543.

[7] Yang, D. et al. 2013, "Solar irradiance forecasting using spatial-temporal covariance structures and time-forward kriging", *Renewable Energy*, Vol. 60, pp. 235–245.

[8] Yang, D. et al., "Solar irradiance forecasting using spatio-temporal empirical kriging and vector autoregressive models with parameter shrinkage", *Solar Energy* [in press].

[9] Meydbray, J., Emery, K. & Kurtz, S. 2012, "Pyranometers, reference cells: the difference", *pv magazine* (April).

[10] Ye, J. et al., "Determination of the PV module temperature coefficient from outdoor testing data" [submitted to *Solar Energy*].

[11] Perez, R. et al. 1987, "A new simplified version of the Perez diffuse irradiance model for tilted surfaces", *Solar Energy*, Vol. 39, pp. 221–231.

[12] Perez, R. et al. 1990, "Modeling daylight availability and irradiance components from direct and global irradiance", *Solar Energy*, Vol. 44, pp. 271–289.

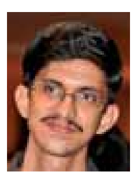
[13] Yang, D. et al. 2013, "Evaluation of transposition and decomposition models for converting global solar irradiance from tilted surface to horizontal in tropical regions", *Solar Energy*, Vol. 97, pp. 369–387.

[14] Erbs, D.G., Klein, S.A. & Duffie, J.A. "Estimation of the diffuse radiation fraction for hourly, daily and monthly-average global radiation", *Solar Energy*, Vol. 28, pp. 293–302.

About the authors

Dazhi Yang received his B.Eng. and M.Sc. from the National University of Singapore, where he is currently working towards a Ph.D. His research interests include statistical modelling for solar irradiance, forecasting methodologies and environmental data mining.

André Nobre received his M.Eng. in technology management from the University of South Australia. He is currently working towards a Dr.Eng. at the Universidade Federal de Santa Catarina in Brazil; the topic of his study is short-term irradiance forecasting for photovoltaic applications in tropical regions.



Rupesh Baker graduated with B.Eng. (mechanical engineering) from the National University of Singapore and has been involved in renewable energy consulting over the last three years. As a PV systems engineer at SERIS, he provides technical consulting services to project developers in Singapore.

Thomas Reindl received his Ph.D. from the University of Regensburg, Germany, and an MBA from INSEAD. He is currently the deputy CEO and cluster director of solar energy systems at SERIS. His research interests include high-efficiency solar PV systems and components, solar potential analysis, irradiance forecasting and PV grid integration.

Enquiries

Dr. Thomas Reindl
Email: thomas.reindl@nus.edu.sg
Website: www.seris.nus.edu.sg

Fab & Facilities

Materials

Cell Processing

Thin Film

PV Modules

Power Generation

Fundamentals of the commissioning tests of large-scale PV power plants

Jorge Coello & **Leonardo Perez**, Enertis Solar, Madrid, Spain

ABSTRACT

This paper presents the minimum aspects to consider for the commissioning of large-scale PV plants. This methodology has been successfully implemented in the commissioning of more than 40 PV facilities worldwide and it represents a very useful tool to assure the good performance of the PV project.

Introduction

In order to guarantee their investment, developers of PV facilities require the contractor to perform a series of tests that determine the correct operation of an installation prior to its commissioning. These tests are referred to as the commissioning tests of a PV project and are essential in both technical and economical terms.

The purpose of the main tests involved in the commissioning of PV plants is to reduce the uncertainty of the final performance of the PV plant under construction. Dealing with this uncertainty is essential for the three main parties involved in the construction of a PV plant: the owner, the contractor and the bank which finances the construction. For the owner, this methodology assures the quality of the components and installation while providing accurate information for the energy production estimation. For the contractor, it is useful to guarantee that total installed peak power and PV plant performance agree with the purchase contract. For the bank, it is clearly useful to reduce an important parameter – the risk – and to offer better credit conditions.

"The purpose of the main tests involved in the commissioning of PV plants is to reduce the uncertainty of the final performance of the PV plant under construction."

Methodology

Enertis Solar specializes in the provision of integral services within the solar PV market. Its approach focuses on the implementation of quality-control processes in each phase of the project, from PV module manufacturing to the design, installation and operation of a large PV plant. The company is a pioneer in the implementation of quality-assurance programmes: in the past it has proposed the carrying out of extensive quality control for PV modules [1], the monitoring of power degradation in PV modules [2], the introduction of electroluminescence (EL) imaging in the quality control of large PV plants [3], a methodology for estimating the actual installed peak power from the measurement of a sample of PV modules in the lab, the implementation of additional field tests to estimate peak power [4], and so on.

The methodology proposed in this paper for the commissioning has a wider scope and includes certain procedures that aim to verify not only the PV modules, but also the whole construction, components and performance.

It is important to note that these procedures should be included in advance in construction contracts in order to facilitate aspects such as fixing the price to the actual installed peak power or the acceptance and rejection of components, among others.

The proposed methodology can be divided into four main groups:

1. Mechanical completion
2. Electrical completion
3. Monitoring system
4. Availability and performance ratio

Mechanical completion
• Inspection to ensure structure built in accordance with plant layout designs (spacing, tilt, orientation, etc.) • Visual inspection of support structures, including galvanizing defects, rust, cracks, torque, etc. • Foundations inspection

Table 1. Main aspects of the mechanical completion.

Electrical completion
PV modules and strings • Verification of peak power • Verification of I_{sc} and V_{oc} • Polarity • IR thermography
AC/DC boxes and system • Visual inspection (fuses, control terminals, fuse holders, cable entry, cable glands and seals, etc.) • Test of breakers and protections • Electrical continuity and insulation resistance of cables • Electrical grounding • Voltage drops
Inverters • Visual inspection • Efficiency of the inverter • Maximum power point tracking • Verification of voltage and current
Transformers • Visual inspection • Torque of connections

Table 2. Main aspects of the electrical completion.

The aim of this paper is to describe some of the tests included in the above-mentioned groups; these tests should be regarded as the minimum requirement for a good commissioning.

Mechanical completion

The mechanical completion includes all inspections related to the support structure (or trackers). The inspections should be performed from the very beginning of the construction in order to avoid recurrent errors and thus minimize the cost of solving any potential issue regarding the structures or their installation. For instance, if a batch of structures is not accepted because of galvanizing defects, and a new consignment is therefore necessary, the installer will then have to discontinue work until the new material arrives, resulting in delays and extra costs. This kind of situation can be avoided if the mechanical completion verification is carried out during the construction and not just before the commissioning. Table 1 presents crucial aspects that need to be included within the mechanical completion review.

Electrical completion

The electrical completion includes many inspections that can be done during the construction stage (peak power, insulation resistance, visual inspections, etc.). There are many others, however, that can be performed only when the facility is in operation (voltage drops, efficiency of inverter, infrared (IR) thermography, etc.). For this reason it is very important to dedicate considerable effort to seamlessly accommodating the inspections in the construction and testing schedules. The electrical completion is divided into the four main subgroups shown in Table 2.

Monitoring system

The monitoring system is a very important tool for the correct operation and maintenance of the PV plant; the installed solution should be flexible, precise and adaptable. It is the authors' recommendation that the system offer two operation possibilities: a basic level and an analysis level.

> "The monitoring system is a very important tool for the correct operation and maintenance of the PV plant."

Traditionally, the commissioning of the monitoring system has been based on checking the installation and verifying that the SCADA (supervisory control and data acquisition) provides reasonable values. In the authors' experience, this methodology is not effective, and ultimately the owner does not really know how the facility works. For this reason, the commissioning of the monitoring system should consist of two main procedures:

1. *Hardware and installation:* all sensors should be checked and the traceability of their calibration certificates verified. It is important that sensors be calibrated in a laboratory that complies with IEC 17025 [5] and be included in an annual calibration plan. Moreover, the correct installation of all components should be checked: many irradiance sensors, for instance, have been found with important tilt differences with respect to the modules.

2. *Data acquisition and communication:* the test should be performed to verify that the monitoring system operates in accordance with IEC 61724 [6]. The minimum scope of this procedure should consist of the verification of irradiance, temperature, voltage, current, power, etc., including the verification of:

- linearity of response
- stability
- integration
- zero integral value

Availability and performance ratio

Unavailability is defined as the period of time during which the PV facility is not producing energy at full capacity. It should be noted that losses of availability may occur

Figure 1. Oxide on a structure as a result of insufficient galvanizing.

Figure 2. An incorrectly installed omega junction.

within the PV plant premises, for which the operation and maintenance contractor is liable, or outside the PV plant facilities, i.e. in the transmission infrastructures. In the authors' experience, an availability of 98% is adequate and likely to be achievable by most of the large PV facilities.

The performance of a PV plant is expressed by the performance ratio (PR) factor, which is defined as a percentage representing the ratio between the expected energy output in real conditions (taking into account all of the losses that occur in the energy generation) and the theoretical energy output in ideal conditions.

The PR measurement should be carried out during a period of 240 hours of continuous operation. The protocol establishes that the availability of the plant must be 100% and the availability of the recorded data should be at least 99.9%. The availability of the plant is analysed through the study of the low-voltage meter records, the alarm records of the inverters, and the trackers' position when applicable. In this test period, the protocol establishes that the real production (the energy produced by the plant during the test period) has to be greater than or equal to the theoretical production (the energy that the plant would produce in the guaranteed performance conditions).

Methodology application

A third party involved in the supervision of commissioning tests must be totally independent and possess extensive technical know-how. An accredited laboratory seems to be the best option for carrying out these services, since its staff includes experienced engineers and scientists with Ph.D. degrees who specialize in photovoltaic energy. Moreover, the IEC 17025 accreditation guarantees complete independence. Three different possibilities of collaboration exist and can be classified according to their confidence levels:

1. *Tests totally performed by an accredited laboratory* (high confidence level). This is the option preferred by the bank; however, in the case of large PV facilities, the cost can be high if the procedures and the selection of samples are not well designed.

2. *Tests partially performed by the contractor under supervision of an accredited laboratory* (medium–high confidence level). This option is a combination of critical tests performed by an accredited laboratory (peak-power measurement, inverter efficiency test, etc.) and simple tests performed by the contractor and supervised by the laboratory (IR thermography, polarity, etc.).

> "A third party involved in the supervision of commissioning tests must be totally independent and possess extensive technical know-how."

3. *Tests totally performed by the contractor under supervision of an accredited laboratory* (medium confidence level). This kind of collaboration is usually the most affordable and most attractive option for the contractor, because the externalization of tests is minimized.

In collaboration types 2 and 3, the laboratory should at least perform all tests on a randomly selected sample and compare the results with those obtained by the contractor. If these are in agreement, the results of the contractor can be validated.

Examples of application

The commissioning testing proposed in this paper has been successfully implemented in more than 40 PV plants

	Facility A
Total capacity	20MWp
Module technology	Crystalline
Total modules	100800
Structure type	10º fixed-tilt 0º azimuth
Total inverters	40 (500kWp)

Table 3. Main characteristics of the tested PV plant.

String	V_M [A]	I_M [V]	P_M [W]	Power deviation
1	617.81	7.87	4864	–1.43
2	622.80	7.85	4892	–0.87
3	625.63	7.65	4784	–3.06
4	626.45	7.73	4842	–1.88
5	635.90	7.70	4899	–0.74
6	634.08	7.73	4901	–0.69
7	624.41	7.78	4855	–1.62
8	629.88	7.63	4803	–2.68
9	626.82	7.55	4731	–4.13
10	627.94	7.69	4832	–2.09
11	619.30	7.59	4703	–4.69
12	631.50	7.77	4908	–0.54
13	634.38	7.83	4969	0.69
14	630.73	7.77	4901	–0.69
15	634.43	7.65	4856	–1.60
16	635.81	7.76	4937	0.03
17	628.40	7.80	4902	–0.67
18	635.54	7.70	4896	–0.79
19	627.41	7.76	4866	–1.40
20	635.21	7.74	4918	–0.35
21	627.06	7.81	4898	–0.74
22	622.44	7.68	4778	–3.19
23	629.54	7.82	4925	–0.20
24	635.69	7.72	4905	–0.60

Table 4. Peak-power measurement results (array field 1, combiner box 1).

SOLAR MEDIA





2014 WORLDWIDE EVENTS

DOING SOLAR BUSINESS UK
One-day seminar
3 June 2014 | Munich, Germany
dsb.solarenergyevents.com

DOING SOLAR BUSINESS AFRICA
One-day seminar
3 June 2014 | Munich, Germany
dsb.solarenergyevents.com

SOLAR & OFF-GRID RENEWABLES WEST AFRICA
Conference
16 - 17 September 2014 | Accra, Ghana
westafrica.solarenergyevents.com

NEXT GENERATION SOLAR PV FINANCE
Conference
29 September 2014 | New York, USA
financeusa.solarenergyevents.com

SOLAR POWER PORTAL GALA AWARDS DINNER
14 October 2014 | Hilton NEC Metropole, Birmingham, UK
sppawards.solarenergyevents.com

SOLAR ENERGY UK
Exhibition
14 – 16 October 2014 | The NEC, Birmingham, UK
uk.solarenergyevents.com

SOLAR ENERGY SOUTHEAST ASIA
Conference
25 – 26 November 2014 | IMPACT, Bangkok, Thailand
seasia.solarenergyevents.com

For further information contact Sue Bradshaw (sbradshaw@solarmedia.co.uk or tel: +44 (0) 207 871 0122).

WWW.SOLARMEDIA.CO.UK

worldwide, in Spain, Italy, the USA, Puerto Rico, India, etc. Some of the results obtained in the commissioning of different PV facilities will be presented in this section.

Mechanical completion: visual inspection of support structures

Figs. 1 and 2 show an example of typical defects detected during the mechanical completion of a large PV plant. Fig. 1 shows that oxide is present on the structure two weeks after its installation. It is very important to perform an adequate galvanizing of the profiles, since the high humidity in tropical locations can be critical for the failure of the project. Fig. 2 shows an incorrectly installed omega junction typically used to fix the modules to the structure.

Electrical completion: peak-power measurement of strings

This test is performed to measure the maximum power of the strings in standard test conditions. It is important to point out that the main purpose of the test is to measure the maximum power in order to detect any defects in the installation and connection of the modules, and not to establish an accurate characterization. The reason for this is that the on-site measurement of maximum power depends on the soiling, electrical interconnection and existing solar spectrum conditions during the test period. Nonetheless, all precautions for minimizing measurement uncertainty should be taken during the tests, which should therefore be carried out by experienced technicians.

The following equipment was used for the maximum-power measurement procedure:

- A reference cell in accordance with IEC 60904-2 [7].
- A temperature sensor to measure cell temperature.
- An electronic load equipped with a data logger to obtain *I-V* curves.

The *I-V* curve was obtained in accordance with IEC 60904-1 [8], while temperature and irradiance corrections were performed in accordance with IEC 60891 [9]. The test was conducted on a sunny day; to minimize spectral errors, the measurements were taken during the period two hours before and after solar noon, when the irradiance in the plane of the modules was above 700W/m^2.

The facility was a 20MW PV plant: the main characteristics are presented in Table 3.

Table 4 shows the test results of 24 strings measured directly in a combiner box and their power deviation values with respect to the nominal value. The power losses due to mismatch and cabling are not considered in the calculation of the nominal power. Fig. 3 shows the peak power of each string within the tolerance range of the modules. The error bars correspond to an uncertainty of ±5% (K = 2). According to the results shown in Table 4, the deviation with respect to the nominal power is lower than the uncertainty of the measurement: all strings can therefore be considered to conform.

Monitoring system: DC voltage verification

The verification of the DC voltage presented in this section was carried out at two large PV plants located in India: Table 5 shows the main characteristics of the plants.

This test aims to verify data provided by the SCADA system for the measurement of the DC voltage in the inverter. The equipment used was a high-precision wattmeter that had been accurately calibrated. The DC voltage values were measured and recorded by the wattmeter; these measurements were then compared with the values displayed by the SCADA system, taking into consideration the uncertainty of measurement.

Data acquisition was performed during sunny days without clouds. To minimize spectral errors, measurements

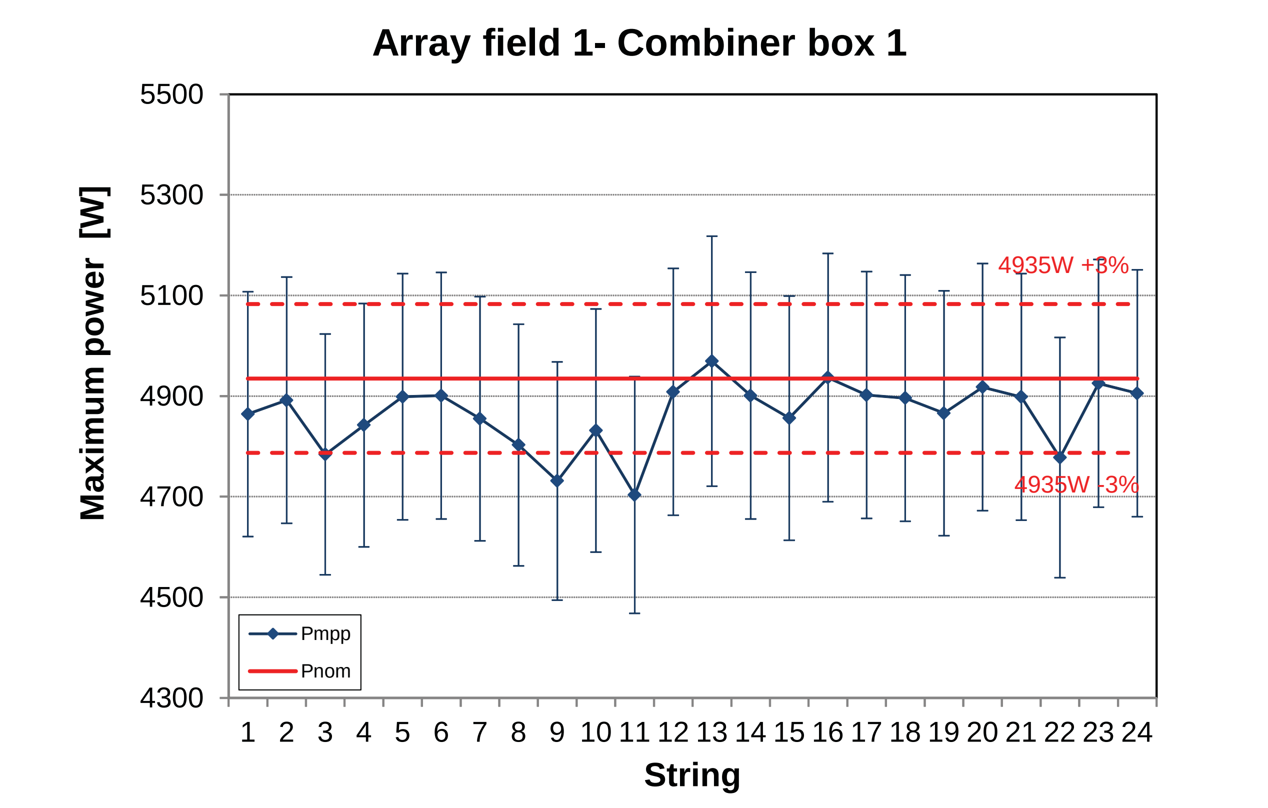


Figure 3. Peak-power position of each string in the tolerance range of the modules (±3%).

were taken during the period three hours before and after solar noon, when the incident irradiance was greater than 500W/m^2. The measurements were collected in one of the lines of the DC input of the inverter.

In accordance with the acceptance and rejection criterion of IEC 61724, the measurement is accepted when the SCADA measurement does not differ from the wattmeter value (reference value) by more than ±1%. Table 6 shows the accepted and rejected measurements.

Results of the DC voltage verification at facility A indicate that out of 361 measurements during the test, 15 samples exceeded the 1% limit: these samples represented 4.15% of the total number. However, better results were obtained at facility B, with the percentage of rejected measurements being 2.77%.

	Facility A	Facility B
Total capacity	5.5MWp	16.7MWp
Module technology	CdS/CdTe (First Solar FS 382)	CdS/CdTe (First Solar FS 382)
Total modules	67200	203100
Structure type	20° fixed-tilt, 0° azimuth	20° fixed-tilt, 0° azimuth
Total inverters	7 (680kWp)	22 (680kWp)

Table 5. Main characteristics of the tested PV plants in India.

	Facility A	Facility B
Total measurements	361	361
Accepted	346	351
Rejected	15	10
Gaps	0	0
% rejected	4.15	2.77

Table 6. Results of the DC voltage verification in the monitoring system.

Availability and performance ratio

The performance of a PV plant is commonly specified in terms of its PR, which is represented by a percentage given by the ratio between the expected and theoretical energy outputs. On the basis of the data provided by the energy meters and the irradiance measured in the PV facilities during an 8-day period, the PR was calculated for both of the facilities detailed in Table 5: the results are given in Tables 7 and 8.

It should be noted that the PR includes the following losses: spectral, angular, shading, soiling, temperature, irradiance level, mismatch, low-voltage wiring, inverter, MPP tracking, availability, degradation, transformation (at plant transformer) and medium-voltage wiring (from plant transformer to plant energy meter). However, neither the medium-voltage wiring losses from the plant's energy meter to the network operator's high-voltage transformer, nor the high-voltage transformer losses, where the recording energy meter is located, are included in the calculation.

Don't let your advertising dollars go down the drain...

Be wise, advertise with the best.

Choose from a range of digital or print advertising solutions and gain brand association and relevant ROI from the world's most read solar news and information resources in English and Chinese language.

Brands of Solar Media:

SOLAR MEDIA

PVTECH · PVTECH · SOLAR POWER PORTAL · DESIGN-BUILD SOLAR · Photovoltaics International · Solar Business focus · Solar Business focus · PVTECH PRO

For advertising opportunities please contact:
Solar Media Ltd, info@solarmedia.co.uk,
Tel +44 (0) 207 871 0122
www.solarmedia.co.uk

> “The results of the implementation of the proposed methodology demonstrated a reduced uncertainty in the final performance of the plants in all cases.”

Conclusions

It is worth noting the importance of assuring quality-control aspects throughout the entire implementation process, beginning at the PV module manufacturing stage and continuing beyond the commissioning, to the operation and management of PV plants that are up and running.

This paper has described some key aspects of one specific step of the quality-control process: the commissioning tests. This was considered to be the most critical stage for the future performance and reliability of a PV installation. The proper commissioning of a new PV installation allows the accurate determination of essential aspects: the detection of early failures and the assurance of availability once the plant is in operation.

The results of the implementation of the proposed methodology for the commissioning tests of large PV plants demonstrated a reduced uncertainty in the final performance of the plants in all cases. The consequence of this is an increase in investor confidence in the PV market.

Facility A			
Date	*E* [kWh]	I_{gen} [Wh/m^2]	*PR* [%]
27 Feb	33,891	7,384	82.79
28 Feb	33,622	7,448	81.42
01 Mar	31,183	6,556	85.80
02 Mar	34,859	7,701	81.66
03 Mar	34,571	7,774	80.21
04 Mar	34,659	7,733	80.85
05 Mar	34,029	7,548	81.32
06 Mar	33,713	7,367	82.54
Total	270,526	59,509	82.00

Table 7. Performance ratio calculations for facility A.

Facility B			
Date	*E* [kWh]	I_{gen} [Wh/m^2]	*PR* [%]
11 Mar	89,972	6,444	83.33
12 Mar	89,963	6,412	83.74
13 Mar	54,851	3,693	88.65
14 Mar	100,720	7,009	85.77
15 Mar	105,255	7,293	86.13
16 Mar	84,606	6,251	80.80
17 Mar	104,679	7,458	83.77
18 Mar	101,908	7,402	82.17
Total	731,955	51,962	84.07

Table 8. Performance ratio calculations for facility B.

References

[1] Coello, J. et al. 2008, “Quality control during the supply of PV modules: Fundamental key to guarantee the profitability of PV installations”, *Proc. 23rd EU PVSEC*, Valencia, Spain, pp. 3784–3787.

[2] Coello, J. 2011, “Degradation of crystalline silicon modules: A case study on 785 samples after two years under operation”, *Proc. 26th EU PVSEC*, Hamburg, Germany, pp. 3500–3503.

[3] Coello, J. 2011, “Introducing electroluminescence technique in the quality control of large PV plants”, *Proc. 26th EU PVSEC*, Hamburg, Germany, pp. 3469–3472.

[4] Coello, J. et al. 2012, “Verification of the installed peak power in the commissioning tests of large PV plants”, *Proc. 27th EU PVSEC*, Frankfurt, Germany, pp. 3983–3985.

[5] ISO/IEC 17025:2005, “General requirements for the competence of testing and calibration laboratories”.

[6] IEC 61724:1998, “Photovoltaic system performance monitoring – Guidelines for measurement, data exchange and analysis”.

[7] IEC 60904-2:2007, “Photovoltaic devices – Part 2: Requirements for reference solar devices”.

[8] IEC 60904-1:2006, “Photovoltaic devices – Part 1: Measurement of photovoltaic current-voltage characteristics”.

[9] IEC 60891:2009, “Procedures for temperature and irradiance corrections to measured I–V characteristics”.

About the authors

Jorge Coello obtained a Ph.D. in photovoltaic solar energy in 2009 from the Solar Energy Institute of the Polytechnic University of Madrid. With 14 years' experience in the solar energy sector, he currently manages the R&D department at Enertis Solar and has published more than 20 scientific articles related to photovoltaic energy.

Leonardo Perez obtained his master's degree in solar energy in 2010 and is currently a Ph.D. candidate in photovoltaic solar energy at the Solar Energy Institute of the Polytechnic University of Madrid.

Enquiries

Jorge Coello, Enertis Solar
Calle Gomera 10
San Sebastián de los Reyes
28703 Madrid
Spain

Tel: +34 91 651 70 21
Fax: +34 91 652 63 77
Email: jorge.coello@enertis.es
Website: www.enertis.es

Photovoltaics International

Advertisers & Web Index

ADVERTISER	WEB ADDRESS	PAGE NO.
ASYS Auto GmbH	www.asys-solar.com	53
BTU International	www.btu.com	45
ET Solar International Ltd	www.etsolar.com	33
EU PVSEC 2014	www.photovoltaic-conference.com	81
Heraeus	www.pvsilverpaste.com	OBC
IEEE	www.ieee-pvsc.org	95
Intersolar	www.intersolarglobal.com/en/intersolar/global-map.html	21
JA Solar Investment China Ltd	www.jasolar.com	IFC
Levitech	www.levitech.nl	49
Luvata Pori Oy	www.luvata.com/sunwire	83
Manz AG	www.manz.com	55 & 67
SCHMID Group/Gebr SCHMID GmbH	www.schmid-group.com/tinpad	37
SNEC	www.snec.org.cn	59
Spire Corporation	www.spiresolar.com	9
Sungrow Power Supply Co Ltd	www.sungrowpower.com	15
Von Ardenne	www.vonardenne.biz	65
Wuxi Suntech Co Ltd	www.suntech-power.com	5

To advertise within Photovoltaics International, please contact the sales department: Tel +44 (0) 20 7871 0122

Photovoltaics International

NEXT ISSUE:

Very high efficiency PERC cells | PV system performance testing | CIGS comeback part 2

THE INDISPENSABLE GUIDE FOR MANUFACTURERS IN SOLAR

Photovoltaics International contains the latest cutting edge research and technical papers from the world's leading institutes and manufacturers.

Divided into seven sections; Fab & Facilities, Materials, Cell Processing, Thin Film, PV Modules, Power Generation and Market Watch, it is an essential resource for engineers, senior management and investors to understand new processes, technologies and supply chain solutions to drive the industry forward.

An annual subscription to **Photovoltaics International**, which includes four editions, is available at a cost of just $199 in print and $159 for digital access.

Make sure you don't miss out on the ultimate source of PV knowledge which will help your business to grow!

SUBSCRIBE TODAY.

WWW.PHOTOVOLTAICSINTERNATIONAL.COM/SUBSCRIPTIONS

Harsh reality of the post Brussels/Beijing anti-dumping agreement

Getting on for a year on from Brussels and Beijing reaching a compromised solution for the supply of Chinese solar PV components to Europe, it is a valid question to ask now: how has this panned out?

First, we should recall some of the goals of those that brought the case, and from the European Commission that brokered the final deal:

- Chinese supply was to be capped (in gigawatt terms) coming into Europe, based on a percentage of expected annual demand;
- A floor pricing was to be established, in particular for c-Si modules from China;
- European solar PV manufacturers would subsequently have the scope to sell at higher ASPs than this floor pricing, allowing them to be competitive again and see higher margins by virtue of (European-perceived) quality.

So has this worked? Well, for the first two bullets above, the answer is yes. But for the third one, it is far from clear. Let's look then in more detail at the post Brussels/Beijing reality.

Leading Chinese Tier 1 c-Si module suppliers now have an accepted pricing level that is higher than they may have had before and is fixed. Downstream buyers of the modules no longer have any scope for heavy handed price haggling. Visibility for the Chinese suppliers is good. So long as the project economics stack up in the key European markets at the module floor price, then the door is open for Chinese module supply.

But it is not what the Chinese suppliers are doing now (with most sticking rigidly to the new legal framework of supply to Europe). It is what had happened to the rest of the PV suppliers – the European (and non-European) makers – that puts an altogether different slant on the post trade deal landscape.

Apart from a very small subset of solar PV module suppliers to Europe (mainly the premium brand suppliers), other module suppliers are having to price below the Chinese floor price in order to get any business: the total opposite of the original goal of all the lobbying and political settlements!

Why? Well, one of the things that the EC failed to grasp was that money is king with those that finance solar PV projects. Only modules that are bankable – and meet the due diligence processes of investors and insurance companies – can be used for large projects. And here, the list is dominated by Chinese module suppliers that have global multi-gigawatt supply potential and are deemed low-risk with good quality.

Either you are on the list of approved modules suppliers, or you are not. And the harsh reality is that the Chinese market leaders feature prominently on almost all of these bankable lists in Europe.

Politicians (and PV manufacturers that fail to meet the due diligence processes) can't change these lists. If that means buying Chinese modules at the floor price level, then so be it. And the rest are left to undercut the floor pricing in order to get business often on small rooftops or in the residential markets.

But the questions don't end there. When the EC did its in-house investigation process (that eventually led to a verdict of guilty on the count of dumping against Chinese suppliers), a key consideration (identical to the US ITC case in 2012) was to estimate manufacturing costs outside Europe. If ASPs are deemed to be less than estimated manufacturing costs (or indeed global averages), then a guilty verdict is fairly easy to justify. (The legality of subsidies is different; dumping is based on ASPs in the marketplace.)

Source: JA Solar

Europe's efforts to prevent an influx of cheap Chinese PV equipment has not worked out as intended.

But is there anyone who would argue that – whatever the exact figures were – manufacturing costs in China are not the lowest in the world? Or at least, that European c-Si manufacturers must have higher manufacturing costs than the Chinese, not least because they have smaller (and often older) capacity, higher labour costs and typically play in one part of the c-Si value chain?

So, if non-Chinese suppliers to the European market are having to sell at below the Chinese floor pricing level, are these suppliers not dumping by an even greater margin than the EC concluded the Chinese suppliers were, prior to the floor price coming into effect?

For now, this remains the biggest unanswered question in the whole post EU anti-dumping exercise. Will the EC decide to investigate non-Chinese suppliers (or even some of the European suppliers) selling below the Chinese floor pricing level? And how will these manufacturers justify these pricing levels when their manufacturing costs are certainly well above the Chinese grouping?

Fortunately for the EC, module pricing is somewhat flat in the global PV industry; so, the floor price level probably does not need to be revised now. And the European market size is fairly static in terms of annual demand in 2014. So the boundary conditions for 2014 don't really need to be adjusted this year. Therefore, so long as everyone is happy with the status quo on pricing deals, there is unlikely to be any appetite to introduce any new uncertainty, and policy makers may indeed take this as a stamp of approval on their original deliberations.

However, ASPs aside, once the case runs its course, there will certainly be questions asked about what it has done in order to restore competitiveness for European PV manufacturers selling into their domestic markets, or whether it has unintentionally created the very pricing environment it was meant to avoid in the first place.

This is an edited version of a blog that originally appeared on www.pv-tech.org

Finlay Colville is vice president of NPD Solarbuzz.

MANUFACTURING THE SOLAR FUTURE

Your definitive hardback guide addressing the core needs of the PV industry! **2014**

A collection of cutting edge technical papers from over 150 leading PV experts and authorities.

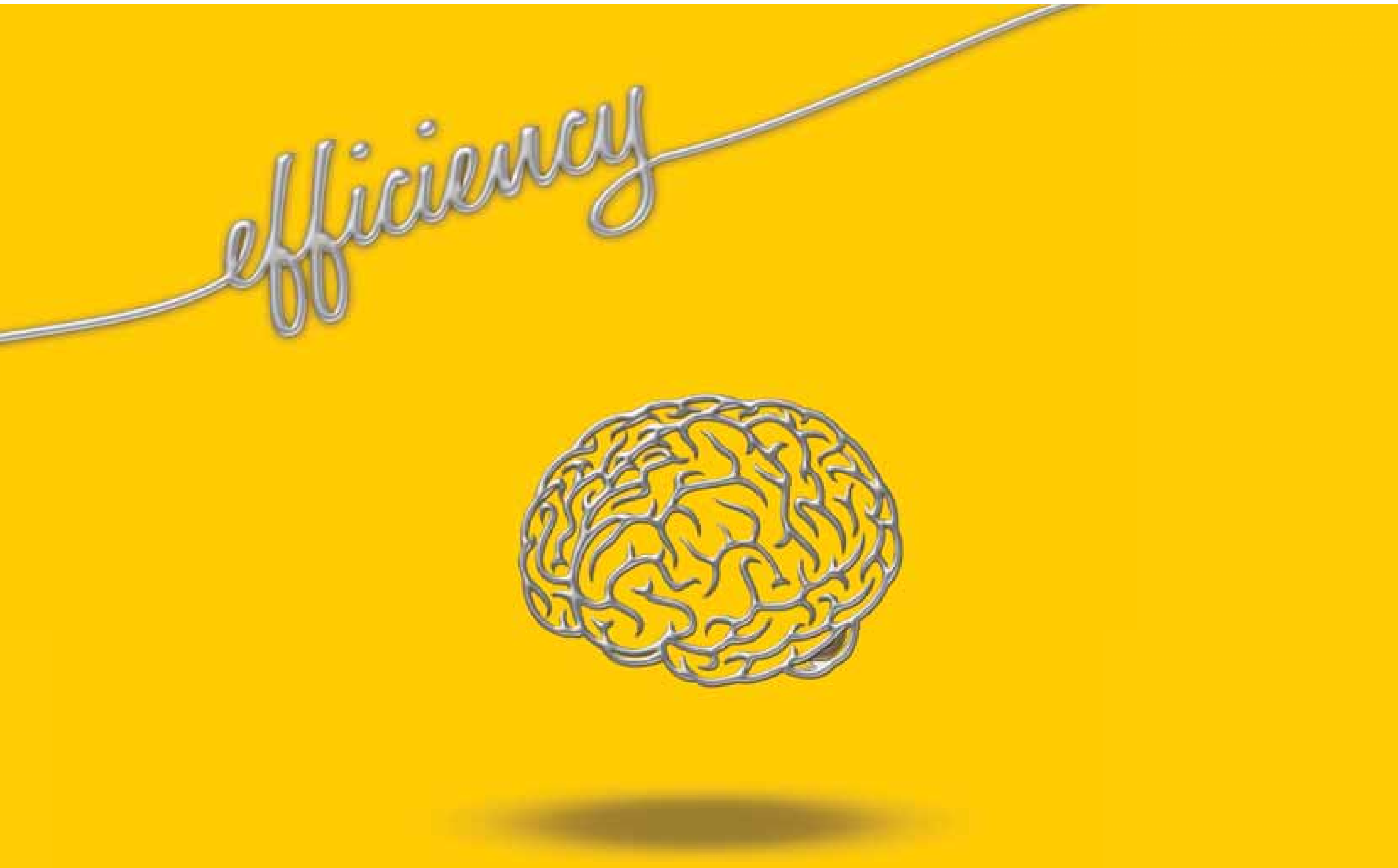
Manufacturing the Solar Future 2014 is the fourth in the Photovoltaics International Production Annual series.

- In-depth technical manufacturing information on PV production processes
- Aimed at helping companies gain the competitive edge
- materials, cell processing, cost of ownership, thin film and power generation
- Indispensable resource for all those seeking to expand their knowledge of current PV manufacturing technologies

www.solarmediastore.com

Contact: Photovoltaics International | 5 Prescot Street | London | E1 8PA | United Kingdom
info@pv-tech.org | www.pv-tech.org | +44 (0) 207 871 0122

Heraeus



Wisdom creates efficiency.

Scan here for
High performance on low surface concentration emitter →

Our Research and Development team is constantly thinking about paste. We are committed to developing leading-edge solutions, which improve the power output and performance of solar cells at a lower cost per watt. We are always mindful of the current and future technology needs of our customers, and are driven to deliver results. So when you think of paste...think of Heraeus.

Leadership through R&D. Breakthroughs via innovation. Achievement by tradition.

Visit us at:
SNEC | Hall W3, Booth 560 | May 20^{th} - 22^{nd}

Heraeus Photovoltaics Business Unit
www.pvsilverpaste.com
China | Singapore | Taiwan | Europe | America | Japan